Developments in the innovation phase

Creating a model of important factors for radically new technologies in the innovation phase

Author

Bram Dees

TU Delft
Delft
University of
Technology

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Bram Dees
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Graduation committee

Chairperson and first supervisor:	Dr. J.R. Ortt, Economics of Technology and Innovation
Second Supervisor:	Dr. L.M. Kamp, Energy and Industry
External Supervisor:	Dr. P.A. van der Duin, Executive Director at The Netherlands Study Centre for Technology Trends

Abstract

Radically new technologies, of which '*the functionality was new to the market or the price-performance ratio was much better than contemporary products*' (Ortt, 2012), can be both risky and rewarding to develop. The challenge is to mitigate the risk and do everything that is necessary to use the technology to its full potential. The pattern of development and diffusion by Ortt & Schoormans (2004) describes three phases for radically new technologies. The innovation phase is the period from invention of a radically new technology until the first market introduction. Two phases follow after the innovation phase: the market adaptation phase starts at commercialization and lasts until large-scale diffusion, the mass market, is reached. The market stabilization phase starts at large-scale diffusion and ends when the technology is substituted by another technology. This research into the first phase develops a model that provides guidance during that innovation phase. The main research question is: **How can important factors that help or hinder the development of radically new technologies during the innovation phase be modelled?** This research question is answered from the perspective of the problem owner of challenges in the innovation phase: the company that develops a product based on a radically new technology.

The main research question is answered after answering three sub-questions: 1) What is the role of the innovation phase in innovation models? 2) What are characteristics of the innovation phase? 3) Which factors help or hinder the development of radically new technologies during the innovation phase?

Sub-question 1: What is the role of the innovation phase in innovation models?

The literature review uses papers from several fields of research: S-curve, pattern of development and diffusion, conditions for large-scale diffusion, Strategic Niche Management, Minnesota Innovation Research Program, Fuzzy Front End, and Sectoral Systems of Innovation. Thinking about the innovation phase from those different perspectives provides a number of interesting insights.

New Product Development is traditionally viewed as a project that develops a product, followed by market introduction and growth of sales. But is "a project" a good name for actions during the innovation phase? That must be reviewed. Also, the role of the company is seen as small, but that must be reviewed for the innovation phase because its role is expected to be more important compared to other phases, when there is possibly just one company working on a certain technology in the innovation phase. Some questions are placed at the notion of factors. Having a basic understanding of dynamics between factors can greatly increase insight in (potential) problems and opportunities. Factors can be described at different levels of detail. The importance of specific factors can vary between phases. All this provides great food for thought for the next research questions.

Sub-question 2: What are characteristics of the innovation phase?

A second literature review is performed, using the same fields of research as in the first literature review, but complemented with more applied research that provides even more empirical data through case studies. To streamline claims from different fields of research to the extent that they can be compared and perhaps even combined, this literature review has four parts: project-level, company-level, market-level, and market creation. The contribution of all selected fields of research to each of the four parts is explored, to find out what happens in each particular part.

Ideas become concrete at the project-level, where expectations are raised and technical developments follow. Such a project runs in the context of the company-level. Increasing expectations, marketing, and managing risk all need top-management support. Support also leads to the needed technical and financial resources for further developments. Many other actors come up at the market-level: the government and its regulatory authorities, research institutes, existing companies, and users. Market creation is not a fourth level, but a process that influences all three levels. The creation of a market proves to be largely unexplored by the selected literature, mention is made of resources, competitions, needed changes, and actions.

The term ‘project’ leads to assumptions of linearity, and limits the scope of necessary actions. The term ‘development efforts’ is adopted as a replacement. That also reflects the conclusion that the role of marketing is currently too small in literature. This literature review points, just like the first literature review, at different levels of detail of factors.

Sub-question 3: Which factors help or hinder the development of radically new technologies during the innovation phase?

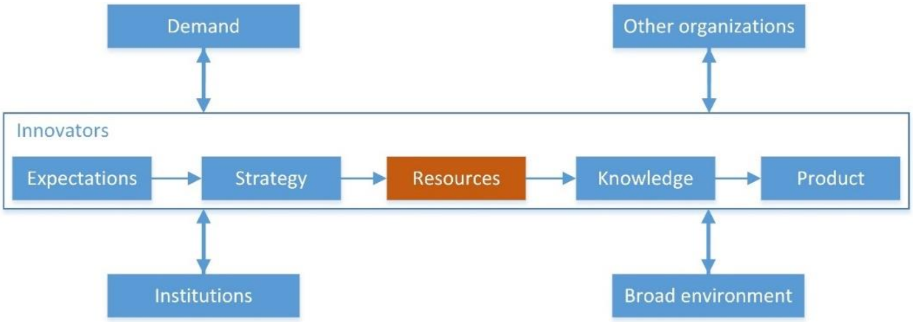
All topics of interest from both the innovation models in the first literature review and all claims in the second literature review, come together in the search of factors for the innovation phase. This is complemented with insights from the case studies. The way that factors can change between phases, their level of detail, and their different roles in different situations are added, this leads to a list of the factors that are most important for the innovation phase. Those are Expectations, Strategy, Resources, Knowledge, Product, Institutions, Other Companies, Demand, and the Broad Environment.

Case studies

Two case studies are performed: 3D printing and Augmented Reality. Both case studies provide new insights and improvements to the list of factors in answer to sub-question 3, but also interesting and detailed storylines about the innovation phases of the two technologies. 3D printing shows that Other Companies should actually be named Other Organizations. Augmented Reality depends on several technologies, the problem of those enabling technologies is solved by including technical resources in the factor Resources. Both case studies show that the Innovators themselves should also be listed, which is therefore added as a factor.

Main research question: How can important factors that help or hinder the development of radically new technologies during the innovation phase be modelled?

The centre of the model is formed by a group of five factors. Those five factors go from Expectations to Product. The Innovator is the self-appointed process owner who wants to create the product. The Innovator tries to manage those five central factors to maximally improve the technology’s chances. There is a special role for Resources, because insufficient focus on this factor results in a complete stop of all development efforts.



The four other factors all have influence on the five central factors. It is up to the Innovators to increase help to the five central factors and to decrease any problems. Examples are to use demonstrations to increase expectations or to secure funding, or to deal with a complete lack of demand for the technology, or with laws that prohibit the product from commercialization.

Reflections and recommendations for future research

An important limitation to the research is the hindsight bias in which the definition of a technology is based on what the technology eventually became. It is also hard to prove a model that is based on factors: the best option is to make it as plausible as possible. The most important recommendations are to add a measurement of the number of Innovators to the innovation phase of the pattern of development and diffusion, to explore the transition from the innovation phase to the market adaptation phase, and to formulate strategies for the innovation phase, based on this model and its factors.

Acknowledgements

There is plenty to acknowledge after this turbulent time. I can honestly say that the last one and a half years required more of me than has ever been asked. It even required more than I could deliver. I have seen my limits and I have been forced to go far beyond them, the consequences of which I can still feel at the time of writing these acknowledgements, in my last days as a student. My last days, because I made it! But I thank this for a large part to people around me.

My wife Maaike never stopped supporting me, I tried to never stop supporting her. Thank you for pushing me, even when I pushed back from time to time.

Changing perspective from being taught in classes to working together at the edge of what is known is refreshing. Roland Ortt and Linda Kamp, my thanks to you for guiding me through this change of perspective. For always bringing this thesis further. For giving me the space I needed. But first and foremost, for going above and beyond what is expected of thesis supervisors, for offering much more support than I would have ever dared to ask. The same goes for Patrick van der Duin. My thanks for your continuous support, and for answering my questions in a way that always solved one problem, but made me face another. It made me look at problems from different angles. And for giving me a place to work, a calm and inviting place to maintain some progress when times were hard.

It was surprising to see that while friends and family weren’t always sure whether to ask for my progress on my thesis, I was always happy to tell them everything. The innovation phase is fascinating, there is a great challenge in clearly describing what you do not understand. This research greatly improved my passion for things that are new, unclear, and challenging. Looking back, I know how I should have started. Thinking back, I know it wouldn’t be the same without the struggle. That goes for life in general.

September, 2019

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3D	Three-dimensional
ANIP	Army-Navy Instrumentation Program (USA)
AR	Augmented Reality
ASTM	American Society for Testing and Materials
AUGSIM	Augmented Simulation
AV	Augmented Virtuality
CAD	Computer-Aided Design
CILAS	The Laser Consortium (France)
CMET	Computer Modelling and Engineering Technology
CNRS	French National Center for Scientific Research
EOS	Electro Optical Systems
FDA	Food and Drug Administration (USA)
FDM	Fused Deposition Modelling
FFE	Fuzzy Front End
FIS	Functions of Innovation Systems
GIS	Geographic Information System
HUD	Heads-Up Display
IP	Intellectual Property
JSR	Japan Synthetic Rubber
JSW	Japan Steel Works
KARMA	Knowledge-based Augmented Reality for Maintenance Assistance
LOM	Laminated Object Manufacturing
MIT	Massachusetts Institute of Technology (USA)
MITI	Ministry of International Trade and Industry (Japan)
NPD	New product development
NPPD	New Product and Process Development
NSF	National Science Foundation (USA)
OPIRI	Osaka Prefectural Industrial Research Institute, or Osaka Institute of Industrial Technology (Japan)
PADSI	Pattern, dashboard, strategy, implementation
PDA	Personal Digital Assistant
R&D	Research and Development
RVP	Relative Value / Price
SCS	Solid Creation System
SLA	Stereolithography Apparatus
SLS	Selective Laser Sintering
SMEs	Small and Medium-sized Enterprises
SNM	Strategic Niche Management
SSI	Sectoral System of Innovation
STL	Surface Tessellation Language or Standard Tesselation Language
STRICOM	Army Strike Command (USA)
STS	Science and Technology Studies
TCP/IP	Transmission Control Protocol/Internet Protocol
TIS	Technical Innovation System
TRE	Telecommunications Research Establishment (United Kingdom)
US	United States (of America)

1. Introduction

Every beginning is difficult, but invention is something beautiful. Working on technological progress is an exciting path. It is in such an environment that this research takes place. The road from a new idea, from a spotted opportunity, all the way until its first introduction to the market. It is a realm of possibilities that most inventions do not survive. It is a risky stage where planned development steps and structure are battling with the chaos and lack of structure. It is the world of radically new technologies, technologies that change life as we know it.

It is easy to dream of a car that drives itself. One of the first steps in this direction stems from 1926, when the first radiographically controlled car was built. A suggestion to make an electronic circuit in the road to guide the cars was made in the 1970s, but it has never been built. The first demonstration of an actual autonomous vehicle was the Navlab from the Carnegie Mellon University in 1984. The innovation phase, the period from invention until first commercialisation, has then begun. More and more researchers worked on the autonomous vehicle, until even the United States Congress itself passed a law to get the United States Department of Transportation working on this. The goal was to demonstrate an autonomous vehicle in 1997, but the project was cancelled. Reduction of research budgets meant the end of funding for the project on autonomous vehicles. While this project stopped, other organizations continued and the first market introduction was an autonomous truck for a mining site in 2008. More advanced vehicles were steadily developed from that moment on, bringing autonomous driving closer to everyday use and closer to public road systems. The diffusion of the self-driving cars is now nearing the mass market, but it is coming slowly. Accidents involving those autonomous vehicles resulted in revoked permits and decreased trust. Laws and regulations do not allow for vehicles to be operated autonomously and have to be changed. It looks like the move of autonomous vehicles to the mass market is certain, but it has cost much time and resources. (Ortt and Dees, 2018). One failed project is mentioned here, but there must have been many failures throughout the many projects and efforts that were conducted on autonomous vehicles. For the United States government it was a lost investment, for other organizations this is bankruptcy.

The pattern of development and diffusion sketches a path from the invention until the first market introduction (the innovation phase), until the start of large-scale diffusion (the market adaptation phase), and until substitution by a new technology (the market stabilization phase) (Ortt and Schoormans, 2004). Guidance is provided during the market adaptation phase by two models: conditions for large-scale diffusion and niche strategies (Ortt, Langley, and Pals, 2013). The conditions for large-scale diffusion use a set of fourteen factors to identify barriers that a radically new technology experiences, barriers that keep it from reaching the mass market, barriers that keep it from reaching large-scale diffusion. The factors also point at the cause of such a barrier. The niche strategies identify combinations of factors, combinations of barriers and their cause to formulate strategies that solve or circumvent the barrier for large-scale diffusion. Those insights help organizations who have a stake in a radically new technology to identify problems and to deal with those problems. This research takes the perspective of the problem owner of challenges in the innovation phase: the company that develops a product based on a radically new technology, and develops the guidance that currently does not exist for the innovation phase, guidance that is needed to get through the innovation phase. In fact, even a clear view on what exactly happens in the innovation phase does not exist. The challenge is to provide some guidance for the innovation phase, to explore how developments are helped and how they are hurt.

2. Research design and research method

This chapter outlines the methodology for this research. There are roughly two parts. The first part works from theory to a conceptual model that shows factors that are important for radically new technologies in the innovation phase, the second part are case studies that challenge, improve, and illustrate the conceptual model.

2.1. Knowledge gap

A 'radically new technology' means that *'the functionality was new to the market or the price-performance ratio was much better than contemporary products'* (Ortt, 2012). The claim that a functionality is new to a market leaves the question open whether that market itself has been created by the radically new technology or whether it replaces an old one, which is similar to what is claimed in the definition of (Garcia & Calantone, 2002): '*radically new inventions establishing landmark new products, and as such, create new industries*'. However, improves on the definition of Garcia and Calantone by taking the term 'landmark new products', which remained undefined before, and explaining how that can either mean a new functionality or a leap in the price-performance ratio. This specificity is clearer and is therefore the definition that is adopted by this research.

When introducing a new product to the market, the goal of companies is to make profit (Cui, Zhao, & Ravichandran, 2011), although other goals like creation of a new market, learn, increase brand awareness, and corporate social responsibility can also play a role. Making profit means trying to achieve (exponential) growth of sales. Companies have to accept that a market will become saturated after some time, flattening the curve that describes diffusion of their product. This is how Rogers (1983) describes a world in which a new product is introduced to the market. That S-shaped curve has been used often. There is much research available that describes and uses the causes, characteristics and consequences of the curve. But how can a company achieve this exponential growth of sales? And how accurate is this description of the world for the case that a technology is introduced?

Rogers knew that his S-shaped curve was a simplified representation of reality. The S-shape is hardly ever smooth, especially in the case of radically new technologies. Ortt and Schoormans (2004) agree with Rogers that the timeline starts at the moment of invention, but after the first market introduction they introduced a new stage, a stage before large-scale diffusion takes off (Figure 1). In that middle stage, the technology is being introduced, sold, changed, developed further, or withdrawn from the market. Different things can happen in different (niche) markets. And only after that chaotic phase is over, the technology can enter large-scale diffusion.

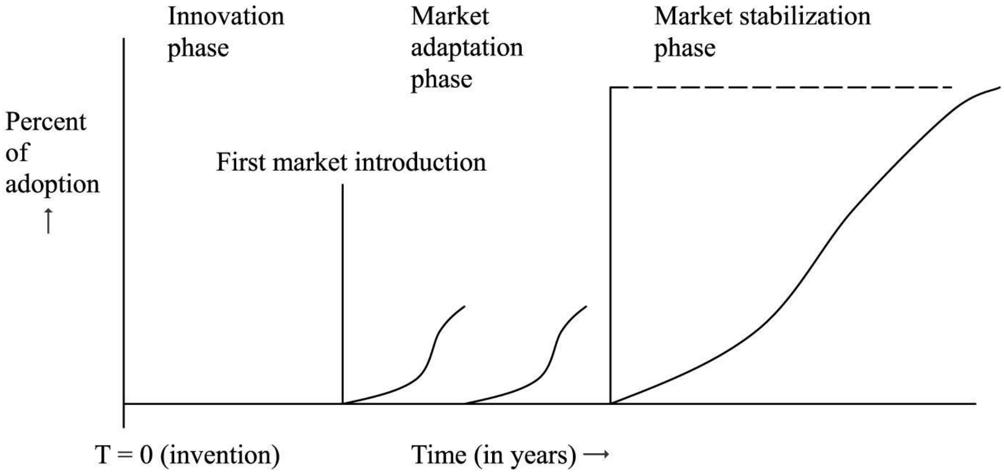


Figure 1 - Pattern of development and diffusion. Source: Ortt and Schoormans, 2004.

The transition from the chaotic phase in niche markets to the exponential growth of diffusion through large-scale diffusion is important to understand. If a company wants to achieve profits through exponential increase of sales, they should understand how and why a new product moves to large-scale diffusion. Ortt and Kamp (forthcoming) describe fourteen factors for large-scale diffusion, this list is already published by Ortt & Dees (2018). Actors, factors and functions can create a barrier that make it impossible for a radically new technology to enter large-scale diffusion. Conditions were found that have to be fulfilled before large-scale diffusion can take off, before the mass market is reached.

The conditions for large-scale diffusion have been proposed by Ortt and Kamp (forthcoming). Factors for the innovation phase have not yet been described in relation to the pattern of development and diffusion. There is a need for a model that gives guidance in the period before the conditions for large-scale diffusion apply, guidance in a phase that is inherently chaotic and deeply unstructured. There is a need for ways to determine what a radically new technology needs to become a product, to become an innovation, to create a new innovation system, ways to begin to understand the chaos that follows right after invention.

Several literature streams include early stages of innovation processes, sometimes as the central focus of the research, but often with only partial timewise overlap with the innovation phase. Research focusses on stages before, during, and after the innovation phase. Models, processes, factors, dynamics, empirical observations, the literature streams contain different elements of the innovation phase and view the phase from different perspectives. The conditions for large-scale diffusion are tailored to use in combination with the pattern of development and diffusion. But they cannot be assumed to be directly and fully applicable to the innovation phase. There is no product price in the innovation phase, a production system does not yet exist and knowledge is only just being developed. A careful review is needed before a list of factors for the innovation phase is formulated.

And that is the knowledge gap that this research addresses. Describing factors that are important for a radically new technology in the innovation phase. Reviewing literature, models, and frameworks to find their connection with the innovation phase gives a knowledge base to work on. Then a dive into the phase itself brings many interesting characteristics to light, helping to understand what is important and what is not, and what role factors play. This research brings the pattern of development and diffusion closer to innovation management practices through filling in the current gap in factors for the innovation phase.

2.2. Research objective

The research objective of this research is to:

Develop a model of factors that help or hinder development of radically new technologies in the innovation phase.

The innovation phase, the time from invention until commercialisation, is a complex period in developments of a radically new technology. That may be surprising: coming up with a new product seems like a relatively simple process, and the time after commercialisation is a very complex time with many actors jumping in and many incremental innovations. The complexity of the innovation phase lies in its lack of structure. Organizations have New Product Development strategies, but radically new technologies are not always invented within such strategies, some emerge elsewhere. Actors start working on an invention, but may stop later. Some inventions are shelved for years.

A phase with so little structure is hard to model and it has not been done before. Similar models are developed, but never for the innovation phase as proposed in the pattern of development and diffusion that is introduced in more detail in Chapter 3. In short, the innovation phase is the phase from invention until commercialisation of a radically new technology. Development of the first model for the innovation phase is both more exciting because it is new work, and harder because there is less theoretical basis to draw from.

This research aims to develop a static model. A chaotic phase is expected to have the importance of factors change over time. Any scenario, any radically new technology has its own characteristics and finding and including all of those, understanding all dynamics between factors, that is a large endeavour. Also, a dynamic model is probably more complex than it is practical. Even if such a model is ever aspired, a static view of the phase in its entirety is a good starting point. The perspective of the model is that of the problem owner of challenges in the innovation phase: the company that develops a product based on a radically new technology. A "company" is slightly arbitrary perspective because innovations can also be developed by individuals or a network of organizations. However, developments by an individual or a network are assumed to closely resemble developments in a company in terms of the aspects that are important in working towards a product that has potential in a niche market or for reaching the mass market. The report often refers to such actors as innovators. An important note is that this points to developers of radically new technologies, individuals or organizations that aim to supply a product. This is not to be confused with the innovators on the demand-side of the market, who are the first group to adopt a new technology. Only the review of the S-curve in paragraph 3.1 deals with innovators on the demand-side of the market. Any other reference to innovators concerns the supply-side of the market: developers of technology and products.

Such a static model is therefore less precise, perhaps less correct, than a dynamic model, especially considering the chaotic nature of the innovation phase. A volatile phase requires continuous adaptation. The model that is developed is not always the most precise, but it is always practical. That is the goal.

2.3. Research questions

The objective to create a model is not very specific. It is stated under the research objective that the model will be static, because a dynamic model is probably more complex than it is practical. This research therefore creates a model from a technology-perspective, meaning that everything in and around the technology is included: the product, the people and organizations working on the product, and every other aspect that has an influence on the product and if and how it reaches the market.

Main research question:
How can important factors that help or hinder the development of radically new technologies during the innovation phase be modelled?

The model consists of factors. Factors are *notions that give understanding of what potentially hinders and helps development and diffusion of a radically new technology*. The addition of the word 'important' implies that there are many factors and that only the most important of those are included. Importance of a factor is primarily based on what selected literature does and does not mention about the innovation phase. Factors that are found in every model are assumed to be important, factors that are mentioned only once are considered and discussed. This method is complemented with case studies. Will this lead to an exhaustive list of all factors that have influence on the development of radically new technologies? No, it will not. But it does provide a view of the most important factors.

The specificity of the radically new technologies excludes incremental innovations. An incremental improvement of washing powder, for example, does not completely overhaul production methods, distribution, or use of the product. Adaptation is needed, but within certain limits. Radically new technologies are those technologies that discontinue the status quo, new combinations of actors are needed at both the supply and the demand side of the market (Ortt & Schoormans, 2004). Perhaps even a new market is created, and with that, the entire network around it. At the very least, there are many more factors to consider for a radically new technology than for an incremental innovation. At the most, all factors and their interactions differ and the way of bringing such an innovation further requires a radically different way of working.

Sub-question 1:
What is the role of the innovation phase in innovation models?

The very first step in understanding the innovation phase is exploring its context and its basic outlines. There are many models that consider innovation in its more radical sense, all showing and explaining certain aspects of it. Many perspectives joined form a colourful picture of what happens in and around the innovation phase. Understanding what happens before and after the innovation phase shows what journey is taken within the innovation phase.

Sub-question 2:
What are characteristics of the innovation phase?

The innovation phase is viewed from different perspectives which come forward in the innovation models of sub-question 1. Diving further in those models, we find many actors, factors, activities, mechanisms, goals and other phenomena in the innovation phase that (can possibly) influence the development and diffusion of the technology. This question dives into all details of the innovation phase, while maintaining an open view to it, 'characteristics' is a rather broad term. The goal is to understand what happens, what could happen, and what should happen in the innovation phase. And also gather enough insight to make formulation of factors possible.

Sub-question 3:
Which factors help or hinder the development of radically new technologies during the innovation phase?

a) Based on theory.
b) Based on case studies.

It was shortly introduced under the main research question what is meant with factors and their importance. One matter that remains is the helping or hindering by the factors. A restaurant owner who attributes his low profits to a lack of customers may have found a problem, while the actual cause of the problem is found in the marketing. And if marketing is indeed found to be the problem, is it then the lack of a marketing strategy that is the problem? Or is it hard to find a marketing manager? Or has one specific advertisement raised controversy among customers? This simple example makes it hard to pinpoint the problem to one factor. One problem or one opportunity can be formulated in different ways. The characteristics of the innovation phase from sub-question 2 form a basis to draw factors from, but factors must be understood better to prevent ending with a complex, unusable, conflicting entanglement of factors.

2.4. Conceptual framework methodology

This research concerns a connection between the innovation phase and factors therein, resulting in an in-breadth approach to find a set of factors that is elaborate and simplified. As a consequence, the results are generalisable, meaning that the model that is developed is used best for the innovation phase of Ortt and Schoormans (2004), but also relates to other theories on factors for an early stage of an innovation. To illustrate and refine the developed theory, two in-depth case studies are performed.

The research starts with a theoretical part in which all three sub-questions are answered. The conceptual framework development that follows from the answers on the sub-questions is the basis that precedes the empirical part of the research (Yin, 2013). The empirical part of the research is qualitative research which suits the more contemplative and interpreting approach that is aimed for (Verschuren & Doorewaard, 2010).

The empirical part is designed in the form of two case studies. The case studies challenge and improve the found theoretical relations between innovation phase, the factors that help or hinder the development of radically new technologies, and the conceptual model. Although a single case study is easier, a multiple-case study is far more valuable since it will provide more convincing evidence (Yin, 2013). This is especially true in the case of this research since innovation, and the development and diffusion of radically new technologies, is a broad field to research where different cases have very different characteristics. The two case studies offer limited reliability to the research as a whole, since they mostly illustrate the conceptual model and add little proof for it.

We describe the relation between sub-questions in this research (Figure 2). Sub-question 1 is answered in chapter 3 where a literature review discusses several innovation models. Each of those fields of research are continued to the answer to sub-question 2 in chapter 4. Chapter 4 is divided in parts as well, but the fields of research from chapter 3 are each reviewed for their claims about the characteristics of the innovation phase. Each field of research from chapter 3 can therefore contribute to each of the parts of chapter 4. The different parts in chapter 4 are different parts in an innovation system. There are four perspectives: project-level, company-level, market-level, and market creation. Actors, factors, activities, mechanisms, goals and other phenomena are described, leading to a thorough description of the innovation phase at four different levels. As was brought up before, not all factors are the same. A factor can be a cause or a symptom of a problem, for example. And not all factors are necessarily equally important. Combining them is therefore not straightforward, which is why chapter 5 starts with considerations about what factors are, how they differ from each other, and how they change. Chapter 3, chapter 4, and the considerations about factors in chapter 5 collectively contribute to the conceptual model in the second half of chapter 5. Application of this model to two case studies is the final step in chapter 6. This illustration and small proof of the model lead to improvements. This makes the final model and closes this research, after the conclusions in chapter 7 and the discussion in chapter 8.

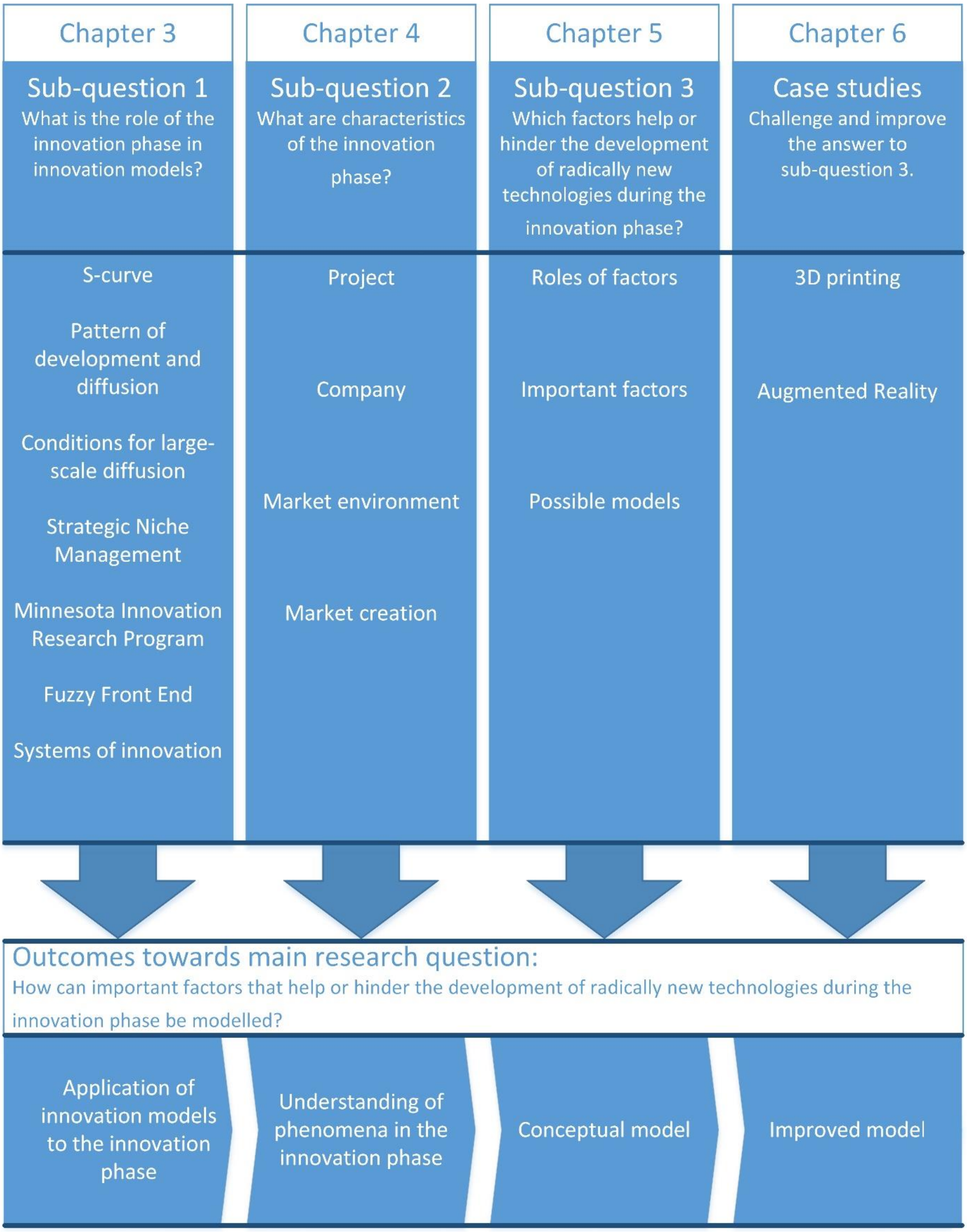


Figure 2 - Structure of the research.

The selected fields of research that describe the context of the pattern of development and diffusion and the conditions for large-scale diffusion are shown below in Table 1. All fields describe innovation, mostly with a focus on more radical innovations and on the chaotic and unstructured beginning of that innovation process. There is a spread in perspectives on innovation processes (project, market, sociotechnical system, or a combination of all those) and in styles (normative or descriptive). See paragraph 3.8.2 for more details on this spread, which is reflected upon after the first literature review.

Table 1 - Selection of literature

Field of study	Article	Sub-q. 1 Models	Sub-q. 2 Characteristics
Towards conditions for large-scale diffusion	Rogers (1983)	X	
	Schroeder (1986)	X	X
	Ortt (2004)	X	X
	Ortt (2013)	X	X
Innovation phase	Moschos (2016)		X
Valley of Death	Markham (2010)		X
	Mannheimer (2016)		X
Strategic Niche Management	Schot and Geels (2008)	X	
	Kemp (1998)		X
Minnesota Innovation Research Program	Schroeder et al., (1986)	X	X
Fuzzy Front End	Koen et al. (2001)	X	X
Systems of innovation	Malerba (2002)	X	X
	Malerba (2004)	X	X

The pattern of development and diffusion starts from the S-curve as proposed by Rogers (Rogers, 1983), which is therefore the first paper to be analysed. By describing how Rogers made assumptions and arrived at the S-curve, it becomes clear where a new model can fill gaps and shortcomings. Ortt (2004) is then analysed in a similar way, enhancing the S-curve with two new phases that do more justice to reality. The transition of the second phase – the market adaptation phase – to the third phase – the market stabilization phase – has been modelled in the next articles. Ortt, Langley, and Pals (2013) describe how certain conditions have a crucial role in the transition from the second to the third phase.

Another perspective has to mirror shortcomings of the pattern of development and diffusion. Instead of a normative perspective, a descriptive perspective can bring observations that are otherwise missed, while still observing innovations in their longitudinal sense: from the beginning until the end. The Minnesota Innovation Research Program has done exactly this and will be reviewed, whilst reflecting on the pattern of development and diffusion. The paper by Schroeder, Van de Ven, Scudder, and Polley (1986) functions as a critical review on the other models, but also as a move towards the second literature review. The descriptive nature of the paper describes well what happened with different innovations in the past, also during their innovation phases. A sociotechnical systems perspective on niches and diffusion is provided by the field of Strategic Niche Management, which is summarized and reviewed by Schot and Geels (2008). Literature on the Fuzzy Front End (FFE) is introduced, mainly to be used in later steps, because of its role in describing the unstructured beginning of innovation. Also the Sectoral System of Innovation is mainly introduced for later use, their perspective on building blocks of innovation systems is a high-level view that other selected literature does not provide.

The field of Science and Technology Studies is considered and excluded, because it appears to focus mainly on a sociological perspective, sometimes enriched with an historical or a philosophical angle, and stays high-level which does not complement the level of detail in which this research explores the innovation phase.

2.4.1. Sub-question 1 – Chapter 3: What is the role of the innovation phase in innovation models?

All fields of literature (Table 1) are introduced in chapter 3, explaining the basis of their ideas and their models and frameworks. Then a review follows for each paper. The review criticizes the paper(s) and points out problems or weaknesses in general, but also improvements that can be made. We then continue this review with more ideas, criticism, and opportunities, but now aimed specifically at factors in the innovation phase, also separately for each of the theories. Each theoretical work must make its contribution to the conceptual model through lessons that were learned during that specific research. That creates three parts for each theory: an introduction, a review, and ideas towards factors in the innovation phase.

This literature review concludes with an answer to sub-question 1, showing how the innovation models combine or compare, and summarizing and exploring implications of findings for the rest of the research. There are implications for the approach and focus of next sub-questions, and there are implications for the conceptual model. All of those conclusions are discussed, listed, and later used throughout the subsequent steps of this research.

2.4.2. Sub-question 2 – Chapter 4: What are characteristics of the innovation phase?

Describing that a technology is being developed and introduced in the market is what happened in the previous step. Now the scope is narrowed down to one of the three phases: the innovation phase. A greater level of detail in describing actors and factors that are influencing a technology is achieved with this narrower scope. This step is looking for actors, factors, activities, mechanisms, goals and other phenomena in the innovation phase that (can possibly) influence the development and diffusion of the technology.

A basis for the description of the innovation phase is found in Ortt and Schoormans (2004) and Ortt et al. (2013). That is where the innovation phase is defined and the first broad characteristics are outlined, mostly concerning the beginning, length, and end of the innovation phase, and about the broad changes and developments that are needed to go from the beginning to the end of the phase. The model proposed by Schroeder et al. (1986) was already used in the previous step of the literature review to compare it to Ortt's model and look for the less supported elements of the pattern of development and diffusion. Their descriptive approach also gives a lot of insight in very specific things that are done or that happen in the innovation phase. Those case-specific events are suggestions for generic characteristics of the innovation phase. Another perspective is that of the Valley of Death, which focusses on the perspective of resources during the innovation phase. This is included in the form of the paper by Markham, Ward, Aiman-Smith, and Kingon (2010), which suggests a way to deal with a possible lack of resources. However, actual empirical observations are not included in that paper. The Master Thesis by Mannheimer (2016) is based on theory on the Valley of Death and enriches this theory with empirical data. The sociotechnical systems perspective is included through the paper of Kemp, Schot, and Hoogma (1998). They consider niche formation from a government's point of view. Koen et al. (2001) describe the Fuzzy Front End of innovation at the project-level. The Master Thesis by Moschos (2016) is based on a mix of the mentioned perspectives and explores the innovation phase from there, looking for important actors and factors while looking for interrelations and strategies at the macro-, meso-, and micro-level. And finally the Sectoral Systems of Innovation that provide the high-level perspective of innovation systems and the building blocks that comprise such a system.

This sub-question is answered through a literature review. Where the first literature review in Chapter 3 focusses on the place of the innovation phase in innovation in general, this chapter uses the same fields of research to dive in the innovation phase itself. Some extra papers are used (Table 1) for this second literature review, going into more detailed claims and case studies in the innovation phase. The innovation models use different perspectives and units of analysis. There is a challenge in combining them in a list of factors that is important for the innovation phase. This sub-question is not answered through case studies. The used literature, especially the Minnesota Studies, are themselves already based on many case studies. Using the selected literature to find characteristics of the innovation phase therefore creates a broader bases than case studies would. However, it also creates a bias in the characteristics of the innovation phase, because the case study data is already interpreted and summarized in models and frameworks, while this research performs a second interpretation step. Details and nuances are bound to get lost in the process. Still, looking for the characteristics of the innovation phase only serves the purpose of increasing understanding of that phase to be able to formulate a list of important factors in a later stage. The case studies of this research reflect on the conceptual model and its list of factors, the characteristics of the innovation phase are part of the basis of the list of factors, making the reflection on the list of factors an implicit reflection of the characteristics of the innovation phase as well.

A work-report is created as a basis of this chapter (Appendix A). Each paper was read in full analysed for claims that concern the innovation phase (many claims of the different fields of literature fall do not apply to the innovation phase). If two claims were found to have something in common, like describing a similar type of actor or a similar mechanism, they were put together in the work-report. Claims can have different similarities with other claims, some claims therefore recur in many different places in the work-report, some only at one place. This was both a way of gathering and ordering data and a way of analysing the papers in a detailed way. That detail is necessary because directly combining different claims and calling it a factor is improvident. Claims are understood in detail and understood in the full context of the entire paper.

Another way of structuring claims in a way that they can be combined, is by observing them at different levels. The chapter is split into four parts: project-level, company-level, market-level, and market creation. The project-, company-, and market-level provide static insights of how developments of a radically new technology can be helped or hindered. Market creation deals with characteristics of creation of a new market, which is less static in nature. Market creation aims to influence and create the three levels. If a paper claims that knowledge is important, there is a difference between claims of the conditions for large-scale diffusion, the Fuzzy Front End literature, and the Sectoral Systems of Innovation framework: they work on different levels. The structure of the chapter keeps separations between such claims.

The characteristics of the innovation are based on literature and the answer to sub-question 1, but weaving all perspectives and views together in one clear vision of the innovation phase and all that it encompasses is bound to result in problems and opportunities. That is a valuable part of this research, which is why after every part (project, company, market environment, market creation) there is a review that considers those problems and opportunities.

The final part of the chapter answers sub-question 2 by summarizing the findings and offers an overview of all conclusions of the chapter that have implications for the rest of the research, especially towards creation of the conceptual model.

2.4.3. Sub-question 3 – Chapter 5: Which factors help or hinder the development of radically new technologies during the innovation phase?

a) Based on theory.
b) Based on case studies.

A deeper understanding of factors is needed to translate lessons from the innovation models in chapter 3 and characteristics of the innovation phase in Chapter 4 to a conceptual model. Chapter 5 starts with an explanation of what is meant with the word 'factor', how factors are not static by nature, even though the conceptual model is a static model, how every factor contains sub-factors, and how factors can play different roles in different situations.

The actual making of the list of important factors for the innovation phase takes all conclusions and suggestions up until this point in account, and happens parallel to development of the conceptual model. In fact, the important factors of the innovation phase are part of the conceptual model.

The list of important factors for the innovation phase is improved with the help of two case studies. The case studies challenge, improve, and illustrate the list of important factors. Methodology of the case studies is described separately in paragraph 2.5.

2.4.4. Main research question – Chapter 5: How can important factors that help or hinder the development of radically new technologies during the innovation phase be modelled?

The development of the conceptual model is an answer to both sub-question 3 and the main research question. The model in which factors are presented is strongly connected to formulation of the list of factors, the level of detail of factors is an example of this. A model that contains three factors asks for a different list than a model with twenty factors. That is why the two are developed in parallel.

A trial-and-error approach starts at the model that is closest to what this research is looking for: the conditions for large-scale diffusion are the inspiration for the first suggestions for a conceptual model. The conditions for large-scale diffusion serve as a benchmark, a model that is somehow related to the conceptual model for the innovation phase. Each next model in this trial-and-error approach is reviewed, both problems and opportunities are found and they serve as improvement steps for the next attempt. This iterative approach continues until there is a model that solves all problems and makes use of all opportunities: the conceptual model incorporates all that was that was learned and contemplated.

2.5. Case study methodology

This research starts with a theoretical part in which sub-questions 1, 2, and 3a are answered. The conceptual framework development that leads from the answers on the sub-questions is the basis that precedes the empirical part of the research (Yin, 2013). The empirical part of the research is qualitative research which suits the more contemplative and interpreting approach that is aimed for (Verschuren & Doorewaard, 2010).

Then the empirical part is designed in the form of two case studies. The case studies challenge and improve the conceptual model and it both challenges and illustrates its claims. The challenges to the model lead to improvements to the answer to sub-question 3, the illustrations are small start of proving that the model fits reality. Although a single case study is simpler, a multiple-case study is far more valuable since it will provide more convincing evidence (Yin, 2013), a more elaborate illustration. This is especially true in this case since innovation, and the development and diffusion of radically new technologies, is a broad field to research. Different cases have very different characteristics. The two case studies will offer limited reliability to the research as a whole, since they will only illustrate some of the possible situations and not all.

The selected cases are chosen in a way that they have different characteristics to allow use of the opportunity to look at theory from different perspectives. A strategic sample is taken to increase the validity of the research, as opposed to a random sample (Verschuren & Doorewaard, 2010). Seawright and Gerring (2008) describe the 'most different' method where case selection happens in a way that specified variables have different values, while other independent variables and the dependent variable have the same value. It means that cases are selected that both concern radically new technologies, but with different characteristics of the technology and with different innovation phases.

There are two goals. The goal of the case studies is to help improve the answer to sub-question 3 and subsequently provide improvements for the answer to the main research question. The case studies together result in suggestions or problems that are used for improvement of the conceptual model. Also, the case studies are a start of illustrating and validating the conceptual model of this research.

2.5.1. Unit of analysis and unit of observation

The unit of analysis is a radically new technology that has gone through an innovation phase. The unit of observation are the actors and events that were important for the development of the radically new technology in its innovation phase.

2.5.2. Case study selection

The case study selection is limited to cases of radically new technologies that have been studied earlier, which have been described using the pattern of development and diffusion, and which are close to or passed the start of large-scale diffusion. This widens the view on the radically new technologies that are studied here, providing context around the innovation phase, especially after the innovation phase. The cases in the Technology Monitor by Ortt & Dees (2018) for four different radically new technologies: 3D printing, blockchain, autonomous vehicles, and Augmented Reality. Two cases are selected from those four, keeping in mind that more difference between cases leads to broader support and illustration of the conceptual model.

Some of the characteristics of the four cases are shortly outlined in

Table 2. Specific characteristics of just the innovation phase itself have not been studied for those cases, so the main dimension to judge differences between innovation phases is the length of the phase. 3D printing and blockchain had shorter innovation phases than autonomous vehicles and augmented reality. Blockchain's innovation is both secretive and poorly documented, its length is therefore unknown. 3D printing and autonomous vehicles are physical innovations, while blockchain and Augmented Reality are both digital innovations. Those two elements give a very basic distinction between the technologies. Having both a different length of the innovation phase (short or long) and a different type of technology (physical or digital) gives to possible combinations of case studies. 3D printing and Augmented Reality or Blockchain and autonomous vehicles. The case of blockchain is hard to describe because of the secrecy and subsequent poor reporting of its innovation phase, which was so secret that even the length of its innovation phase could not be determined. Therefore, the preliminary choice for the case studies of this research falls on 3D printing and Augmented Reality.

Table 2 - Characteristics of four radically new technologies, based on Ortt & Dees (2018).

	3D printing	**Blockchain**	**Autonomous vehicles**	**Augmented Reality**
Length innovation phase	Short (4 years)	Short (1-11 years)	Long (24 years)	Long (26 years)
Type of technology	Manufacturing process	Digital transaction and registration platform	Physical system that combines technologies	New digital functionality
Intellectual property	Important	Less important	Less important	Less important
Laws and regulations	Quality control and lack of regulations	Lack of regulations	Goes against laws and regulations	Lack of regulations
Fear of	Printing guns	Criminal use	Accidents	No large fear
Role of public	Many hobbyists help	Anyone can develop	Only use of cars, small role	Small role
Knowledge	Easy to use	Problems with understanding	Use is easier than manual cars	Easy to use
Expectations	Personalized products	High, many applications	Safer than manual driving	Not very high, but many applications

Looking at other differences between 3D printing and Augmented Reality in

Table 2 shows some similarity in the role of laws and regulations, difference in fears around the technology, difference in the role of the public, similarly low need of knowledge for users, and differences in expectations around the technologies. Although some similarities exist, there are enough differences to find 3D printing and Augmented Reality fitting and complementary subjects for the two case studies of this research.

2.5.3. Case study protocol

The case studies start with a search to create a dataset that together gives a comprehensive description of the innovation phase of the radically new technology. A work-report is created to order all material. The work-report is the basis on which paragraphs 6.1 and 6.2 are written. Conclusions, remarks and observations in the case studies are used to improve the conceptual model in paragraph 6.3, in which the final model is presented as well.

Search

The Technology Monitor (Ortt & Dees, 2018) is in the first place based on a limited number of scientific publications. Our case studies take the same sources and those are used for finding keywords in the innovation phase of that technology, like important actors, patents, companies, organizations, and products. Those keywords are used in Google's search engine, as well as in Google Scholar, to find more information on those topics. Additionally, the Wikipedia page of the technology is reviewed in search of claims surrounding the innovation phase. Lastly, a Google search on "history [name technology during the innovation phase]" is added.

Results are only *included* when something new is added or when it is a reliable source that confirms something in the work-report. Other search results are *excluded* from the work-report, like confirmation of known information which is not any more reliable and has already been shown in at least two sources. However, the most important reason for exclusion is when the information is relevant only after the innovation phase and when it also does not imply any development during the innovation phase. An example is a product launch one year after the innovation phase ended, which implies developments during the innovation phase. In that case the source is not excluded.

Work-report

The list of keywords and the results of the searches are the start of each work-report. Then two parts follow: a timeline and all of the factors. This structure, this outline, is then filled with data. Each and every source that is included in the search is analysed and every claim that concerns the innovation phase of the radically new technology is copied to all relevant parts of the work-report. That means that one claim can be copied to multiple placed. Starting a company because the invention is superior to what is currently on the market is both an important element for the timeline, shows the expectation that the technology is superior, and the start of a company is a strategic move in bringing the technology further. Such a claim is therefore copied to all three of those places in the work-report. Meanwhile, there is an openness towards any possible new factors that were not yet included in the conceptual model.

Each of the copied parts of sources is larger than the claim that is the reason for copying. Some text around the claim is copied to provide context and understanding of the claim that is made. That is why each bit of text that is copied to the factors in the work-report has a highlight of the word or words that are deemed relevant to that factor.

In some cases, a small consideration is added to the copied text by the author. Those considerations stand out from the copied text because the follow after the reference, it is put between brackets, and it is written *italic*.

Write

Paragraphs 6.1 and 6.2 are written on the basis of the work-report. First is the definition of the technology as put forth by Ortt & Dees (2018), which is accepted for this research as well. Then a timeline and then each of the factors of the conceptual model follow in the subsequent paragraphs. Each case study finishes with the conclusions of the case study and remarks towards the conceptual model.

3. Literature review 1: innovation models

Many publications speak of innovation. Innovation is defined in many ways, and viewed from many different perspectives and angles. Before this research can start making suggestions, its foundation in current knowledge must be explored. The literature review considers past publications and reviews the made observations, but also shortcomings of the papers. In doing so, we reach an analysis that shows the starting point of this research. The basis on which the rest is built. This outlines the complex road from an overarching innovation model to specific factors for the innovation phase.

All fields of literature are introduced in Chapter 3, explaining the basis of their ideas and their models and frameworks. Then a review follows for each paper. The review criticizes the paper(s) and points out problems or weaknesses in general, but also improvements that can be made. We then continue on this review with more ideas, criticism, and opportunities, but now aimed specifically at factors in the innovation phase, also separately for each of the theories. Each theoretical work must make its contribution to the conceptual model through lessons that were learned during that specific research. That creates three parts for each theory: an introduction, a review, and ideas towards factors in the innovation phase.

This literature review concludes with an answer to sub-question 1: What is the role of the innovation phase in innovation models? The review shows how the innovation models combine or compare, and summarizes and explores implications of findings for the rest of the research. There are implications for the approach and focus of next sub-questions, and there are implications for the conceptual model. All of those conclusions are discussed, listed, and later used throughout the subsequent steps of this research.

3.1. S-curve

Rogers (1983) describes the diffusion of innovations as an S-shaped curve (Figure 3). The development of a new product is seen as a project after which responsibilities for the product are transferred to the marketing and sales departments. Those departments will take care of monetizing the investment by maximizing sales of the product.

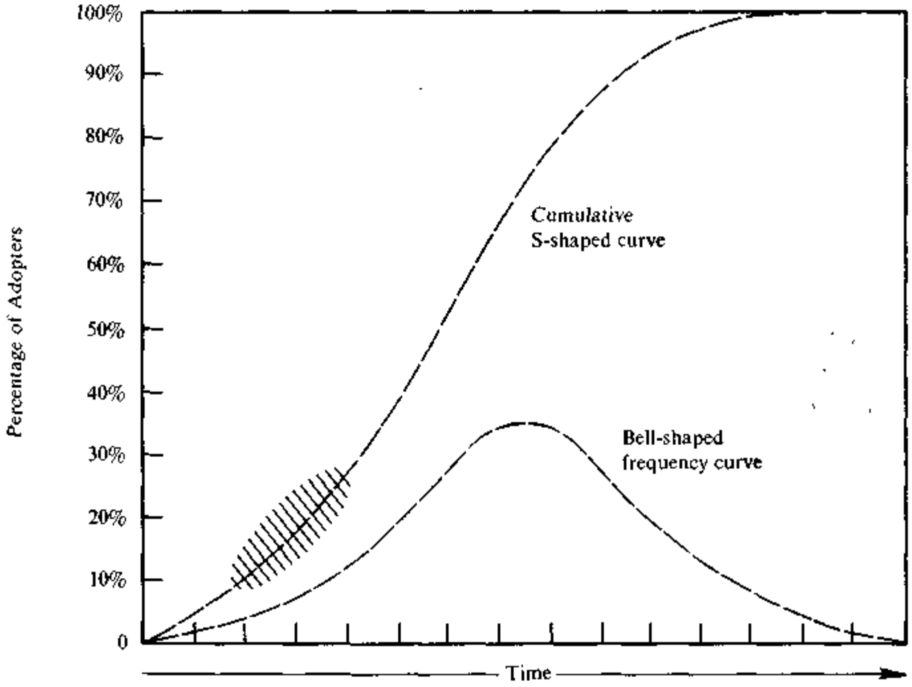


Figure 3 - S-curve of adoption. Source: Rogers, 1983.

A project works from research to commercialization, from technology to application. After market introduction, sales will increase over time and diffusion of the product rises with it. Rogers observes a self-reinforcing mechanism that makes the speed of diffusion increase, resulting in exponential growth. When approximately half of the market is using the new product, there are less potential customers, but news is still spreading fast. Diffusion still increases fast, but the high pace of the beginning cannot be maintained and the slope of the diffusion curve diminishes slowly. The potential customers who still did not switch when almost everyone around them already did, will then start to consider buying the new product as well. Finally, everybody is using the new technology. Then the new developments become old and are replaced with even newer developments. A next product will be developed and diffusion of that new product will start. Customers of the first technology will start to switch to the second, and the diffusion curve of the first technology will begin to go down.

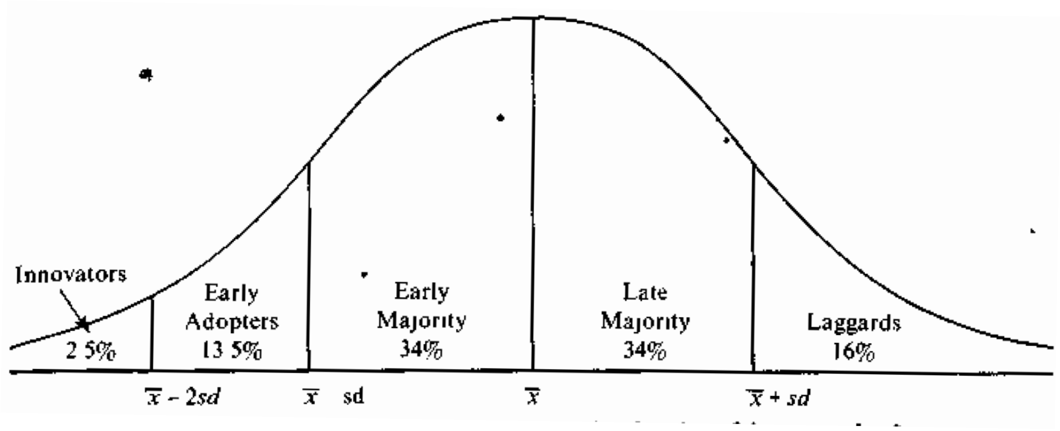


Figure 4 - Adopter categorization. Source: Rogers, 1983.

The adopters of a new technology are categorized. Five categories are distinguished, each group with its own characteristics and personality traits (Figure 4). The adopter distributions prove to approach normality, which is why the categories of adopters can be based on that: the average forms the middle and standard deviations define the group sizes. The first group to adopt a new technology are the innovators. A small group of people who really like new technology, who also like to experiment with it. The product does not have to be flawless for the innovators, they like to work on it themselves if needed. The early adopters are next, demanding a little bit more. The product does not have to be perfectly fool proof, but it has to deliver value to their daily life. Then the early majority forms a large group of customers. Now everything must work perfectly and the product has to be easy to use. The late majority follows right thereafter, possibly with even slightly higher demands to the product. But once they switched, almost the entire market is using the product. Except for the laggards. The laggards are reluctant to change. When everyone around them owns the new technology and it becomes more necessary to own the product too, the laggards may switch in the end.

3.1.1. Review

The first remark is a matter of definition. Rogers describes groups of adopters, the first of which are the innovators. The innovators are people who do not demand a flawless product, a group that does not mind improving and changing the product for their own application and to their own taste. They are therefore innovators on the demand-side of the market. This research on the innovation phase describes innovators quite often, but on the supply-side of the market. This review of the S-curve is the only part of the report that refers to innovators on the demand-side of the market. Every following reference to innovators concerns individuals, organizations, or groups that work on development a radically new technology on the supply-side of the market.

The S-curve is simplified (Ortt & Schoormans, 2004). There is almost no empirical research available that observes a smooth S-shaped diffusion curve. Especially in the case of radically new technologies, diffusion curves tend to be discontinuous, far from smooth, and going up and down multiple times while the market explores different applications. A company that tries to make their sales follow the S-shape of the curve, will often find that they fail. When decision-makers act on the premise that something has been done wrong if the diffusion curve does not have a smooth S-shape, ill-judged decisions can be made. A model which is simplified to the point where extra assumptions and exceptions are needed for each case it is applied to, can hardly make any general remarks about innovation.

One of the characteristics of the S-curve that make its application case-specific, is the quantification of the market and customer groups. Rogers shows the curve in a graph with "percentage of adopters" on the Y-axis in Figure 3. Although historical case studies may provide reliable data on this percentage, current technologies do not. The potential market for a radically new technology is very hard to determine and will continuously change with new developments. The use of the model is not to provide a framework for historical studies, but to provide practical implications, to help decision-making in a company. The market for televisions was estimated at one per household. However, an average of 2.93 televisions per household was reported in the US in 2010 (Nielsen, 2010). But, to be fair, the diffusion may be better quantifiable for other products, since the potential market for owning a dishwasher and having access to internet can possibly be estimated beforehand. And looking at many of the more radical innovations of the last century, many do indeed resemble an S-curve (Figure 5). But the percentage of households and number of sales can be unequal, even with a factor 3 in the case of the television market in the US.

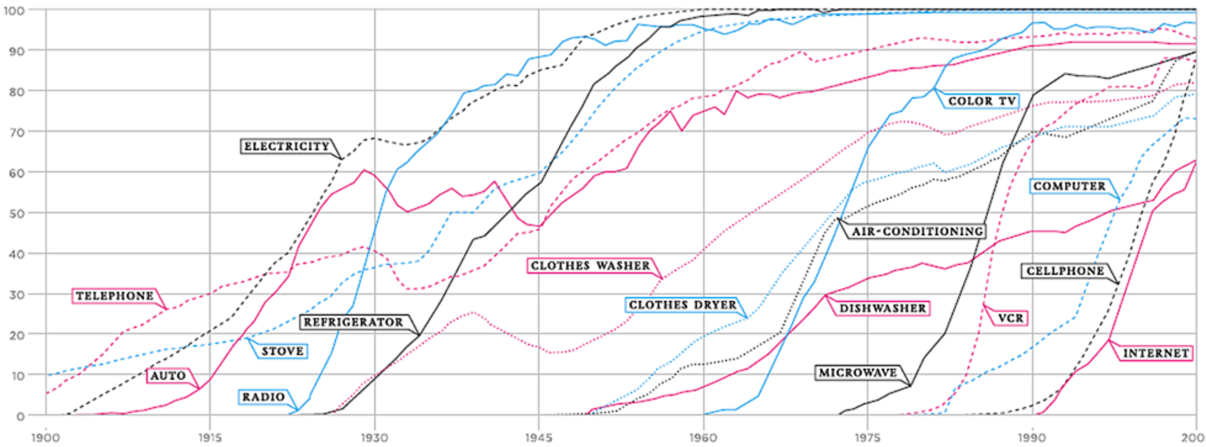


Figure 5 - Diffusion of innovations in the last 100 years in the US. Source: Cox and Alm (2008).

S-curves show up when looking at technology at an aggregate level. But what aggregations? Different technologies were the foundation of different types of televisions. Different companies have been working on the technology and have been selling different televisions based on the same underlying technology. Also, the graph in Figure 5 describes only the US market, so the S-curve summarizes the different types of televisions produced by different companies in a certain geographic area. Those are at least three different aggregations in one graph: aggregation of the companies, aggregation of the products, and a geographic aggregation. Those three aggregations are again complicating the quantification of market size and adoption. Let's focus on one of the three aggregations: the types of televisions. The first television was not sold to the full 100% of today's total market, but was substituted by the next type of television before the market was saturated. The first diffusion curve flattens and later declines and the second S-curve comes up and picks it up where the first type of television left it. The graph for the diffusion of televisions will become less smooth when zooming in, because mistakes, failures, bankruptcies, and other problems become more visible. Many organizations tried many different things in the market, but their S-curves can stop before the mass market was reached. The point is this: a smooth S-curve is not a realistic target for the scope of one company and looking at one type of television. Most S-curves are an accumulation of multiple underlying diffusion curves, which don't have to look like an S at all.

Actually drawing an S-curve can be complicated even further. Technologies can be applied in very different ways. Even the autonomous vehicles turns out to have different applications, ranging from trucks in the mining industry, to taxi services, to autonomous vehicles for the general public (Ortt & Dees, 2018). One company can learn during the development of a product and stop the developments to start something new. The milestone that Rogers presupposes where the development project is completed, after which sales can begin, is not rigid. Developments continue for a long time after sales have started. Rogers neglects learning, trials and errors, and developments during the beginning of the S-curve.

3.1.2. Towards factors in the innovation phase

Measuring diffusion is arbitrary when the total market size cannot be defined. Moreover, diffusion is not an indication of anything before commercialization, because diffusion will then by definition be zero. This point is revisited in the review of the pattern of development and diffusion.

3.2. Pattern of development and diffusion

It is later argued that innovation cannot be captured in one S-shaped curve, because of the time and events between invention and large-scale diffusion (Ortt & Schoormans, 2004). One of the problems with finding the S-curves for specific technologies is that the diffusion curve is far from smooth and does not seem to resemble the expected S-pattern at all. To solve this, Ortt distinguishes three phases where the first one is the innovation phase, lasting from the invention until the first market introduction, the second is the market adaptation phase where market introductions fail and large changes happen, the third and final phase is the market stabilization phase where we see the S-curve as proposed by Rogers (Figure 6). This model has been developed on the basis of 'breakthrough technologies', which has the same definition as the 'radically new technologies' in his later article (Ortt, 2012). Because this theory is the basis for the conditions for large-scale diffusion and because those two theories form a given basis for this research, a review of the limitations of the model is performed first.

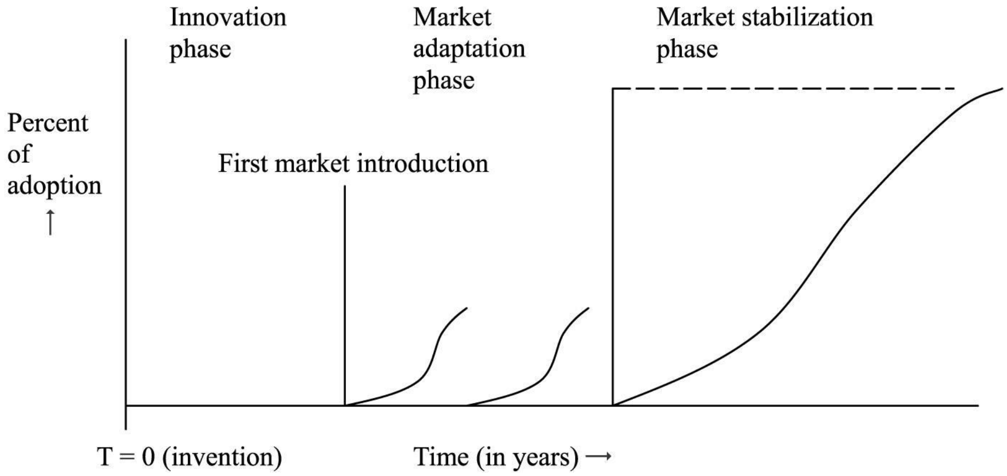


Figure 6 - Pattern of development and diffusion. Source: Ortt and Schoormans, 2004.

3.2.1. Review

The moment of invention is defined as the first demonstration of a technological breakthrough, after which a process of technical refinement and development of the technology starts which is called the innovation phase. The innovation phase ends when the first commercial market introduction is done and therefore leaves out some of the great changes that can be made to the technology. The innovation phase can either include no changes to the product at all, or severe changes and many attempts to incorporate the technology in different products for different markets. In this sense, the innovation phase is a summary that only shows the beginning and the end of the development process and shows little of the technological development that has taken place. When we then continue to the market adaptation phase, we start seeing the developments in the form of different attempts to begin a new S-curve, which can fail, until one or more of them enter large-scale diffusion. That milestone is seen as the beginning of the market stabilization phase, which lasts until the potential market has adopted the technology and diffusion starts to go down again, possibly as a result of another technology that substitutes the one that is currently being analysed. Developments during the last of the three phases, the market stabilization phase, are only visible in what they do to the diffusion of the technology as a whole. Multiple products in multiple markets, undergoing different developments are only shown as an aggregate curve. This also brings us to the point where we can observe that all curves, both in the adaptation and the stabilization phase, can have different meanings because applications of the technology can happen in different markets and industries.

The observations from the previous paragraphs make some of the limitations of the model explicit. The developments of the technology are invisible in the first phase, some of the developments in the second phase are visible, while others may not be shown, and the developments during the third phase are only visible in the form of one curve that describes an aggregate of possibly multiple markets and industries. This makes it hard to find the moment of invention of some technologies, which is especially a limitation in cases where great advances in performance or functionality could lead to defining the emergence of a new technology that would need its own analysis of its pattern of development and diffusion.

The S-curve was observed to aggregate at least three different dimensions: companies, products, and geographic locations. Consequently, the diffusion curve that measures the accumulated diffusion provides little foundation for strategic decisions of one specific company that is developing the radically new technology towards one specific application in one geographic location. More company-level information is needed in a decision-making process to operationalize the market information than the S-curve provides.

3.2.2. Towards factors in the innovation phase

The pattern of development and diffusion splits up the period before the S-curve in two phases. Not much is specified about the nature of the innovation phase, also visible in the missing of a unit of measurement on the Y-axis. If a model for factors in the innovation phase were to make use of the pattern of development and diffusion, a measurement for the innovation phase should be proposed.

Technological development from an idea to a product is not visible in the pattern of development and diffusion. Technological development in later phases are visible in their effect on cumulative diffusion. Since it is expected that technological developments play a large role in the innovation phase, some representation of the development steps that are taken must have a place in a model that contains factors for the innovation phase.

3.3. Conditions for large-scale diffusion

The discussed pattern of development and diffusion is a tool that can be used to identify in what stage of development and diffusion a radically new innovation is, but just like it will give limited insights in how the development was shaped over time, it also gives limited insight in other factors that influenced its development and diffusion up until that point in time where the analysis is performed. Ortt et al. (2013) developed a list of niche strategies that companies can adopt when working on a radically new technology that is in the market adaptation phase. The part of the paper that covers the conditions for large-scale diffusion of radically new technologies is discussed next.

Table 3 - Core factors (source: Ortt et al., 2013)

Factors	Description
1 New high-tech product performance	A product (with all subsystems, features and components) is required with a sufficiently good performance and quality (absolutely or relatively compared to other competitive products). Lacking performance, low quality, unintended side-effects of products or accidents with products can hamper large-scale diffusion.
2 New high-tech product price	A product (with all subsystems, features and components) is required with a reasonable price (absolutely or relatively compared to other competitive products). A prohibitively high price can hamper large-scale diffusion.
3 Production system	A production system that can produce large quantities of products with sufficiently good performance and quality (either absolutely or relatively compared to competitive products), is required for large-scale diffusion. A lack of a production system, unintended side-effects of production or accidents in production, can hamper large-scale diffusion.
4 Complementary products and services	Complementary products and services for the development, production, distribution, adoption, use, repair, maintenance and obsolesce of products are required for large-scale diffusion. Unavailable system elements (or incompatibility of them), unintended side-effects of complementary products and services or accidents, can hamper large-scale diffusion.
5 Actors and coordination; Network formation	Availability of required actors and sufficient coordination of their activities to develop, produce, distribute, repair, maintain and obsolesce products as required for large-scale diffusion. Coordination can be emergent and implicit (e.g., the invisible hand or market mechanism) or can be formal and explicit (e.g., an industry association). If types of actors and coordination among these actors are needed yet missing, large-scale diffusion is hampered.
6 Customers	Customer segments are required for large-scale diffusion. Customers need to be knowledgeable about the product and its use, and should be willing and able to use it and pay for it. If customers are lacking, large-scale diffusion is hampered.
7 Supportive institutional aspects	The supportive institutional aspects refer to formal policies, laws and regulations describing how actors (on the supply and demand side of the market) should deal with the product and the socio-technical system around it. They refer to norms and requirements regarding products, production facilities, complementary products and services. These formal policies, laws and regulations can stimulate or hamper large-scale diffusion.

Table 4 - Influencing factors (source: Ortt et al., 2013)

Factors	Description
1 Knowledge and awareness of technology	Combination of fundamental and applied technological knowledge. Fundamental knowledge refers to the technological principals involved in the product, production and complementary products and services, and the surrounding socio-technical system. Applied technological knowledge refers to the knowledge required to develop (design), produce, and control the technological principles in a product, its production and complementary products and services. A lack of technological knowledge hampers large-scale diffusion.
2 Knowledge and awareness of application and market	This knowledge refers to knowledge of (1) potential applications, (2) knowledge of the market (structure) and the actors involved. This knowledge is required for all actors including customers to formulate strategies, articulate product requirements and find or target other actors. When relevant actors lack these types knowledge, large-scale diffusion will be hampered.
3 Natural and human resources	The availability of human resources with the required skills and knowledge, and the availability of natural resources, and other inputs, such as components and materials, is required to produce and use a new high-tech product. These inputs can be required for the production system, for complementary products and services, or for the product itself. Organizations that have a role in aligning these resources, such as labor unions are included. A lack of such inputs hampers large-scale diffusion.
4 Financial resources	Financial resources and the organizations (e.g., banks incubators) or platforms (e.g., crowd funding or micro-credit) to provide these resources, are needed for development and diffusion of the innovation, the production system and complementary products and services but also for adopting, implementing and maintaining the innovation. Lack of financial resources on the supply and the demand-side of the market can hamper large-scale diffusion.
5 Macro and meso-economic, institutional and strategic aspects	Macro- and meso-economic, institutional and strategic aspects refer to the overriding economic situation, such as a recession or the situation in one or more industries causing stagnation. Economic and strategic interests of countries and industries are often formulated as generic institutions. If these economic, institutional and strategic aspects are unfavorable, large-scale diffusion will be hampered.
6 Socio-cultural aspects	Socio-cultural aspects refer to the norms and values in a particular culture or industry. These aspects might be less formalized than the laws and rules of the institutional aspects, but their effect might hamper or stimulate development and diffusion of radically new high-tech products in different industries. They include methods and habits, norms and values in industries ("the way to do things"). They also include interest groups or stakeholder groups outside the supply chain.
7 Accidents or events	Accidents or events, such as wars, nuclear incidents, natural disasters and political turmoil, or the risk of these accidents or events, can hamper or stimulate development and diffusion of radically new high-tech products in different industries.

The list of actors, factors and functions required for large-scale development and diffusion (only referred to as 'factors' in the rest of the original paper, but referred to as 'conditions for large-scale diffusion' in this research to avoid confusion in later chapters) is compiled by comparing different innovation system models (Table 3 and

Table 4). The conditions are then combined into one new model (Figure 7). All the mentioned conditions have the ability to hamper the development and diffusion. When all conditions are met, it is still possible for a technology not to enter large-scale diffusion. In other words, the seven core factors in the model are claimed to be necessary conditions, not sufficient conditions. This effectively means that there is more context of radically new technologies than is described in this model, which results in a limitation to the generalisability of this model in explaining the start of large-scale diffusion. In other words, the conditions do not describe reality in its entirety, it is a simplification. (Ortt, Langley and Pals, 2013).

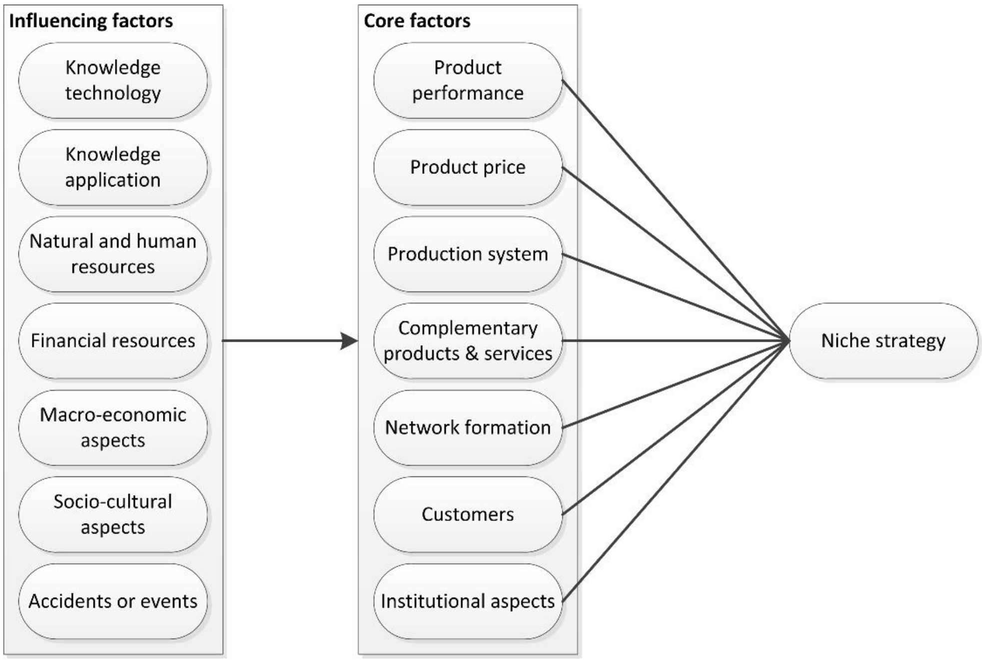


Figure 7 - Conditions for large-scale diffusion of radically new technologies. Based on: Ortt et al. (2013) and Ortt and Kamp (forthcoming).

The paper continues by describing two categories of conditions as shown above in Figure 7: the left group are the influencing factors, the contextual factors that influence the core factors which are formed by the group of seven to the right. The core factors are necessary conditions that must be fulfilled before a technology can reach large-scale diffusion. In other words, if one of the core factors is not fulfilled, it forms a barrier for large-scale diffusion. For example, reaching the mass market is impossible when there are no customers for the technology. Although this is an obvious conclusion, it is not a helpful statement. The core factors themselves do not explain the cause of the barrier. But the cause should be found before a niche strategy can be formulated. That is why there are influencing factors. An influencing factor is the cause of the barrier in one of the core factors. The paper continues to describe what combinations of influencing factors and core factors can occur and which niche strategies can be used to either circumvent the barrier that exists, solve the barrier, or create a new market in which that barrier does not exist.

3.3.1. Review

The conditions for large-scale diffusion are designed to describe barriers for the transition from the market adaptation phase to the market stabilization phase, for the milestone of switching from one phase to another. They do bear relevance to the entire market adaptation phase, because that is the phase for choosing and reaching niche markets or for reaching large-scale diffusion. However, the importance of this model to the transition from the innovation phase to the adaptation phase and for the innovation phase as a whole is unexplored. This research is needed to examine the applicability of the conditions for large-scale diffusion to the innovation phase.

Looking through the conditions for large-scale diffusion now, a first limitation already shows. The conditions deal with large processes, like an economic recession, but also with the innovation itself through product performance and product price. The diffusion and change in a network on the one hand and the product on the other. The company is the connection between the two, but is mostly left out of the conditions, although elements can be found in some of the conditions. The company is seen as instrumental to the market and the innovation, almost as if there are few right ways to develop a radically new product based on the technology, and at least one company will figure that way out after which the rest will learn from that success.

The paper does not discuss further relations between conditions that may exist. An example are the institutional aspects that can, although sometimes only slightly, influence each of the five other core factors through policy and regulations. By not accounting for such influences it is thinkable that when a technology does not enter large-scale diffusion, a problem can be identified through this model while there is a more subtle root problem behind it. The limited understanding of dynamics between conditions will also result limited understanding of the nature of a barrier. Barriers are perceived as higher or lower than they actually are in reality, when forces that work on the barrier are oversimplified. Those limitations have a strong influence on this research: developing strategies to cope with barriers is more effective when root causes for the barrier and interactions between barriers are known.

The two theories above by Ortt et al. (2004, 2013) enable us to describe where a radically new technology stands in terms of development and diffusion, what has happened with the technology in different markets and industries, and to identify what conditions have been hampering large-scale diffusion in the past market introductions, and what conditions are doing so in the current applications. By analysing the conditions for different points in time it is possible to show trends in each of the conditions and give advice for the future through determining the conditions that hamper the large-scale diffusion.

3.3.2. Towards factors in the innovation phase

The fourteen factors are factors surrounding the step from a niche market to the mass market of a radically new technology. This research aims to find factors in an earlier stage, in the innovation phase. The expectation is that the fourteen factors show an overlap with the factors for the innovation phase. The models for describing the innovation phase and the market adaptation phase for a technology cannot be entirely unconnected. The model of one phase does not necessarily have to be directly applicable to the other phase, but some form of relation follows from logic. An example supports this: if high expectations of a technology in the innovation phase is important, than expectations probably have some role in the market adaptation phase as well. However, such a factor is not necessarily represented in both models, because each factor can be different in different phases. Factors are not necessarily equally important in each phase. Nor are they necessarily described in the exact same way, factors can change for example in the level of detail that the model for a phase requires. This expected connection makes the conditions for large-scale diffusion a starting point for the search for a model in the innovation phase and is therefore considered as a model in the conceptual framework development. Translation will be needed from large-scale diffusion to the specific timing and circumstances surrounding the innovation phase. This translation mainly takes place in Chapter 5 when the conceptual model is developed. The conditions for large-scale diffusion are two things: a set of conditions and fourteen factors. The theory is applied to the innovation phase in both those ways to find which ways are most fitting to that specific phase.

The limited focus of the conditions for large-scale diffusion on the role of companies and organizations is a point of attention for a model for the innovation phase. If an invention is made in one company, then that company has a crucial influence on the progression of the invention. Developments in later phases can also have a profound influence, but the chance that a technology will be shelved is smaller when many organizations work on the same technology then when one organization is working on it. Is it always true that one organization works on a technology in the innovation phase and multiple organizations in subsequent phases? No, but the expectation that such a logic could exist is enough to pay some explicit attention to the role of an organization in developing the conceptual framework of this research.

A basic understanding of the dynamics between important factors in a phase leads to a quick overview of roles that factors play. The fourteen conditions for large-scale diffusion cater to this by combining one influencing factor with one core factor, which combination points towards a niche strategy. However, many other dynamics are possible: more than two factors that influence each other, factors within the groups of 'influencing factors' or 'core factors' that influence each other, positive feedback loops, negative feedback loops, and many dynamics are case-specific. Is it realistic to include all dynamics of factors for the innovation phase in the model that this research develops? Many dynamics are case-specific and therefore not generalisable, and it would be a large scope to both determine which factors are important and what the dynamics between them are in just one research. However, the topic must at least be considered in developing the conceptual framework because of its expected importance.

3.4. Strategic Niche Management

Strategic Niche Management is a framework in which technological niches are instrumental for sustainable innovation journeys (Schot & Geels, 2008). The first definition of SNM is: "*The creation, development and controlled phase-out of protected spaces for the development and use of promising technologies by means of experimentation, with the aim of (1) learning about the desirability of the new technology and (2) enhancing the further development and the rate of application of the new technology.*" (Kemp et al., 1998). The sociotechnical systems perspective of the framework makes SNM applicable as both a research model and a policy tool (Raven, 2005). Schot and Geels (2008) describe how the field of SNM has developed over a period of ten years' time and distinguish between 'early' and 'later' SNM research.

Early SNM describes factors that form barriers for the introduction and use of sustainable innovation and distinguishes seven types of factors that "*impede the development and use of new technologies*" (Kemp et al., 1998):

1. Technological factors.
2. Government policy and regulatory framework.
3. Cultural and psychological factors.
4. Demand factors.
5. Production factors.
6. Infrastructure and maintenance.
7. Undesirable societal and environmental effects of new technologies.

Three processes in niche formation are proposed on the basis of the seven types of factors. Coupling of expectations encompasses the whole process from creating expectations and making promises to actors that join efforts through the alignment of those expectations. The articulation process is the finding of implications of the new product, necessary changes for adoptions, and ways to realize those changes. The current network has to be changed to support the new technology, this network formation can prevent defensive actions against the niche formation and are needed to align strategies and visions. (Kemp et al., 1998).

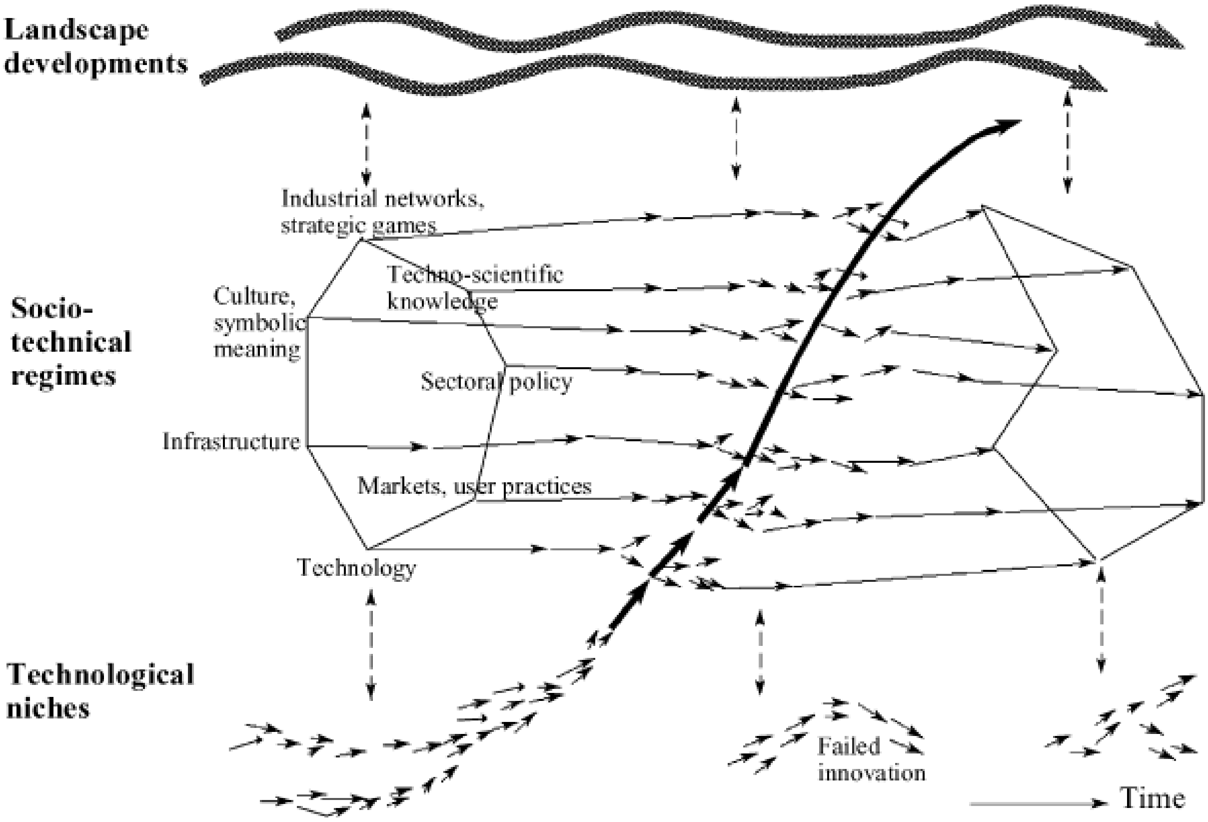


Figure 8 - Multi-level perspective on technological transitions. Source: Geels (2002).

Geels (2002) worked on the multi-level perspective as part of 'later' SNM (Figure 8). The technological niche is where an innovation begins. Technological transitions happen as a result of linkages between the different levels. Changes in the landscape and the sociotechnical regime create a window of opportunity for a new technology to become linked with the seven dimensions in the sociotechnical regime. Radical technologies in technological niches are not developed in the same direction because a dominant design has not emerged yet. Once a new sociotechnical regime is established, it has an influence on the landscape level and may lead to changes there as well. (Geels, 2002).

3.4.1. Review

Three different publications in the field of SNM all observe lacking research to "*how new technologies can come out of these protected niche environment and enter the mainstream market*" (Kamp, Ortt, & Harahap, 2015). While that is a gap in SNM literature, such a model has already been discussed in this chapter in the shape of the conditions for large-scale diffusion.

Table 5 - Comparing SNM's dimensions with factors from the conditions for large-scale diffusion

Dimensions in the sociotechnical regime	**Conditions for large-scale diffusion**
Technology	Product performance, product price
User practices and markets	Customers, knowledge of application
Culture, symbolic meaning	Sociocultural aspects
Infrastructure	Macro-economic aspects
Industry structure	Network formation
Policy	Institutional aspects
Techno-scientific knowledge	Knowledge technology, knowledge application

Comparing the dimensions from SNM with the conditions for large-scale diffusion shows a degree of similarity (Table 5). They are different models of course, but both speak of market niches for radically new technologies an deal with overlapping sets of factors. The conditions for large-scale diffusion are therefore instrumental to closing the gap in SNM literature regarding the move of a technology from a niche to the mainstream market. There are also differences between SNM and the conditions for large-scale diffusion. SNM's technology is split in the conditions product performance and product price, while SNM's culture and symbolic meaning are combined in the conditions sociocultural aspects. There are also more subtle differences. Industry structure and network formation have an overlap, but arguably both factors have parts that are not described in the other factor.

The three mechanisms coupling of expectations, articulation processes, and network formation (Kemp et al., 1998) follow from the seven types of factors that they propose and are introduced above (technological factors, government policy and regulatory framework, cultural and psychological factors, demand factors, production factors, infrastructure and maintenance, undesirable societal and environmental effects of new technologies). Why aren't those seven factors used to find specific types of policy that are beneficial for introduction and use of sustainable technologies? The factors form an interesting list that can be the basis of concrete strategies, concrete policies that are the solution to frequently occurring problems. This research takes the conditions for large-scale diffusion as starting point. In turn, the conditions for large-scale diffusion find part of their origin in SNM literature, but then turns toward a company perspective instead of a sociotechnical systems perspective. Instead of only making general observations about the innovation phase, the barriers perform a greater role. Continuous use of barriers for large-scale diffusion for finding, choosing and possibly implementing strategies prevents the risk of not using all the insight that the barriers give.

The market is seen as the selection environment for the many ideas and technologies that people work on. To see the market as the selection environment for upcoming technologies underestimates the disrupting nature of radically new technologies. A complete overhaul of the status quo, of the existing market, leads to large differences in the position towards the new technology. While working on the developments from technology to product, the eventual customer segment can be guessed, it can be hypothesized and even tested, but it cannot be reliably defined. There is uncertainty in the application of the technology which directly results in uncertainty about the customer segment. In a sense, market knowledge is not applicable, because the market will change and the knowledge becomes obsolete. Is market knowledge then unnecessary during the innovation phase? No, it is actually vital. Knowing the current market and envisioning another market creates a path of change, market knowledge is needed for designing the next steps that are necessary for adoption of the end-product.

Sequences of projects towards niche development and interactions between regimes and niches need further investigation (Schot & Geels, 2008). The notion of 'sustainable innovations' transitions to 'radical innovations' in some articles. If many projects and innovations stop before reaching the market, or before a sociotechnical regime has formed, then it must be important to understand how sequences of projects and interactions between regimes and niches work. The applicability of SNM to radical innovations is limited by this gap in the research. SNM is sometimes said to suggest top-down creation of niches (Schot & Geels, 2008). Schot and Geels (2008) refute this by explaining the focus on endogenous steering. Surely, suggestions for endogenous steering will improve when underlying mechanisms are well-explored. Those critique points makes SNM more applicable to the market-level of radical innovations than to the project-level.

3.4.2. Towards factors in the innovation phase

The seven types of factors that SNM proposes are claimed to be important for introduction and use of sustainable innovations: "*factors that impede the development and use of new technologies*" (Kemp et al., 1998). There are similarities and differences between "introduction and use of sustainable innovations" from SNM and "invention" and "commercialisation" according to the pattern of development and diffusion. Without going into those comparisons, the same conclusion is drawn about the seven types of factors from SNM as was drawn above about the conditions for large-scale diffusion: with some form of translation, at least partial relevance of the proposed factors is expected for the innovation phase. Enough reason to review these seven types of factors during the conceptual framework development.

What stands out in terms of terminology is the "types of factors", compared to the fourteen factors that together constitute the conditions for large-scale diffusion. The seven types of factors contain plurality in themselves as in "technological factors" or "demand factors", implying a larger underlying list in which factors are split up in other factors. What SNM literature implies here are different levels of detail in factors that are important across the phases of the pattern of development and diffusion. Who knows how far factors can be split up, further and further into more detailed factors. This must be considered in the conceptual framework for two reasons. The first is that levels of detail can constitute part of the translation of factors between phases in the pattern of development and diffusion. It is likely that factors that are important in an early phase are related to the conditions for large-scale diffusion or the seven types of factors through some form of translation, part of the translation may be a different level of detail. Another use for considering levels of detail is the opportunity to tweak factors to better fit the unit of analysis. If factors do seem important but do not fully satisfy what is searched for, changing that factor to a factor in a higher or lower detail level can solve the problem.

The review reveals how market knowledge is important for a radically new technology, because the creation of entirely new market can be helped through formulation of a path of change from the status quo to the envisioned regime. In that way, (market) knowledge that exists within an organization can greatly influence the development and diffusion of a technology. This is considered as a possible factor for the conceptual framework.

3.5. Minnesota Innovation Research Program

Normative models are sometimes criticized to become self-fulfilling prophecies, where the researcher will find the exact mechanisms that he or she presupposes (Schroeder et al., 1986). A descriptive model has the advantage of being more thorough and detailed, with the risk of being less generalisable. By a longitudinal observation of the innovation processes of seven innovations, this paper makes a first step to developing a descriptively more accurate model. The seven observed innovations are: hybrid wheat, cochlear implants, therapeutic apheresis, naval weapon systems, a new business start-up, site-based management of public schools, and strategic human resource management (Schroeder et al., 1986).

The paper begins with an analysis of seventeen process models, in which they find three issues. First is an unclear relationship between process models in general and innovation process models. Secondly, they criticise current models for using a priori defined stages or phases when doing research, making the models self-fulfilling prophecies. Models are over-simplified when a linear progression of stages or phases is assumed. Third is the normative nature of most process models, while empirical evidence is limited. And when empirical data has been used for validation of the model, it hardly consists of real-time observations while it is known that knowledge of success or failure of an innovation creates a bias in the research. The longitudinal nature of this study is supposed to avoid those issues.

Six descriptive observations summarize the cases of the seven observed technologies:

1. Innovation is stimulated by shocks.
   Examples of shocks are "new leadership, product failure, a budget crisis, and an impending loss of market share". The general belief that necessity, opportunity, or dissatisfaction are major preconditions for stimulating people to act is consistent with the observations.
2. Proliferation of the initial idea into several ideas.
   Only the beginning of the innovation process seems to be simple. After the proliferation towards additional ideas, linear progression through stages or phases is no longer observed. Overlapping development cycles, multiple overlapping development activities, and efforts to manage the process as a controlled chaos, are reported.
3. Setbacks and surprises are inevitable and should help learning.
   New-to-the-world innovations rely primarily on trial-and-error, combined with some extrapolation. For trial-and-error learning, setbacks and errors must be detected and corrected.
4. Old and new will exist together and become linked together over time.
   When new innovations are implemented, they are connected with current technology and organizational arrangements.
5. Restructuring of the organization.
   There is often a restructuring of organizations during the innovation process, both formal and informal, both temporary and permanent.
6. Top management involvement.
   Top managers are observed to be: very knowledgeable, directly involved, and performing critical roles.

The six observations are used to build an innovation process model that is based on empirical evidence (Figure 9).

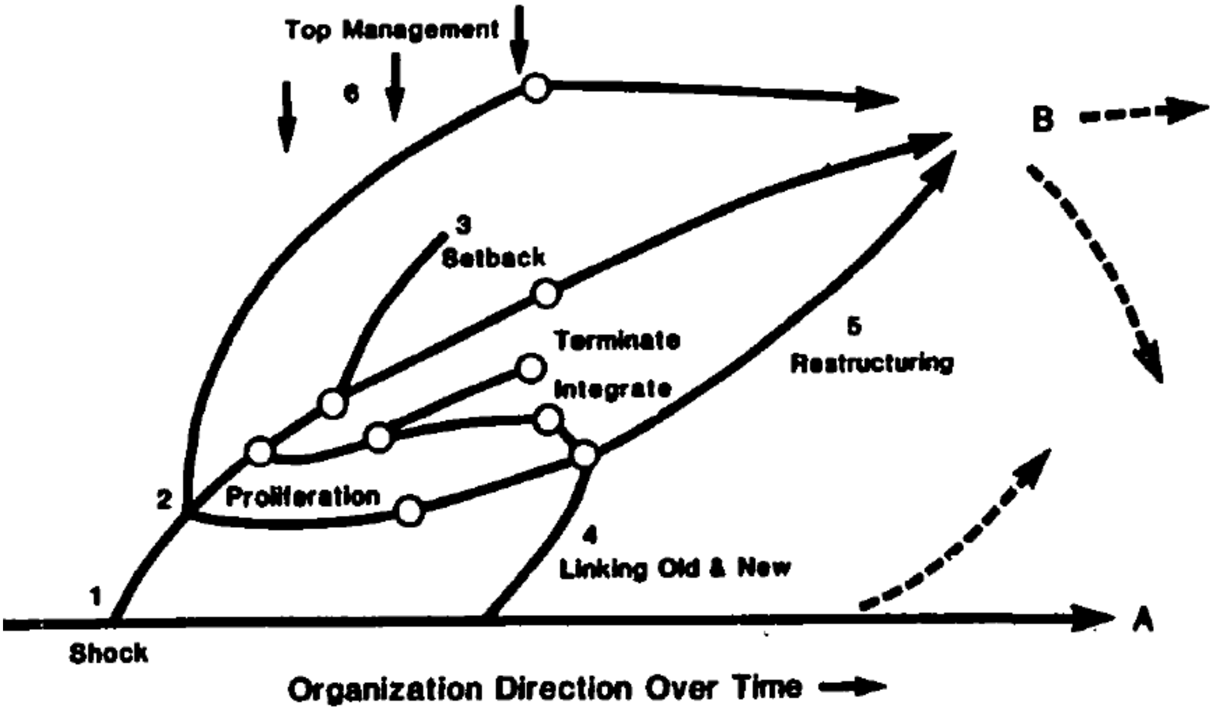


Figure 9 - Emerging Innovation Process Model. Source: Schroeder et al. (1986)

An organization moves in direction A, but will change direction towards B as result of a shock. Proliferation will create many co-existing paths that get ended, shelved, or combined. The new will become linked to the old and restructuring of the organization finalizes the implementation. All the while, top management supports the process through close involvement.

3.5.1. Review

Schroeder et al. start with a thorough review of the problems with current process models in general. A deliberate distance from the normative models is felt through the descriptive identification of phenomena in seven different innovations. But can't the implications of a model, rooted in descriptive data, be described without entering the realm of normativity? The reader misses reflections on how identified problems with current process models are solved by the new model, which problems are not solved by the new model, how remaining problems can be solved in a descriptive way, how this new model can be used, what the limitations of the new model are, how the new model can be used where industries mostly base themselves on normative models, and what other implications of the new model are. The missed opportunities can be felt when new "organizational direction B" becomes "point B" a few paragraphs later. It remains unclear what new directions are, when they are achieved and how that can be done.

An interesting observation is the different ways of learning described in innovation process number three. New-to-the-world innovations are claimed to be reliant on trial-and-error learning and some extrapolation, as opposed to imitation. Trial-and-error works through error detection and correction. That conclusion implies that factors for the innovation phase (this research) and conditions for large-scale diffusion (Ortt et al., 2013) should be continuously monitored throughout the innovation process as part of the effort to detect errors in the product itself and in the system surrounding the product, but also in the way that factors are influenced and to what extent the desired outcome is achieved.

The restructuring of organizations is one of the observations that was relevant across all cases. Although it isn't claimed in the observations, it could be argued that restructuring organizations is something that needs to happen for all innovations, or something that is perceived as helpful. This links to the condition for large-scale diffusion "Macro and meso-economic, institutional and strategic aspects", specifically the strategic aspects in that condition.

The beginning of the pattern of development and diffusion is defined as the moment of invention (Ortt & Schoormans, 2004). Schroeder et al. now claim that ideas can be terminated and 'shelved' for an average of almost ten years. Innovations apparently start before what Ortt assumes to be the beginning. When investigating the history of a radically new technology, ignoring the start of an idea through a shock, proliferation, and termination and ignoring all context at that time, the beginning of a technology may seem different from what it really was. Then influence of parallel innovation paths of variations of a technology can then be greatly underestimated. Schroeder et al. criticise current models for "using a priori defined stages or phases when doing research, making the models self-fulfilling prophecies." That criticism also applies to Ortt's model, but not one on one.

Where the Minnesota studies focus on one company for each technology, Ortt's pattern of development and diffusion is a system-level model, observing an entire market. Compare it to the S-curve: diffusion curves of companies seldom look like S-curves, but at an aggregate level the S-shape begins to emerge. In other words, Schroeder's criticism does not have to apply completely. It is perfectly possible for Ortt's pattern to describe an actual phenomenon, not just a self-fulfilling prophecy. The pattern is, however, a simplification of reality, which leaves the possibility for (important) specifics to get lost in the translation from reality to theory. Ortt saw this risk and catered to it by allowing for different scenarios. By leaving out phases in the pattern, many special cases can be described. This makes the pattern more generalisable and better applicable to different technologies. However, it is still a simplification in which some specifics can get lost, as we will come back to in the next paragraph.

When trying to link the Emerging Innovation Process Model to the innovation phase in the pattern of development and diffusion, the first model appears to describes the timespan of at least the innovation phase, and possibly more. The shock that changes the organization's direction can be a long time before the moment of invention, it can also be the moment of invention itself. On the left side, early in the process, Schroeder et al.'s model covers either the same time span in the innovation process as Ortt's model, or more. On the right side, late in the Process Model by Schroeder et al., already in during observation three (setback, terminate, integrate) the first commercial introduction of a product can be done, linking to the beginning of Ortt's market adaptation phase. The setback can then be a failed first market introduction, as illustrated by the hybrid wheat case where contamination of the new seeds formed one of the setbacks. Schroeder et al.'s model therefore describes not only the innovation phase, but also the transition into the adaptation phase and possibly even to the stabilization phase. One of the assumptions of the pattern of development and diffusion is that the milestones that define the boundaries of the different phases can be found. It has to be possible to pinpoint them to one specific moment in time. Not all events that are observed by Schroeder necessarily fall in the same phase of the pattern by Ortt, it becomes clear that the milestones form a limitation to said pattern. Activities that belong in the innovation phase for one radically new technology, may belong in the market adaptation phase for another radically new technology. The same phases summarize a slightly different content. The case study by Geels (2002), which returns later in this report, describes how steam engines were used on ships while a great number of major developments were still to come before the first steamships would set sail. The Segway, described in the introduction, was only introduced when it was almost fully developed. The same milestone can lead to incorrect assumptions about when certain activities took place.

3.5.2. Towards factors in the innovation phase

Six observations, six phenomena that are important in the early stages of a radically new technology. Are they mechanisms or factors? Schroeder et al. do not go any further than observations, the translation of observations towards factors or mechanisms that are deemed important must still be done. The observations are considered in the conceptual framework development.

It is not a factor in itself, but learning processes are helped by keeping up a continuous flow of input of information. In that sense, a model that covers factors in the innovation phase can be such a flow of information. The conditions for large-scale diffusion do not just describe factors, but also give pointers for strategic decision-making. If factors for the innovation phase are ever expected to function as information source about progress or as a basis for strategic decision-making, then the factors must be repeatedly monitored to use learning opportunities and subsequently change and improve actions. Deciding on the best course of action is easier when problems are known and understood.

The review shows that the timewise relation between the Emerging Innovation Process Model by Schroeder et al. is variable compared to the pattern of development and diffusion. Therefore, the six observations do not always happen in the same phase. If observations cannot be expected to always occur in the same phase, then the changing relevance and the changing roles of factors will not always occur in the same phase either. It is perfectly possible for a factor to be important in the innovation phase for Technology A but in the market adaptation phase for Technology B. This is cared for during the development of a model for factors in the innovation phase.

3.6. Fuzzy Front End

Koen et al. (2001) define the Fuzzy Front End (FFE) as "*those activities that come before the formal and well-structured New Product and Process Development (NPPD) or Stage Gate™ process*" as visualized below in Figure 10. They also protest the use of the term "Fuzzy Front End" and prefer to call it "Front End of Innovation" (FEI). Their main reason is the mysteriousness and the suggested unknowability and uncontrollability of the phase through the word "fuzzy". They do not see the front end as fuzzy and therefore suggest a change of name. The Front End consists of five key elements:

1. Opportunity identification.
2. Opportunity analysis.
3. Idea genesis.
4. Idea selection.
5. Concept & technology development.

Those elements are not sequential but can be gone through in every possible different way: different orders, and repetition of elements. (Koen et al., 2001). Suggestions for managing the Fuzzy Front End are given by Kim and Wilemon (2002) through a list of twelve methods.

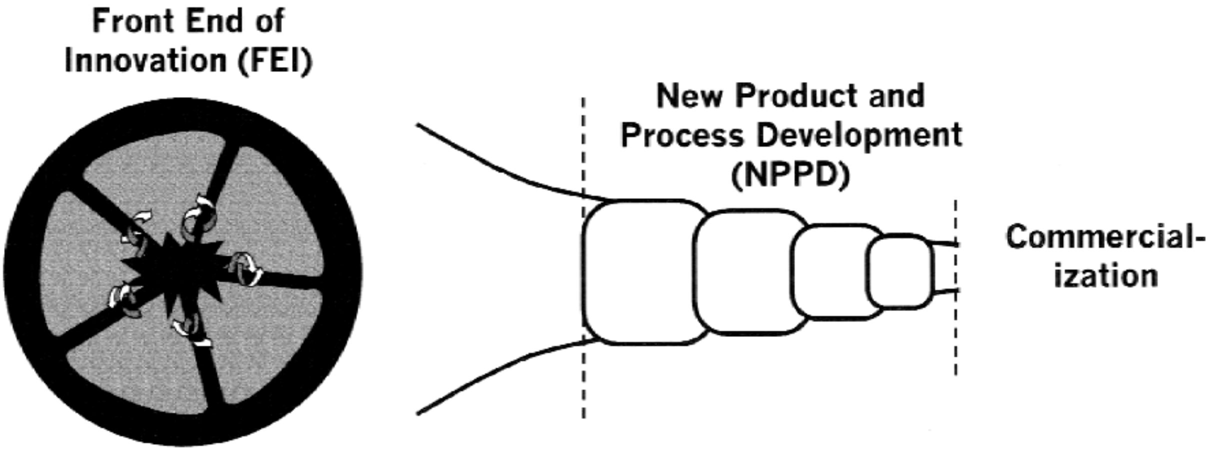


Figure 10 - The Front End of Innovation in the innovation process. Source: Koen et al. (2001).

Most of the innovations are incremental and development efforts are started top-down in a company by including concrete goals in the company's strategic goals. However, discontinuous innovations enter an organization from the other side: through an individual that receives information from the environment and identifies an opportunity. When this opportunity is presented to corporate-level decision-makers, they may decide to initiate a project to explore the opportunity further. This information flow for discontinuous innovations has been modelled and is shown in Figure 11 (Reid & De Brentani, 2004).

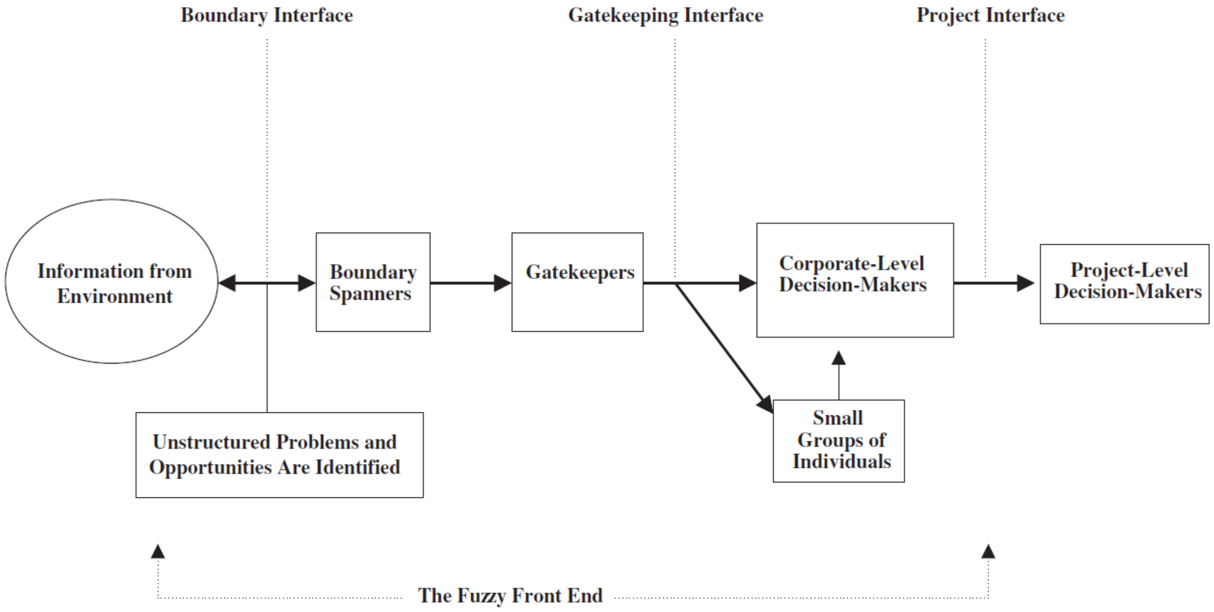


Figure 11 - Information flow in the Fuzzy Front End for discontinuous innovations. Source: Reid & De Brentani (2004).

3.6.1. Review

The timewise relation between the FFE and the Innovation Phase as described in the pattern of development and diffusion, is partly overlapping. The FFE starts at the very first beginning of the innovation process: at the moment that one individual receives information that leads to a potential opportunity. An opportunity leads to an idea. The reviewed literature does not specify in what shape or form the idea is presented to the organization when the individual decides to take that step. It is also not specified in what shape or form the idea is presented to decision-makers in the organization. The innovation phase starts at the moment of invention: "*the first demonstration of a technological breakthrough*" (Ortt & Schoormans, 2004). The opportunity presents itself before the invention is done, we can therefore conclude that the FFE starts before the Innovation Phase. Then there are two options. First, the opportunity is identified by the boundary spanner and passed on without further changes and a project is started. In this scenario, the FFE of that project has ended before the moment of invention, then the Fuzzy Front End of the first project is over before the Innovation phase has started. The second scenario is when an individual, like the boundary spanner or the gatekeeper, invents the new innovation. The decision-makers will then be presented with an invention instead of only an opportunity. The FFE for that project then ends during the innovation phase. Looking at the end of the innovation phase and the Fuzzy Front End: we see that the Innovation Phase ends at the moment of the first commercialization, while the Fuzzy Front End ends before the NPD process. The Fuzzy Front End of that development project therefore does not last until the end of the Innovation Phase.

There is a split between the Fuzzy Front End and the New Product and Process Development (NPPD) process in the model in Figure 10. After the transition to the NPPD, development efforts are expected to become more rigorous in the shape of, for example, a stage-gate process. This is a rigid presentation of a probably much more fluid transition, in which the methods of the FFE can work through the beginnings of the NPPD process as well, maintaining some 'fuzziness' throughout the entire project . Because of this, the theory can still apply during late stages of the innovation phase. Propositions from the FFE literature are included in the analysis of characteristics of the innovation phase.

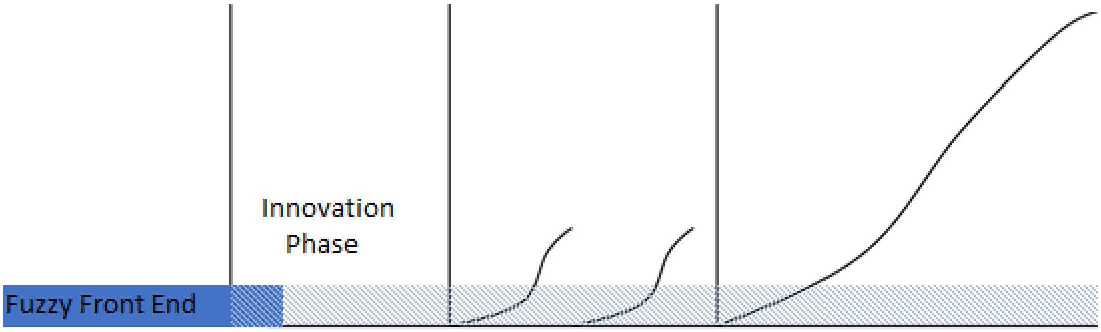


Figure 12 - The Fuzzy Front End and the innovation phase

It is not one project that covers the full development of one technology into one product. It takes much time, multiple projects, and many development steps to finally reach the mass market. The market adaptation phase contains many product and process improvements to help a product reach the mass market. Projects during the market adaptation phase are more incremental in nature than the more radical innovations during the innovation phase, and more process innovations than the product innovations during the innovation phase. And each project, each innovation step, has a Fuzzy Front End. For example: an incremental improvement through a process innovation during the market stabilization phase, initiated by the a managerial request to reduce production costs by a certain percentage. The start of a project to make production cheaper with no specified means to reach that goal has a Fuzzy Front End. The project starts with a broad discovery of possible ways to reduce costs, which shapes the project and clarifies which skills and resources are needed to reach the prescribed goal. The Fuzzy Front End is generally most fuzzy during the innovation phase, but most projects have a such a fuzzy start. In other words, there will always be Fuzzy Front Ends of subsequent projects, during every phase in the pattern of development and diffusion (Figure 12).

The Fuzzy Front End describes the unstructured steps that are taken before a structured and more formalized process is started. Those steps can be viewed from the perspective of the environment, of a company, and of an individual. But Reid and De Brentani (2004) show how more discontinuous innovations should be viewed at an individual level. Although the engine at the centre of the FFE still consists of the leadership and culture of the organization (Koen et al., 2001), even for those individuals, literature on the FFE cannot be directly used to complement models on development and diffusion for what is called the innovation phase. The individual perspective of the Fuzzy Front End, especially for discontinuous innovations, is different from the technology perspective of this research.

3.6.2. Towards factors in the innovation phase

Where the pattern of development and diffusion can be seen as an S-curve of which the time before the S-curve is split in two different phases, the Fuzzy Front End can be seen as a split of the milestone "invention" in several key elements. It will be interesting to consider those detailed steps in the conceptual framework development of this research.

There are probably factors that are especially important during the Fuzzy Front End of a project. The factors do not have to be exclusively attributed to the Fuzzy Front End, they may already be important because of other reasons, but at least some connection is expected. But the review concluded that there are projects with Fuzzy Front Ends throughout the entire pattern of development and diffusion. The first project regarding a radically new technology can be seen as the most fuzzy of all the following FFE's, then factors that are expected to connect to a Fuzzy Front End are expected to be most relevant during the innovation phase. What does then happen to the factors throughout the pattern of development and diffusion? They are more important during the innovation phase than during later phases. This mechanism is also expected to be observed for other factors. There must be a connection between factors in all three of the phases.

3.7. Sectoral Systems of Innovation

Malerba (2004) defines a Sectoral System of Innovation (SSI) as "*a set of new and established products for specific uses and the set of agents carrying out market and non-market interactions for the creation, production and sale of those products. Sectoral systems of innovation have a [sector specific] knowledge base, technologies, input and demand.*" It is the entire system around a technology, including supply and demand and about any actor that can have an interest in technology. Malerba lists individuals (consumers, entrepreneurs, scientists), firms (users, producers, suppliers), non-firm organizations (universities, financial institutions, government agencies, trade unions, technical associations), subunits of larger organizations (like R&D or production departments), and groups of organizations (like industry associations). The first definition of five building blocks of sectoral systems of innovation is in a 2002 paper (Malerba, 2002): knowledge base and learning processes; basic technologies, inputs and demand, with key links and dynamic complementarities; type and structure of interactions among firms and non-firms organizations; institutions; processes of generation of variety and of selection. It was probably the interaction between the different building blocks that created problems, because the incorporation of 'learning processes' and 'dynamic complementarities' already speaks of certain dynamics and interactions, while the building blocks themselves also show interaction. In his 2004 book, Malerba proposes four building blocks:

1. Knowledge and technologies.
   Sectors have different sets of knowledge and technologies, but those domains are also capable of transcending sectoral boundaries.
2. Actors and networks.
   Systematic interactions through market and non-market relations drives innovation and production.
3. Institutions.
   Interactions are shaped by institutions: norms, routines, common habits, established practices, rules, laws, standards.
4. Demand.
   Demand is a heteregeneous group of individual consumers, firms, and the public sector. Their interaction with producers is shaped by Institutions.

The explanation of the last building block, Demand, already points to it: there is interaction between the building blocks. And there is change in the SSI as well. Major discontinuities can change everything. A sector with a Schumpeter Mark II pattern (most innovative developments and progress comes from a low number of large companies) can change to a Schumpeter Mark I pattern (most innovative developments and progress comes from new companies) as a result of such discontinuities. It can lead the sector to a need for new competencies and a change in industrial leadership. A Sectoral System of Innovation is subject to transformation through co-evolution of its building blocks.

3.7.1. Review

Sectoral Systems of Innovation are aimed at innovation in general, not just at radically new technologies. An illustration of this are the sectors for which the Sectoral Systems are explored: pharmaceuticals, and internet and telecommunications are mentioned, but also the sectors of machine tools and services are described (Malerba, 2004). Looking at the definition of Sectoral Systems of Innovation, two more things stand out. First: when "a set of new and established products" is the basis of your innovation system, then this innovation starts working long after the underlying technological principle has been discovered, possibly long after the moment of invention. And that brings us to the second observation: creation, production, and sale are keywords that imply that this framework encompasses more than just the innovation phase of the pattern of development and diffusion. Both observations lead to the conclusion that Sectoral Systems of Innovation do not relate to one phase in the development and diffusion of radically new technologies: it applies to all of the phases. This conclusion forms no objection to the framework, but it does form a limitation to its use in this research: a general claim about a technology in the timespan of the pattern of development and diffusion does not have to be specifically and especially important for the innovation phase. That is why claims about Sectoral Systems of Innovation do not necessarily indicate an important element for the factors in the innovation phase.

It is not a framework for innovation systems in general, but specifically for *sectoral* innovation systems. That implies that theory on innovation systems was deemed to general for guiding decision-making in innovation systems, that there is value in reviewing the framework for each and every sector. While recognizing that claim, this again limits the use of the framework for the case of radically new technologies. Radically new technologies have the potential to create an innovation system that did not exist, to completely change actors and their relations. And that is not always limited to a specific sector. Think of blockchain for example, which is mainly known for its application in the financial sector, but which can also be used for digitizing and executing smart contracts, for registration of real estate and marriages, for voting, and for validating the authenticity of documents (Ortt & Dees, 2018). An innovation system for radically new technologies is not necessarily sectoral. This was recognized by other scholars and, for example, Markard and Truffer (2008) worked on combining different views on innovation systems (national, sectoral) with the multi-level perspective (niches, regime, landscape). That paper leads to increased use of the term Technological Innovation Systems, as in the paper by Vasseur, Kamp, and Negro (2013). But the elements of the innovation systems differ between papers, and so do descriptions about interactions between elements. This research on the innovation phase adopts the four elements of the Sectoral Systems of Innovation as proposed by Malerba, but will refer to them as elements of a System of Innovation and leave out the Sectoral specification, because it is clearly possible to apply the four elements in a broader way than just to Sectoral Systems of Innovation.

Just like with Strategic Niche Management, Malerba applies his framework mainly to public policy. It can be argued that public policy is the most important field of application of his framework, because public policy has much influence over a sector as a whole. However, there is also potential in the framework for companies that aim to create something new. Malerba misses out on the opportunity to show not only what there is in an existing innovation system, but also what should be created for a new innovation system.

3.7.2. Towards factors in the innovation phase

It is not just that the framework of Sectoral Systems of innovation is used carefully because the framework is broader than just radically new technologies and the innovation phase. Malerba (2002) poses four questions, two of which are: “*How do new agents come into being and what are the main sectoral differences in the rate, type and determinants of entry?*” and “*How do new sectoral systems emerge, and what is the link with previous sectoral systems?*”. Although those questions are not answered in his work, they do reflect where the framework is best used in this research towards factors in the innovation phase. The next literature review is structured around levels: the project-level, company-level, market-level, and market creation. Malerba’s framework is used at the levels where it fits best. Those are not the project-level and the company-level, but only the market-level and market creation. The explanations of the different elements of Sectoral Systems of Innovation include statements about things that are important in those elements. But such statements at the level of an innovation system cannot be assumed to be equally true for projects and companies. Using Malerba's work at every level of the literature review in the next chapter would lead to unsupported speculation. It would lead to statements that are possibly untrue because something that is true for an innovation system, is not necessarily important at the project-level or company-level. Therefore, the views and insights of the Sectoral Systems of Innovation are only applied to the parts of next chapter's literature review about the market-level and about market creation.

The four building blocks of Sectoral Systems of Innovation have interaction with each other. It is described under building block Demand that all customers have interaction with production actors and that their interaction is shaped by Institutions. The framework continues with the claim that a Sectoral System of Innovation is subject to transformation through co-evolution of its building blocks. It says nothing about how the building blocks normally interact, and very little about how change works: how it is started, managed, and stabilized again. The conclusion is the same as it has before with other frameworks: the presented theory is lacking claims about the dynamics of its components. Perhaps the insights that are created with the current model are deemed sufficient, but exploring some basic dynamics can reveal much for actors who actively try to influence the change of an innovation system. Or for those who try to create such a system. Towards the innovation phase, this research aims to propose at least some basic dynamics in its model.

3.8. Conclusions of literature review 1

Some conclusions in Chapter 3 have implications for further chapters. This paragraph lists relations, similarities and differences between the literature streams and then repeats the claims from this chapter that are revisited in later chapters.

3.8.1. From S-curve to conditions for large-scale diffusion

The review of the S-curve shows oversimplifications that limits the operationalisation of the theory. Aggregations of companies, different products based on the same technology, and geological aggregations together make one S-curve a poor basis for analysis of development and diffusion of a radically new technology, let alone for strategic decision-making. The S-curve needed to make way for an expansion of the analysis of diffusion into three phases.

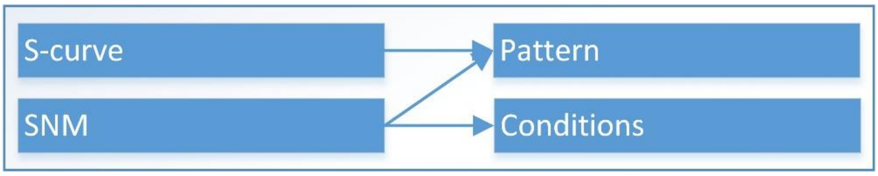


Figure 13 - Towards the pattern and the conditions

The pattern of development and diffusion is the more detailed version of the S-curve. SNM also forms part of the basis for the pattern of development and diffusion. Many products go through a phase in which different market niches are entered, tried out, and often left again. SNM pointed to this observation and searched for factors that influence this starting and stopping, factors that influence the introduction and diffusion of sustainable technologies. Ideas about niches got a place in the pattern of development and diffusion in the market adaptation phase. The conditions for large-scale diffusion built on the factors found in SNM. Although SNM formed part of the inspiration for the pattern and the conditions, the sociotechnical systems perspective from SNM is different from the somewhat more technological approach of the conditions. Where SNM analyses niches and regimes, the conditions aim at development and diffusion. This nuance is also visible in the factors: the conditions for large-scale diffusion have a few more purely technological factors. This is how Rogers' S-curve and SNM's sociotechnical systems perspective contributed to the pattern of development and diffusion and the conditions for large-scale diffusion.

3.8.2. Differences between literature streams

The pattern and the conditions both look at radically new technologies in their full context, at the market-level. Analysis of an innovation based on those pre-specified phases and factors creates the risk of the self-fulfilling prophecy, together with the hindsight bias. This was catered to by allowing for scenarios in which the different phases of the pattern of development and diffusion are added or left out. Even though the models find a large part of their basis in descriptive research, the fact remains that the framework has a normative flair to it by prescribing which conditions must be fulfilled in order to reach large-scale diffusion.

Table 6 - Differences between literature streams

Literature streams		**Differences**	
		Perspective	**Style**
S-curve	**Pattern**	Market	Normative
	Conditions		
	SNM	Sociotechnical systems	Normative
	Minnesota	All	Descriptive
	FFE	Project	Normative
	SSI	Innovation system	Descriptive

The same normativity is found in the SNM and FFE literature. The Minnesota studies break this pattern by performing longitudinal case studies. Their descriptive model is basically a combination of the most frequently occurring mechanisms throughout the case studies. In doing so, their observations cover phenomena on different perspectives: project-level, company-level, and market-level, from the perspective of companies, NGOs and governments. The Sectoral Systems of Innovation are also descriptive, describing which building blocks are generally found in innovation systems. SNM is focused on the sociotechnical systems perspective and FFE focuses solely on project-level observations. The combinations of those streams of literature forms diverse set that represents different approaches. This research aims to combine insights about the innovation phase and come up with one model for factors in the innovation phase.

The method in chapter 4 for describing characteristics of the innovation phase aims to compare and combine all sorts of claims and statements that relate to the innovation phase. The challenge is to compare and combine apples with apples, and not apples with oranges. Table 6 gives some insight to how different models and frameworks compare. Chapter 4 accounts for the found differences through its four different parts. The innovation phase is described from the project-level, the company-level, and the market-level. The fourth part describes market creation.

3.8.3. Towards factors in the innovation phase

Some observations, insights, and remarks in this chapter have implications for further steps in this research. All literature that was reviewed in this chapter has led to some insight or thought that is continued in a later stage of this research. Table 7 below repeats and summarizes only the insights from the reviews that are revisited in later chapters.

Table 7 - Implications of Chapter 3 towards factors in the innovation phase

Literature	**Suggestion**	**Revisited in**
S-curve and pattern	Find a measurement for the innovation phase if the pattern is used in the conceptual framework.	Discussion
Pattern	Technological developments are not visible.	Chapter 5
Conditions	Review importance of the fourteen conditions.	Chapter 4
	Review the role of a company and its representation in the factors.	Chapter 4
	Find some basic dynamics or relations between factors.	Chapter 5
SNM	Review importance of the seven types of factors.	Chapter 4
	Review the role of market knowledge in the factors.	Chapter 4
	Review thinking in "projects".	Chapter 4
	Review levels of detail in factors.	Chapter 5
	Use factors to choose strategies.	Discussion
Minnesota studies	Review importance of the six observations	Chapter 4
	Review importance of factors from other phases.	Chapter 4
	Strengthen representation of the company-level perspective.	Chapter 4
	Monitor factors continuously.	Chapter 5
	Operationalization of results.	Discussion
	Review applicability of niche strategies in innovation phase.	Discussion
	Review applicability of strategies for the innovation phase to later phases.	Discussion
FFE	Review importance of the five key elements.	Chapter 4
	The emphasis on factors varies between phases.	Chapter 5
SSI	Review the role of the building blocks at the market-level and for market creation.	Chapter 4
	Find some basic dynamics or relations between factors.	Chapter 5

Technological developments in the innovation phase are not visible in the graph of the pattern. Measurement of diffusion is shown to be based on several aggregations and nothing is measured during the innovation phase. Because (technical) developments are not shown in a diffusion curve and because nothing is measured in the innovation phase which is central to this research, a measurement would be needed if the pattern for development and diffusion is used in the conceptual framework development.

The importance of the conditions for large-scale diffusion during the innovation phase was brought up and should be reflected upon when working towards a model for the innovation phase. A condition that is important for reaching large-scale diffusion does not necessarily imply importance of that condition during the innovation phase. The conditions for large-scale diffusion showed a number of factors concerning the innovation itself, and a number of factors concerning the market environment of the innovation. The company perspective has an implicit place in some factors, but is generally less represented than the innovation and its market. The role of the company in the innovation phase and how this role is represented in the factors is reviewed in the development of the conceptual framework. Conditions for large-scale diffusion can influence each other in many different ways, with direct and indirect influences and positive and negative feedback loops. Some basic idea about the most important dynamics between the conditions leads to increased insight and to ways to influence those conditions. The same logic applies to the innovation phase, where some basic dynamics between factors can enable quick insight in characteristics of a specific case.

The seven types of factors that SNM proposes for the introduction and use of sustainable innovations are relevant for the innovation phase. In what way is yet unclear, but a relation is expected. The factors will therefore be reviewed in describing the characteristics of the innovation phase. The facts that SNM speaks "types of factors" and that SNM proposes broad factors points to the possibility of distinguishing different levels of detail in factors. Levels of detail of factors have the potential to make factors more fitting to the perspective that is taken in an analysis or to show the connection between factors of different phases. This is also reviewed when working towards the conceptual framework. Viewing the market as a selection environment seems unreliable, because a radically new technology will need to create new combinations on both the supply and demand side of the market, thus creating a new market. Knowing that the status quo has to change to accommodate the full potential of the radically new technology, market knowledge is instrumental to sketching a path of change. Market knowledge is therefore expected to have a role in the innovation phase, because that is the moment that change is envisioned but not yet realised. Strategic Niche Management identifies barriers to the introduction and use of sustainable technologies, but then continues to describe three generic processes in niche formation. The potential for the use of barriers at a more detailed and applied level is lost. To not lose the potential of the factors in the innovation phase in a similar way, they should eventually be used for choosing strategies. That is, however, a step further than this research goes, but the point is revisited in the discussion. The role of the government in the innovation phase can be larger than SNM literature suggests. However, when taking the perspective of the innovating organization the question becomes: what can the innovating organization do to increase the government's role to its advantage? That will be reviewed in the discussion. The role of projects remains unclear and sequences of projects are largely neglected in current research. The role of a project in the innovation phase is reviewed in the next chapter.

The six observations in the Minnesota Studies that describe recurring phenomena across different innovations are taken into account towards the conceptual framework. The trial-and-error learning that is observed in many of the cases leads to the suggestion to monitor the factors in the innovations phase. This requires continuous monitoring of the conditions for large-scale diffusion. Continuously monitoring is seen as useful for predicting and finding problems in the development and diffusion of the innovation of which an organization is working. It may also present opportunities in solving the problem. The overlap between the innovation phase and the adaptation phase, that became explicit through the model of the Minnesota Studies, can result in broader applicability of factors that were designed for one specific phase. In this case, the potential applicability of the conditions for large-scale diffusion to the factors in the innovation phase. The results from longitudinal case studies across several radical innovations can potentially lead to well-performing strategies. However, they have not led to any strategy in the Minnesota Studies, leaving much of the observations unused. The overlap between the innovation phase and the adaptation phase, that became explicit through the model of the Minnesota Studies, can result in broader applicability of strategies that were designed for one specific phase. In this case, the potential applicability of the niche strategies to the innovation phase and the applicability of this research's strategies to the market adaptation phase. Because this research aims to develop a static model, and not operationalize this model towards strategies, this point is addressed further in the discussion. Restructuring of organizations is one of the observation that was relevant across all cases and leads to reviewing the role of company-level characteristics of the innovation phase in the next chapter.

The five key elements of the Fuzzy Front End show relevance to the period of the innovation phase and are therefore reviewed towards a model for the innovation phase. But the FFE shows relevance to more than just the innovation phase: each phase contains projects and all projects have a fuzzy beginning. It could therefore be that factors in the innovation that link to the FFE are also relevant in later phases, but to a lower degree. The opposite is also true: factors that relate to a phenomenon that is important in a later phase can also be relevant to the innovation phase to some extent. Even if the same factors are important in different phases, the emphasis on the factors or the roles of the factors can still differ, which is an insight that helps the conceptual framework development.

The Sectoral Systems of Innovation showed limited applicability to this research towards the innovation phase and its contribution to the next chapter is therefore limited to only the market-level and market creation. This prevents comparison of claims from other models and frameworks that are possibly contradictory, while SSI did not actually aim that claim specifically at radically new technologies or the innovation phase. There is no description of the relations between the four building blocks of SSI. Some basic idea about the most important dynamics between the building blocks leads to increased insight and to ways to influence innovation systems. The same logic applies to the innovation phase, where some basic dynamics between factors can enable quick insight in characteristics of a specific case. Even if those basic dynamics are represented by arrows between factors of a static model.

3.8.4. Answering sub-question 1: What is the role of the innovation phase in innovation models?

The innovation phase is the period from invention of a radically new technology and lasts until the first market introduction. Two phases follow after the innovation phase: the market adaptation phase starts at commercialization and lasts until large-scale diffusion – the mass market – is reached, the market stabilization phase starts at large-scale diffusion and ends when the technology is substituted by another technology.

The importance of the conditions for large-scale diffusion during the innovation phase was discussed and is reflected upon when working towards a model for the innovation phase. A condition that is important for reaching large-scale diffusion does not necessarily imply importance of that condition during the innovation phase. The conditions for large-scale diffusion showed a number of factors concerning the innovation itself, like product performance and product price. A number of factors concerns the market environment of the innovation, like customers and suppliers. The company perspective has an implicit place in some factors, but is generally less represented than the innovation and its market. A company culture and values, for example, can have a large influence on its effectiveness and efficiency in working on a technology. Apparently, effectiveness and efficiency is assumed for the market adaptation phase, but it cannot be assumed for the innovation phase, with a low number of organizations working on a technology. The role of the company in the innovation phase and how this role is represented in the factors is therefore reviewed in the development of the conceptual framework. Conditions for large-scale diffusion can influence each other in many different ways, with direct and indirect influences and positive and negative feedback loops. Some basic idea about the most important dynamics between the conditions leads to increased insight and to ways to influence those conditions. The same logic applies to the innovation phase, where some basic dynamics between factors can enable quick insight in characteristics of a specific case.

Strategic Niche Management adds more to the market adaptation phase than to the innovation phase. Their most important notion is that of technological and market niches, which are instrumental in the progression of the technology. The creation of niches starts before commercialization, and therefore in the innovation phase, and the factors in becoming a sociotechnical regime show similarities with the conditions for large-scale diffusion. There are also differences between SNM and the conditions for large-scale diffusion. SNM's technology is split in the conditions product performance and product price, while SNM's culture and symbolic meaning are combined in the conditions sociocultural aspects.

There are also more subtle differences. Industry structure and network formation have an overlap, but arguably both factors have parts that are not described in the other factor.

The trial-and-error learning that is observed in many of the cases of the Minnesota Studies leads to the suggestion to continuously monitor the factors in the innovations phase. Continuously monitoring factors is seen as useful for predicting and finding problems in the development and diffusion of the innovation of which an organization is working. It may also present opportunities in solving problems. The overlap between the innovation phase and the adaptation phase, that becomes explicit through the model of the Minnesota Studies, can result in broader applicability of factors that were designed for one specific phase. In this case, the potential applicability of the conditions for large-scale diffusion to the factors in the innovation phase.

The Fuzzy Front End shows relevance to more than just the innovation phase: each phase contains projects and all projects have a fuzzy beginning. It could therefore be that factors in the innovation that link to the FFE are also relevant in later phases, but in a lower degree. The opposite is also true: factors that relate to a phenomenon that is important in a later phase can also be relevant to the innovation phase to some extent. Even if the same factors are important in different phases, the emphasis on the factors or the roles of the factors can still differ, which is an insight that helps the conceptual framework development.

The Sectoral Systems of Innovation did actually not describe the innovation phase, but the theory is expected to contribute more to characteristics of the market-level and market creation.

The innovation phase is an inherently chaotic phase. Any step or factor that is described needs the nuance of deep uncertainty. The project that realizes the transition from a technology to a product is planned in steps, but needs to adapt continuously. The project depends on unexpected ideas and the incidental meetings of problems and solutions, a model for success does not exist and cannot be created. There are specific subjects that often require attention, recurring problems or opportunities that many technologies meet. Finding such subjects requires a deeper knowledge of the innovation phase and its inner workings.

4. Literature review 2: characteristics of the innovation phase

By describing the innovation phase in further detail, the gap between innovation models in Chapter 3 and factors in the innovation phase is closed. The literature review on innovation models revealed the problem of the hindsight bias and showed how innovation models describe the market environment through several aggregations, like aggregations across product types, different organizations, and a geographical aggregation. Factors in the innovation phase are expected to work at another level of detail than the S-curve. This is based on a simple logic: creating a complex system begins in the creation of some of its elements. That means a need for observations at a much more detailed level than an S-curve can deliver. Instead of diffusion curves, those observations will consist of many different actors and factors that are found in literature.

The road from an idea to a commercial market introduction is an exciting and risky one. Although innovation can be planned in a corporate strategy, the emergence of a new idea is the small step that triggers a chain reaction. Computer company Apple originates from a self-taught electrical engineer who built boxes for making free long-distance phone calls, eventually the company is responsible for the general lay-out of personal computers (Isaacson, 2011; Ortt & Dees, 2018). Apple is an example of unexpected outcomes from the innovation phase. It illustrates how complex it is to make generalisable observations about the phase when so little is certain, when even the product you are working towards can change completely. Moschos (2016) found a rough structure by proposing three levels: the project, the organization, and the market environment. This chapter is structured in a similar way, starting at the project-level. One addition is made in this chapter. The question for a new technology is not only what the system around the technology looks like, but also how this system is created, as becomes clear throughout the reviews of each paragraph. Therefore, a fourth paragraph is added: "Market creation". That paragraph describes the process of creating an innovation system, a process that influences the project-, company-, and market-level.

The innovation phase starts when a technology is available in "*some rudimentary form*" (Ortt & Schoormans, 2004). That can mean a whole range of different things: "*the moment an idea is presented, a patent is filed, the principle of a technological breakthrough is demonstrated, or the first pilot application of a breakthrough technology is started*" (Ortt & Schoormans, 2004). Articles about both the Minnesota studies and the Fuzzy Front End show in Chapter 3 how some activities can have taken place before the moment in time that this definition of 'invention' applies. The invention is now out in the open. At least some actors have access to the idea. Further developments can begin. When the conditions for large-scale diffusion are analysed for such a new idea, most conditions will probably be causing a barrier. There is lacking knowledge, low quality, no production, no complementary products (unless through backward compatibility), no network, no customers, and possibly some relevant institutional aspects. Much work is needed to build a system that contains all those elements, to create a system that contains all building blocks that Malerba (2004) finds in all innovation systems: knowledge and technologies, actors and networks, institutions, and demand. However, the question remains whether all elements are needed during the innovation phase. Which set of factors is important for further development? For reaching the market adaptation phase?

Not only a lot of resources and work are needed to achieve a market introduction, accomplishing all this takes time. Ortt reports an average of seven to ten years from invention to market introduction for breakthrough communication technologies. Other research is mentioned too, claiming average lengths of 15 to 23 years and 28 years for the innovation phase. (Ortt & Schoormans, 2004).

This chapter is a bottom-up description of the innovation phase, based on the literature that was introduced and reviewed in Chapter 3. Statements and observations in literature that concern the innovation phase are copied into a work-report, sentences and paragraphs that are copied are categorized to the topics that they describe. If a statement or observation concerns multiple topics, it is copied to both of those topics. The work-report is included in Appendix A. The elements from the work-report that work at the project-level of innovation together form the basis on which paragraph 4.1 is written, company-level elements form the basis of paragraph 4.2, market-level topics for paragraph 4.3, and claims that relate to market creation for paragraph 4.4. The paragraphs 4.1 until 4.4 form a first perspective of the innovation phase, based on literature. Elements that are mentioned in multiple sources, elements that describe generic phenomena in the innovation phase, and, most importantly, elements that do not conflict with claims from other sources, all of those are shown in bold and are summarized in a text box. With this, the reader is provided with a short overview of the elements that literature deems important for the innovation phase. A review of every paragraph brings criticism to this first perspective, mostly making clear where literature is currently lacking and where improvements are needed. The conceptual framework provides improvements through a new perspective, a perspective that is complementary to the first perspective in this chapter and again reflects on important factors in the innovation phase.

This chapter is structured around four parts: the project-level, company-level, market-level, and market creation. Malerba's framework is used at the levels where it fits best. Those are not the project-level and the company-level, but only the market-level and market creation. The explanations of the different elements of (Sectoral) Systems of Innovation include statements about things that are important in those elements. But such statements at the level of an innovation system cannot be assumed to be equally true for projects and companies. Using Malerba's work at every level of the literature review in the next chapter would lead to unsupported speculation. It would lead to statements that are possibly untrue because something that is true for an innovation system, is not necessarily important at the project-level or company-level. Therefore, the views and insights of the (Sectoral) Systems of Innovation are only applied to the parts of next chapter's literature review about the market-level and about market creation.

The method of this chapter, as described in more detail in Chapter 2, is a bottom-up description of the innovation phase based on literature. A major downside of this method is the fact that the completeness of the description cannot be proven. The list of factors that is deemed important during the innovation phase based on the literature that is used, is potentially incomplete or even incorrect, depending on views of other literature or best practices that have not been used here. There is no knowing whether a chapter like this one is complete. The reply to this is that sufficient literature has been used from sufficiently different literature streams to have at least the most important characteristics of the innovation phase included in this chapter. Potential incompleteness leads back to the methodology and its assumptions in the choice for literature.

There are upsides to describing the innovation phase on the basis of different streams of literature. A diverse set of sources at the basis of a bottom-up approach is a good start for the creation of a comprehensive description of said phase. Little interpretation and application of the theory was used, the focus was on combining and integrating models and frameworks into one coherent story. Reviewing this bottom-up model makes two things explicit. Interpretation of the literature has its limits, and nuances and details get misinterpreted, lost, or mixed with other insights in the process of combining all elements in one story. Second, there is no guarantee that the found mix of literature streams can together form a complete description of actors, factors and mechanisms that are relevant during the innovation phase. Reconsidering paragraphs 4.1, 4.2.7, 4.3.6, and 4.4 (the review at the end of each paragraph) brings remarks, improvements and suggestions. Those considerations are summarized at the end of this chapter in paragraph 4.5 and are revisited during the development of the conceptual framework in the next chapter.

4.1. Project

The first of the levels on which we search for characteristics of the innovation phase is the project-level. It is the start of it all, the place where ideas are created and where the first efforts towards development are made.

4.1.1. Shaping a project

Shaping a project

- Opportunity
- Proliferation
- Selection
- Planning
- Roles
- Promise
- Hobbyist versus company

It all starts with this one great idea. An **opportunity** that is spotted by someone, by an individual (Reid & De Brentani, 2004). That someone can be anyone: from a hobbyist in a garage to an organized team in a multinational organization. Once that opportunity is spotted, multiple applications **proliferate** from that one idea (Schroeder et al., 1986). One or more of the possibilities are **selected** and next steps are **planned**. The project has now started and realization of the selected application(s) form its end-goal. The shape that the projects take still ranges from one or more hobbyists informally working on an idea at home to a formalized well-defined NPD process (New Product Development process). The Fuzzy Front End is the unstructured period before the more formalized NPD process and is a time of iteration between the possible steps that are between creating and executing ideas (Koen et al., 2001). Opportunity identification, opportunity analysis, idea genesis, idea selection, and concept & technology development are the key components of the FFE, all driven by the engine: executive-level management support (Koen et al., 2001). This relates to the FFE's assumption that the information flow includes boundary spanners, gatekeepers and corporate-level decision-makers and more. They assume a relatively large role for the company. To some extent, most projects have a project manager, a project team, and a product champion, even when all **roles** are fulfilled by one and the same hobbyist. The product champion is the person who advocates for the project to secure resources and promote a long-term commitment from actors to the project (Markham et al., 2010). The project's activities focus mostly on confirming assumptions at first. The **promise** that the technology shows must be confirmed and the commercial potential has to be found to keep resources committed (Schroeder et al., 1986).

4.1.2. Technical developments

Technical developments

- Technical refinement
- Poor link to user needs
- High price

Rogers' view (1983) proposes a smooth start of the diffusion curve from the moment of first introduction, continuing into large-scale diffusion in the first attempt. That view presupposes much technical development before the first market introduction, which is accurate. Much **technical refinement** is needed in the innovation phase (Ortt & Schoormans, 2004). Two big problems in the early phase of development are the **poor link to user needs** and the **high price** (Kemp et al., 1998).

4.1.3. Review

The project is said to start bottom-up, from an employee spotting an opportunity or from a hobbyist with a great idea. This idea evolves into a project. The project will be risky, but it is then placed in its company environment and later in the market environment. But that is optimistic view of the literature. These proposed steps in the process can even be called linear and similar to incremental innovation. Both the Fuzzy Front End literature and the Minnesota studies mention that the period around invention is inherently chaotic, unstructured and uncertain. What happens in the case of radically new technologies is not linear and not easily compared with incremental innovation processes. Ideas come up, are thought of by multiple unconnected people at the same time, proliferate into multiple ideas, are forgotten, are not acted upon, and are acted upon in many different ways. And ideas that lead to radically new technologies are not necessarily recognized as such.

To shape such an idea into a project is trying to fit something organic, irregular, and uncertain in a structured and linear enclosure. People with the right knowledge that want to work on the project have to be found. Physical resources have to be arranged for or allocated to the project. Financial resources must be made available. Setting up collaborations is essential, but also complicates setting up a project. Defining the project goal in a direction that is profitable for the company in a later development stage, is practically impossible to do with a degree of certainty. In this sense, projects for the development of radically new technologies may find more similarities with fundamental research than more applied R&D. The resources that are allocated to this project are unlikely to lead to a positive return on investment in a few years' time, moreover, it is unclear how and whether a return will ever be realised. A project without a clear goal is basically draining resources until it dies out and development stops. What does a company get in return for its investment with such a low financial incentive? Experience and learning are assets in the process from an idea to a product. Projects with unclear outcomes lead to projects with some direction, which eventually lead to the actual development of a product. But this linear, three-step representation of development steps is unrealistic as well.

Projects change. The entire essence of the project changes continuously as knowledge of the radically new technology increases and the goal gets adjusted accordingly. Projects can change both for better and for worse: planning, goal, personnel, available funds, external support (organizations, experts, consultants, hobbyists, policy makers). That is, if the project delivers anything with some potential at all, within the timeframe that is allowed by decision-makers. Because projects do not only change, they also stop. Similar chaotic possibilities for ideas are also true for projects. Projects are started, happen parallel in different organizations that work on the same or a similar technology, are not always publicly known, have to adjust their goal, do not reach their goal, have to change, do not find an application for a technology, are stopped, and are forgotten. Linearity would be an unrealistic assumption.

All this uncertainty, change, working parallel in similar directions, stopping, and restarting, reveals how literature, even when knowingly describing fundamentally chaotic processes, still presumes linearity. Structuring the innovation phase into a model and describing similar steps that are often seen across a wide variety of innovations is partly responsible for the apparent linearity. A model is always structured, even when describing a chaotic phase. However, claiming that an idea evolves into a project which evolves into a product, is view that fits incremental innovation. An incremental view that does not correspond to the reality of radically new developments. This research proposes to stop describing all activities at the project-level as a 'project'. The terminology should be changed to 'development efforts' instead to do more justice to both the length of the innovation phase and the diverse activities in the innovation phase. Thinking of the innovation phase as a project may lead to the incorrect assumption or feeling that the length of the innovation phase for a specific technology is defined by the length of a development project that follows the sequential steps of the stage-gate model. That is not the case. The length of the innovation phase is determined by the accumulated length of many activities. The phase consists of more than just projects. It starts with the time that it takes to come up with ideas, to actually start acting on the idea, the time that is spend on tinkering and toying with the idea, and even the time that the idea is shelved and not developed any further. Efforts can then be shaped into a project, or stop altogether, the project can stop entirely until somebody else comes up with the same idea again, and another company starts a project on the topic. Sequences of projects can be dedicated to further research, companies can work on the same or similar developments at the same time without knowing about the other, and there is no guarantee that developments won't simply stop again, even after all this effort. Much work must also be done in networking, connection supply and demand of knowledge, finding the right people, applying mock-ups of a possible product. The innovation phase does not consist of just a project or a sequence of projects. It is highly diverse and all the needed development efforts can be worked on at the same time, by the same or by very different organizations, and everything can stop and be resumed or restarted later. To just call all those activities 'a project' does no justice to everything that happens. But all activities do have a similar goal (not the same goal, because of different directions that companies go with one and the same technology): further developing the radically new technology at hand. The innovation phase therefore consists more of 'development efforts' than a 'project'.

The paragraph on technical development is short, while it also claims that technical refinement is an important part of the innovation phase (Ortt & Schoormans, 2004). Used literature does not elaborate on technical change, the focus is on what the technology needs to become an innovation. More on the components that need to surround the radically new technology to make it embedded in a market, less on the technology itself. This may very well be the only option: every technology has its own characteristics and trying to address those technical steps from the perspective of innovation management has little value. However, speaking of a development project without addressing the development steps of the technology itself creates problems with the applicability of frameworks, models, and suggestions. Models and frameworks should account for technical difficulties: they may point to problems that should be addressed, while the technical developments form the underlying problem. A missing infrastructure is a problem for a X, but dealing with that problem works differently when the technology of the infrastructure has not been developed than when investors cannot be found or a government is stopping the build of a large infrastructure. The point is this: the models and frameworks in chapter 3 should reconsider the role of technical development steps and specific characteristics of a technology in their theories, because even the combined view is minimal.

4.2. Company

Six main topics are discussed in this paragraph:

1. Expectations.
2. Risk.
3. Technical resources.
4. Marketing.
5. Top-management support.
6. Financial resources.

There are four critical resources for an innovative project to survive (Markham et al., 2010): technical resources, marketing, top-management support, and financial resources. Going through those four resources for projects will give a view on how a project functions within the organization where it has been set up. When the project is observed within a company, there are more dynamics between the project and the company in which the project takes place than just 'resources for survival' that a company offers to keep the project going. The first is 'expectations', mainly addressed by Kemp et al. (1998) and Ortt and Schoormans (2004). The second is 'risk', mainly addressed by Kemp et al. (1998), Mannheimer (2016), and Schroeder et al. (1986). Moschos (2016) also proposes that 'firm-specific techniques' and 'organizational culture and values' as factors that affect the innovation phase.

However, no support for those factors is found in other literature and through examples and case studies that were used in the observed literature. Those two suggestions are therefore not included in this bottom-up model, but the ideas are revisited in Chapter 5, when a model for factors in the innovation phase is proposed.

4.2.1. Expectations

New innovations have to prove themselves. That already starts at the project-level, where an opportunity is shared to find other enthusiasts. This is expanded to **raising expectations** and **making promises** now that the project enters the company environment (Markham et al., 2010). A radically new innovation challenges a company at many levels: it changes the supply network, the internal workflow, customer segments (Ortt & Schoormans, 2004), and the needed skills and knowledge (Mannheimer, 2016). Good communication about the potential upsides of an innovation can start early, because **support has to be found**. It is not just a **reluctance to change** that results in the lacking support. Actors judge a new technology on the basis of their current knowledge and therefore on the basis of the current technology (Kemp et al., 1998). Also, manufacturers assume that consumer demands cannot be changed (Kemp et al., 1998). Without belief in the technology, resources will not be allocated to the risky process of bringing it to the market. **Past experience** also shapes expectations as was seen in the diffusion of communication technologies, especially in the case of broadband mobile communication where earlier innovations paved the road for diffusion of newer innovations (Ortt & Schoormans, 2004). Another example is the parallel that is seen between TCP/IP (internet) and blockchain. Since the natures of the internet and blockchain are very similar regarding several characteristics, the diffusion of blockchain is expected to go faster than that of the internet (Ortt & Dees, 2018). The reason is that it is a known transition, a series of changes that society has seen before, probably resulting in a faster diffusion of blockchain (Iansiti & Lakhani, 2017).

Expectations

- Raise expectations
- Make promises
- Finding support
- Reluctance to change
- Past experience

4.2.2. Risk

High expectations do not necessarily lead to a clear development path. **Trial and error**, failure, **uncertainty**, **risk**. They are all buzzwords that are repeatedly mentioned when describing the work on a radically new technology. In the hybrid wheat case, many innovation participants had dropped out by the 1970s because of the high risk of the research. The release of the first hybrid variety in 1978 had difficulties with stability, impure seed stock, and low seed availability (Schroeder et al., 1986). Development of innovative Naval systems was followed and showed a major product failure at the costs of several millions of dollars (Schroeder et al., 1986). Small biopharma firms develop a drug until the point of clinical trials. Then the costs and financial risks are generally unacceptably high for a small firm, a larger firm is found to co-develop the drug and reach the market (Mannheimer, 2016). An organization can **share risk** with partners in a form of collaboration, but still, **risk must be taken** to cross the Valley of Death (Mannheimer, 2016). Not every organization will choose to fight across the Valley of Death, **many organizations** avoid risks by building on current consumer preferences (Kemp et al., 1998). The lacking promise of interested customers for the new product gives **little incentive** to develop the new product

Risk

- Trial and error
- Uncertainty
- Risk
    - Take risk
    - Share risk
    - Little incentive
    - Participants
    - Investors

(Kemp et al., 1998). Finding **investors** for high-risk projects is hard (Mannheimer, 2016) like seen with banks, which show a similar reluctancy (Kemp et al., 1998).

4.2.3. Technical resources

Technical resources

- Low product performance
- Dependency on research
- Dependency on development

Allocating resources and steering a product to commercial viability creates a number of dynamics around the development efforts. Many projects are **dependent on further research and development**, especially at such an early stage where product **performance is generally low** (Ortt & Schoormans, 2004). An indication of this is the long time it takes for companies to make the first market introduction, like with the breakthrough communication technologies that averaged seven to ten years to reach the market for the first time (Ortt & Schoormans, 2004). Or the innovation phases of augmented reality and autonomous vehicles: 26 and 24 years (Ortt & Dees, 2018). Some technologies do not face this barrier. The basis of blockchain, the Bitcoin whitepaper by Satoshi Nakamoto, was published in 2008 and its market introduction was in 2009 (Ortt & Dees, 2018), and TNT immediately entered large-scale diffusion after a short development period (Brown, 1998).

4.2.4. Marketing

Marketing

- Focus on research decreases
- Marketing efforts increase
- Competing technologies
- Share enthusiasm
- Overcome resistance
- Strategic decisions
    - Secrecy
    - Goal of marketing

Marketing has played a role in quite a few case studies and examples in the used literature, but its role is hardly made explicit. The goal of marketing, the used marketing methods, or its importance; very little is said about marketing in the innovation phase. A secondary search was needed to gain at least some idea of what marketing could mean during the innovation phase. That is consistent with Markham's (2010) findings in literature: "*Most large firms are deficient in bringing the marketing vice president and marketing organization into a compatible and parallel role with the CTO.*"

The **focus on research decreases** throughout the innovation phase (Ortt & Schoormans, 2004). Development is still necessary and will stay important, although its nature may change from fundamentally different designs to more incremental changes (Ortt et al., 2013). Due to the non-linear nature of developments in the innovation phase, this shift in focus can however happen several times before the mass market is reached. The development of the cochlear implant saw a proliferation of options after which multiple technologies started to **compete** (Schroeder et al., 1986). As a product becomes more concrete and dependency on research decreases, other innovation efforts, like **marketing efforts, increase** (Mannheimer, 2016; Ortt & Schoormans, 2004). Biopharma companies start projects with a discovery and an R&D phase, after which projects evolve towards a business orientation (Mannheimer, 2016). Development towards a product means overcoming resistance (Kemp et al., 1998). Communication was important in forming a project and in giving the project a place in the company, but as development progresses, the will to make a great new product known to the world comes with it. Both to **share enthusiasm** and to **overcome resistance**. Exceptions are made for technologies that are kept **secret**. Blockchain must have been partly developed in secret: the moment of invention cannot be further determined than the period of 1998 until 2008 (Ortt & Dees, 2018). When there are no strategic reasons for secrecy, communication about ongoing development efforts can serve different goals. An example is the list of five **goals of content marketing** that was published by Hall (2013).

1. Brand Awareness.
2. Brand Loyalty.
3. Customer Education.
4. Customer Engagement.
5. Talent Recruitment.

Marketing can at first serve as a way of influencing the company's reputation and image. There are certain benefits to being known as an innovating company. The subtle step to brand loyalty makes people and organizations return to your company out of interest for what is offered to them. Valuable content spikes loyalty and helps retaining customers. This valuable content can go further to not only spike interest in your company, but also to educate the world about what you can offer. Customer education is especially relevant for radically new technologies. Explanation of underlying principles and benefits are unknown to the public when your product or technology offers an entirely new functionality. Marketing then also leads to customer engagement. Customer engagement leads to all kinds of beneficial collaborations, like recruiting talent. However, those observations follow from a secondary search, not from the literature that was selected to together describe the innovation phase. This problem is revisited in the review of this paragraph.

4.2.5. Top-management support

Top-management support

- Bottom-up beginning
- Valley of Death
- Long-term commitment
- Several roles
- Commitment versus resources
- Strategy
- Change organizational structure
- Ensure skills and resources
- Establish collaborations

Most radically new innovations start **bottom-up**, simply with an idea (Ortt & Schoormans, 2004; Schroeder et al., 1986). Most research and development is aimed at incremental innovations (Kemp et al., 1998) and more radical ideas can spark anywhere in- and outside the organization (Reid & De Brentani, 2004). It is a great challenge to bring an idea from its well supported starting point in research, to the well-supported process of commercialization. The **Valley of Death** in between those points is a period where many developments are stopped due to lack of resources (Markham et al., 2010). Bringing a radically new technology to the market is therefore dependent on **long-term commitment** (Moschos, 2016; Ortt & Schoormans, 2004). However, several sources report how managers are not brought into the development process, like not including the marketing vice president, or a communication gap between a CFO and the R&D department (Markham et al., 2010). Markham et al. (2010) see three **roles** that must be fulfilled to bridge the Valley of Death: "*Champions make the organization aware of opportunities by conceptualizing the idea and preparing business cases. Sponsors support the development of promising ideas by providing resources to demonstrate the project's viability. Gatekeepers set criteria and make acceptance decisions.*" In this model, the champions are giving their long-term commitment. A balance must be struck between **commitment and available resources**, since overcommitment can lead to bankruptcy (Moschos, 2016). The needed time and resources should not be underestimated which makes top-management support vital to successful commercialization (Kemp et al., 1998; Markham et al., 2010; Schroeder et al., 1986). This top-management support is seen to include at least two elements: **strategy** and **organizational structure**. It is difficult to find support for radically new innovations when strategies do not allow any resources to be allocated to such risky projects. The allocation of **resources** starts in the strategy. New management due to budget cuts and a new HRM manager were the changes that led to the start of new innovations in two of the innovation studies by Schroeder et al. (1986). Markham et al. (2010) report case studies from different sources that describe formal structures in companies to help boost innovation: ABB provides one-month funding for selected projects, other companies support informal projects, create incubators, or give researchers time to develop completely new ideas. However, needed resources change over time. The change in perspective from research to commercialization also leads to changing needs for certain **skills** (Mannheimer, 2016), expertise and experience. Top-management support is therefore also needed to change the organizational structure as the project progresses. The project team must consist of the right people at the right time, external support and **collaborations** can bring necessities that the organization is missing (Mannheimer, 2016). A consultant was hired to evaluate the potential of a patent in a case study on barcode technology (Moschos, 2016). Innovations on the cochlear implant, apheresis, and a naval system all share having a change of management. Those changes were directly linked to improved results in the development efforts (Schroeder et al., 1986). A provider of electricity utilities and a producer of incandescent lightbulbs joined efforts in spreading use of electricity, because it was a shared interest. Later, those companies stopped collaborations because selling as much electricity as possible is contradicting the goal of making efficient lightbulbs to reduce electricity bills (Ortt & Schoormans, 2004). Those examples show that organizational structure has effect on every level of the innovation: the project-level, the company-level, and the market environment in which the company can collaborate with different organizations to further support the development efforts.

4.2.6. Financial resources

Sometimes, budgetary cuts can lead to a new innovation that is born out of necessity, but often a new innovation will be continuously searching for sufficient **capital** (Kemp et al., 1998; Mannheimer, 2016; Schroeder et al., 1986). The **early stages of a new technology often provides funds** (Ortt & Schoormans, 2004). This is also the stage in which **governments** offer subsidies for development of products based on a new technology (Kemp et al., 1998; Mannheimer, 2016). Car manufacturers tend to adopt strategies towards cost leadership or differentiation, not towards producing for market niches. New products are therefore often marketed by new companies (Kemp et al., 1998). Innovations by biopharma firms are also often marketed by **smaller firms** (Mannheimer, 2016). But when subsidies run out and the developments are oriented towards commercialization and marketing instead of R&D, the projects are still risky, which is why banks and other investors are reluctant to invest and proof of the potential is required for securing additional funds (Kemp et al., 1998; Mannheimer, 2016). **Larger firms** may not need external investment, but securing funds internally is not necessarily any easier. A case study on apheresis illustrates that budgets can even be reduced, in that case leading to an entirely new marketing program (Schroeder et al., 1986).

Financial resources

- Search for capital
- Early stage is funded
- Governmental subsidies
- Small companies
- Large companies

4.2.7. Review

A company is just as versatile as the development efforts that it’s trying to uphold. The same chaotic nature emerges as found in the development efforts, in which companies are founded and companies go bankrupt, they merge, and split, and sell business units, they change strategic direction and have personnel changes. They are trying to support development efforts, but don’t know in which direction those developments should go. Literature does not give any directions about working without clearly defined goals and about working on developments under highly uncertain conditions. A company must do more than support its projects because development efforts are broader than a development project. But what? The same incremental and linear elements that were found at the project-level continue in the company-level of the model. When the four critical resources for the survival of an innovative project form a fitting framework for the description of activities during the innovation phase at the company-level, it becomes clear that literature works with the same assumptions at the company-level as it did at the project-level. Paragraphs have been added for expectations and risk, but the broader set of activities that is needed for supporting development efforts (see the review about the project-level characteristics of the innovation phase) is missing. Because the innovation phase is broader than 'a project', company-level elements of the model should be tailored accordingly. This has two implications. First, also at the company-level the terminology should be changed from a 'project' to the 'development efforts'. Second, the activities that are described should also entail broader activities than just looking inside to its own efforts. Having an outward focus is just as important. Because the close relation of this second point with activities in the market environment, this point is revisited in the next paragraph (market) where the missing elements are identified and added.

New developments can easily be copied when they are made public. That is a good reason for companies to keep a new product secret during development, and postpone any external communication until the moment of the product launch. Radically new technologies have the potential to completely change both the supply and the demand side of the market. In the case that both those sides have to change in order for the product to be successful in reaching the mass market, secrecy throughout the development of the product may be a bad idea. Changing a market takes, among other things, a lot of time. The sooner the process of change is started, the sooner it could be finished. Sharing creates the risk of being copied, but it is the best option when the alternative is to lose all investments in the technology. It is difficult to estimate *ex ante* how much time the market needs to come to a point where it can and will support development efforts, but historical cases show that projects and companies often run out of resources before results like sales are sufficient for another round of investments. Assuming that increased exposure of the technology does indeed lead to earlier involvement of other actors in the industry in which extra resources are provided as well, it is best to increase exposure early in the process. Then why does the literature not mention marketing as a tool during the innovation phase? Marketing seems to start around the product launch, not before it. Other forms of exposure are suggested, but very limited. Current literature therefore underestimates the importance of external exposure of the development efforts to attracting collaboration and resources in the innovation phase. It underestimates what the effect can be on the chances of success for a company. In this sense, current literature still reasons from the perspective of Rogers' S-curve, in which the success of a technology is measured through accumulated diffusion. Knowledge about the need for marketing and other forms of exposure during the innovation phase is strongly lacking.

4.3. Market environment

The step to the market environment adds a whole new layer of complexity. The previous two paragraphs dealt with a project and the survival of development efforts in a company. Such a project touches upon the interests of many actors. Whether or not the interests of actors align with the development of the innovation, depends on the innovation and on the actor. Moschos (2016) identifies eleven groups of actors and reaches a much more detailed description than other sources of literature do. Some of the actors he identified are not mentioned by other sources at all, and Moschos does not provide further insight in the roles of those actors either. Malerba (2004) lists individuals (consumers, entrepreneurs, scientists), firms (users, producers, suppliers), non-firm organizations (universities, financial institutions, government agencies, trade unions, technical associations), subunits of larger organizations (like R&D or production departments), and groups of organizations (like industry associations). Malerba does not provide any insight in the roles of those actors, when in the innovation process they are active, and which actors are active in every innovation system, and which are technology (or sector) specific. Only actors whose roles are described in more detail in multiple sources add to this chapter's description of the innovation phase. This paragraph distinguishes:

1. Government.
2. Regulatory authorities.
3. Research institutes.
4. Existing companies.
5. Users.

The difference between the government and regulatory authorities has not been defined my Moschos, nor by Mannheimer, who uses the same two terms. The government is responsible for creating and executing laws and regulations (BusinessDictionary, 2019) and can use its power to support favourable technological developments. The government can decide to give a mandate for performing (part of) those actions to a regulatory authority that oversees a specific industry, like the FDA for example.

The original list of actors by Moschos also includes universities, policy-makers, suppliers, providers of complementary products, scientists, and autonomous entrepreneurs. As said, there was no detailed information about their role that would add to this chapter. Moreover, more actors can be thought of that aren't included in this list, but that have at least some role to play. Examples are NGOs, activists, pressure groups, banks, and other financers. Either more research is needed, or their roles are not deemed significant enough by researchers. The case studies also provide insight in the actors at the market-level and those views are used to empirically complement the theoretical conclusions in this chapter. Until there is a suggestion that there is value in treating those other actors separately in a model, we assume they are not important enough during the innovation phase to include them in the list of important factors.

4.3.1. Government

Government

- Support
  - Subsidies
  - Network
  - Pilot project
- Need for technologies
- Laws and regulations
- Local/regional/national/ international

Governments can **support** R&D activities in different ways. New developments for example offer environmental, social, and economic opportunities and can result in an increase of, for example, income and welfare. A simple form of support is giving out **subsidies** for new developments. Governmental subsidies can be used for R&D, not for marketing a new product (Kemp et al., 1998). Even if a government is offering subsidies, it does not always make clear what **need there is for specific new technologies** (Kemp et al., 1998). Another possible form of support is to help companies in a more practical sense with developments. Connecting organizations with similar interests or providing pilot projects are more practical ways of supporting developments. Governments are often described in literature as one actor, but it is such a large actor that different interests occur for different parts of the government. What the literature fails to mention are governmental ways to support innovation apart from the obvious subsidies. A small secondary search leads to some examples of possibilities beyond subsidies. The EU created the Horizon 2020 programme to achieve "*more breakthroughs, discoveries and world-firsts by taking great ideas from the lab to the market*" (Horizon 2020, 2017). This is a very broad scope. As opposed to an **international** governmental body such as the EU, **local governments** can define a city's needs much more specific. Examples are the Dutch cities Amsterdam and Dordrecht. They both offer smart city programs that include subsidies and **networking** opportunities for citizens, companies, knowledge institutions and public authorities (Amsterdam Smart City, 2019; Smart City Dordrecht, 2019). For Dordrecht, this programme links both to the city's goals of growth and attracting higher educated people to the city as to the economic and social advantages of attracting high-tech projects and companies. Amsterdam lies in the **province** of Noord-Holland, the province has its own programme for stimulating innovative projects and SMEs (Small and Medium-sized Enterprises), supported by the EU. This innovation fund offers convertible loans on a project-basis (Innovatiefonds Noord-Holland, 2019). The city Dordrecht lies in the province of Zuid-Holland: this province offers to become the launching customer for start-ups through the Startup in Residence programme. This means a paid **pilot project** for which a test location and support from local governments can be appointed to an innovative project (Startup in Residence, 2019). Another task of governments is to control regulations, both through **laws and regulations** as through installing regulatory authorities.

4.3.2. Regulatory authorities

Regulatory authorities

- Industry dependent
- Barrier/support

The selected literature touches only lightly on the subject of regulations and regulatory authorities. An industry where lots of regulations exist is the field of healthcare, especially when it comes to the development of new drugs (Mannheimer, 2016). A case study on apheresis reports how an FDA approval (Food and Drug Administration) in the US (United States of America) preceded field trials (Schroeder et al., 1986). This approval was needed before field trials were allowed to begin. Mannheimer (2016) also reports interactions between regulatory authorities and a biopharma firm on the way to trials and approvals. That is very **different from many other industries** where a new-made product can be tested, improved and tested again until the product is ready for commercialization without the intervention of any regulatory organization. In that sense, regulations can slow down developments, or possibly even block them entirely. Laws and regulations can also **support** developments in a direct or indirect way. Direct support is currently happening for 3D printed buildings in Dubai: 25% of all new structures must be 3D printed by 2030 (Anderson, 2016). There is very little regulation blocking the adoption of 3D printing in construction, except for finding a way to prove material and construction quality to meet safety standards (Kaa, Dees, Steenhuis, & Ortt, unpublished). From the very first start of the development of the autonomous vehicle, there has been a regulatory **barrier**. Many countries participated in the Vienna Convention on Road Traffic, one of the principles of this convention is that the driver of a vehicle is always in control and responsible (Convention on Road Traffic, 1968) which goes against the whole purpose of autonomous driving. Tests with autonomous vehicles on the public road provide an example of indirect regulatory support through solving a regulatory problem: laws and regulations can introduce an exception to existing regulations to allow for temporary and conditional violation of the convention of Vienna.

4.3.3. Research institutes

Research institutes

- Central role
- Partly funded by government
- Supply and demand of researchers and research funds
- High risk leads to collaborations

Research institutes often have a role in the innovation process. Ortt and Schoormans (2004) even state that research institutes and universities play the **central role** during the innovation phase. **Governments often provide part of the funding** of such organizations. The amount of researchers is limited and doing research is a costly matter, especially regarding the high risks for the case of radically new technologies. Having a good position in the market of **supply and demand for researchers and research budget** is therefore important for success (Ortt & Schoormans, 2004). Research on a radically new technology has a high potential, but is also risky in its early phase. Most of the participating public institutions dropped out of the research on hybrid wheat because of the high risk (Schroeder et al., 1986). The need for researchers and researcher budgets, and the high risk, together **lead to collaborations** between researchers and commercial developers such as in the case of the cochlear implant (Schroeder et al., 1986).

4.3.4. Existing companies

As long as the innovation phase is continuing, nobody in the market has introduced the radically new technology (by definition). That means that other organizations in the market are producing or supplying a different technology then the one being developed. There is **incumbent technology** and all organizations function with that technology. Some companies work on the same radically new technology. Biopharma firms **hardly face competition in the early stages of development**, because competitors that are working on the same technology often create a different product with it (Mannheimer, 2016). Companies **incur risk through changing** the status quo, threatening their current financial performance. Manufacturers of incumbent technologies tend to be risk averse, in the sense that they prefer building on current consumer preferences (Kemp et al., 1998). But even for those who will not take the great risk of developing a radically new technology, a new technology offers **opportunities** through the need for complementary products and services (Ortt & Schoormans, 2004). All existing organizations in the market can be **harmed**, can profit or remain **unaffected** as a result of a radically new technology. The market has an interest in new developments, for better or for worse. Which role an organization assumes is discussed in paragraph 4.4, when the position of the innovating company in the market environment is analysed.

Existing companies

- Supply incumbent technology
- Little competition in early stages
- Change leads to risk
- Change leads to opportunity
- Harm/no effect/opportunity

4.3.5. Users

A radically new technology is developed to fulfil an existing function in a different way or to fulfil an entirely new function. The consumers and organizations are functioning without that new technology. A disruption of the **status quo** and adoption of the new technology will only happen when it offers enough improvement to also overcome the time, energy and sunk costs that are needed for the **switch** to the new technology, and, most importantly, when potential users **know about the new technology**. Not all users require the same leap in price/performance ratio, some are more reluctant to adopting a new technology than others, as already claimed by Rogers (paragraph 3.1). The fact remains that a technology in its early stage is poorly developed in terms of user needs and the price is too high (Kemp et al., 1998; Ortt & Schoormans, 2004). The performance of the technology must increase and the price must decrease to reach a larger customer base.

Users

- Status quo
- Switching costs
- Knowledge of technology

4.3.6. Review

The fundamental ambiguity and chaos surrounding a radically new technology is found at the market-level as well. Many problems are encountered like not finding an application for the technology, not finding customers, not getting people and organizations to change, organizations revoking their support, and competing parallel efforts. Meanwhile, there has been no mention of needed resources for changing the market and little mention of ways to change the market. But the market will have to change before adopting a radically new technology: new combinations of actors are needed at both the supply and the demand side of the market (Ortt & Schoormans, 2004), and those changes take time and often meet resistance (Kemp et al., 1998). To then see the market as the selection environment for upcoming technologies underestimates the disrupting nature of radically new technologies. A complete overhaul of the status quo, of the existing market, leads to large differences in the position towards the new technology. While working on the developments from technology to product, the eventual customer segment can be guessed, it can be hypothesized and even tested, but it cannot be reliably defined. There is uncertainty in the application of the technology which directly results in uncertainty about the customer segment. In a sense, market knowledge is not applicable, because the market will change and the knowledge becomes obsolete. Is market knowledge then unnecessary during the innovation phase? No, it is actually vital. Knowing the current market and envisioning another market creates a path of change, market knowledge is needed for designing the next steps that are necessary for adoption of the end-product.

The linear elements in the model have led to viewing the innovation phase as a project while it consists of many efforts and long times with no efforts at all. This review argued that those development efforts should more be viewed as continuously dying, whilst trying to prevent that from happening. A continuous fight for maintaining the right to exist. Focussing on survival has implications at the market-level. Although those elements have been mentioned in the literature as 'important' and as 'relevant factors', efforts at the market-level hardly go further than that. Importance is emphasized, but barely operationalized into strategies or even mechanisms that describe change in the market as a whole, tailored to radically new technologies. Networking, lobbying, collaboration. It is not hard to come up with generic strategies for companies with an external scope. The challenge is the incorporation of strategies for influencing the market with other activities during the innovation phase, the challenge is working on changing the market when the end-product is largely unknown. It is not clear why exactly, but literature is evidently lacking a view on changing existing markets and creating new markets for the case of radically new technologies.

There is a step that the literature skips. There are claims about the performance of the technology and about its price, but there is no mention of how improvements of those elements is supposed to lead to an increase in the customer base. Surely, for the potential users to even consider adopting a technology, they must first be aware of it. The technology has to be known and understood to a level where it can be compared to the status quo. The role of marketing was missing at the company-level and appears to be missing at the market-level as well.

A final observation is that, especially on the market-level, this chapter represents the technology-push perspective more than the market-pull perspective. It is important to note that radically new technologies do not always originate in R&D departments of large corporations. Sometimes the need for a new functionality forms the first step. An example of such a technology is blockchain. The inventor(s), Satoshi Nakamoto (an unknown person or group), collaborated with others in the final development stages of the Bitcoin. Those others were people who tried to develop similar currencies before. People who were looking for a way to do transactions in a network without having third parties involved. People who aspired transparency and digital safety. It was only after its market introduction in 2009 that the first blockchain products and services were developed by companies, and with those products and services came the first marketing of blockchain technology as well. (Ortt & Dees, 2018). Although this chapter does not explicitly limit developments to the technology-push perspective, it is important to note in this review that market-pull exists in radically new technologies as well.

4.4. Market creation

Paragraphs 4.1 and 4.2 describe how an invention leads to a project and the dynamics that are encountered when that project enters the more formalized environment of a company. New interests of an increased number of actors surrounding the development efforts together shape the research into a marketable product at the market-level. An incumbent market is now described, but the market has to change during the acceptance of the new product. The creation of a new market is a large undertaking. Where the project-, company-, and market-level provide static insights of how developments of a radically new technology can be helped or hindered. Market creation deals with characteristics of creation of a new market, which is less static in nature. Market creation is a process that aims to influence and create the three levels.

4.4.1. Resources for success

To achieve change in the market, to introduce a radically new technology requires not only technical development, but also business development activities (Markham et al., 2010). Supply and demand for researchers and research funds stands at the start of this (Ortt & Schoormans, 2004). A position in the market for supply and demand for researchers and research funds can be influenced through using governmental subsidies (Mannheimer, 2016). Paragraph 4.2 describes how surviving the Valley of Death requires changing resources on the path from research to commercialization. That strongly links to the change of innovation roles during that same process. Innovation roles change as the innovation phase progresses (Markham et al., 2010). Markham distinguishes three roles: "*a champion to adopt and advocate a project, a sponsor to provide project sanctioning and resources, and a gatekeeper to establish criteria and make decisions about the future of the project*". However, those roles have a relatively strong internal scope for most projects. They are designed to cross the Valley of Death, in which having the right skills and right resources proves challenging (Mannheimer, 2016). The need for **resources to change a market** is not treated separately in the literature.

Resources for success

- No mention of resources for changing the market

4.4.2. Competition

When a new technology emerges, manufacturers in the incumbent market **do not necessarily join in the development of that new technology**. A new technology means increased risk and building on current consumer preferences is seen as a way to avoid risk (Moschos, 2016). Different companies that decide to enter such developments do not necessarily immediately compete with each other. Biopharma tend to develop the same technology in different directions into **different products** (Mannheimer, 2016). When the **application** of the new developments does finally become clear, also the competition emerges. Competition can consist of either companies working on the same or a similar product, or actors from the incumbent market that is threatened by the new technology. Moschos (2016) found that the barcode and different RFID concepts were being developed in parallel. That has resulted in uncertainty in the market for potential adopters of the technology, resulting in a barrier for adoption. However, this is an explicit assumption by Moschos, he found no mention of such a mechanism in literature.

Competition

- Not everyone develops new technology
- Developments for different products
- Application can lead to competition

4.4.3. Needed changes

Needed changes

- Knowledge and technology
    - Increase performance
    - Decrease price
- System
    - Supply and demand side
    - Combinations/network of actors
    - Infrastructures
    - Procedures
    - Alliances
    - Complementary products and services
    - Institutions
- Time and resistance

For a radically new technology to reach large-scale diffusion, many aspects of the market have to change. A System of Innovation contains several building blocks: **knowledge and technologies**, **actors and networks**, **institutions**, and **demand**. Depending on the current state of the innovation system, which can be non-existent altogether, those building blocks give a view on what must be changed or created.

Transitions require change from both the technology itself and the system in which it is produced (Kemp et al., 1998). The technology itself is likely to need an **increase in performance**, while the **price must decrease** (Ortt & Schoormans, 2004). Within this system we discriminate between the **supply and demand side**, in both of which **new combinations of actors** have to be made (Ortt & Schoormans, 2004). However, changes on both sides take time and resistance can be expected from many actors, even from within the company that is leading developments (Kemp et al., 1998). Ortt continues, claiming that diffusion requires "*new **infrastructures**, new **procedures**, new **alliances** between organizations, new customer segments and so on*". Infrastructure is an element that is mentioned more often (Kemp et al., 1998), but none of the literature elaborates on what such a change in infrastructure is supposed to look like. Lastly, **complementary products and services** may be unavailable or expensive, requiring changes before they can support the diffusion of the radically new technology at hand.

4.4.4. Actions

Actions

- Not specified in literature
- Niches are instrumental
    - Coupling of expectations
    - Articulation processes
    - Network formation

Apparently, many changes have to occur in large systems for successful large-scale diffusion. How changes are to be achieved may depend not only on actions by the company that is developing the product, but also on actions by other actors. Business development as part of the innovation phase is mentioned (Markham et al., 2010), but **not specified** any further. Niches are seen as instrumental to the diffusion process and the processes in niche formation are specified further: coupling of expectations, articulation processes, and network formation (Kemp et al., 1998). The assumption that niches play an important role is in line with almost all claims and examples earlier in this chapter, with the exception of the example of the diffusion of TNT which did not go through a market adaptation phase before entering large-scale diffusion. **Coupling of expectations** encompasses the whole process from creating expectations and making promises to actors that join efforts through the alignment of those expectations. The **articulation process** is the articulation of finding implications of the new product, necessary changes for adoptions, and ways to realize those changes. The current network is changed to support the new technology, this **network formation** can prevent defensive actions against the niche formation and is needed to align strategies and visions. (Kemp et al., 1998).

4.4.5. Review

Literature says little about how a new market is created, although some idea is given by SNM's proposal that technologies start in technical niche and transition to a market niche, and by the Systems of Innovation that describe the building blocks that are found in existing innovation systems, which therefore gives a view on what must be done for creation of a new innovation system. This paragraph on market creation contains the least content of all paragraphs in this chapter and the content is also least supported by literature. There is no mention of any needed resources for creating a market, and little mention of possible strategies to achieve change as well. The only point that is elaborated on, are the different elements that have to change for a new market to emerge. How is it possible that so little is found on market creation? Changing a market does not happen at the market-level. Just like radically new technologies generally follow from bottom-up developments, complete change and complete overhaul of a market also happens bottom-up. That is possible because the elements that together form a new market, are not necessarily interdependent. However, they can influence one another. Changes in the market generally happen at the company-level. One company starts collaborations with another one on developments. Another company starts developing a complementary product or service. Now the combination of actors on the supply side is directly followed by upcoming complementary products and services. But are they linked now? Not necessarily. It is possible for the developer of the complementary product or service to act as a distributor of the new product and add value to it by offering its complementary product alongside the main product. This is the start of a new market without including any market-level dynamics yet. This observation makes it important to revisit relations between actions and characteristics at different levels. At which level of detail should factors in the innovation phase be described to be detailed enough to be actionable, but not too detailed to be pragmatic?

4.5. Conclusions of literature review 2

The insights from literature form a story about the innovation phase. They describe the most important ins and outs and the reviews provide question marks that reply to the ideas that research has put forward. The next paragraph summarises the story that was found in literature, the paragraph after that summarises the insights that are continued to the development of the conceptual framework in Chapter 5. The points for the conceptual framework consist mainly of the reviews that were performed throughout this chapter, but are of course supplemented with the main characteristics of the innovation phase.

4.5.1. Towards factors in the innovation phase

All paragraphs describe and summarize a point of this chapter that is continued in the conceptual framework development. Table 8 then lists all of those points. We start with characteristics of the innovation phase, which are an addition in itself. The other points have been brought up in the reviews throughout this chapter.

Table 8 - Implications of Chapter 4 towards factors in the innovation phase

Suggestion
Use the found characteristics of the innovation phase.
'Development efforts' instead of 'project'.
Review characteristics of the technology.
Consider 'firm-specific techniques' and 'organizational culture and values' as factors.
Increase the role of marketing.
Market knowledge sketches a path of change.
Consider the level of detail of factors.

The characteristics of the innovation phase that were found in literature have been described at length in this chapter and the frame in each paragraph lists all elements. Those elements add to the understanding of the innovation phase and are therefore all considered in the creation of a model that contains factors for the innovation phase.

The thinking in a project that brings developments from a radically new technology to a product is evident throughout the literature. Elements of linear thinking trickle down to the description of the innovation phase, making it seem like technical developments bring an idea to a product which is then sold. The creation of new combinations of actors both on the supply and demand side of the market, overcoming resistance with all relevant actors, creation of a new innovation system, the creation of a new market. Working on a radically new technology entails much more than just technical developments, more than just a project or a sequence of projects. The term ‘development efforts’ is proposed as a substitute for ‘project’ in the innovation phase to do more justice to the broad set of activities and the non-linear nature of the phase.

The characteristics of a project for a radically new technology tend not to focus on the technology itself. Perhaps that is justified: technical development steps concern a different field of research than managing the innovation. However, the two are inevitably intertwined. The place of characteristics of the radically new technology themselves is considered in the conceptual framework development.

The suggestions to see ‘firm-specific techniques’ and ‘organizational culture and values’ as factors that affect the innovation phase did not find support in literature, but that does not make them incorrect. The lack of support could also indicate that most researchers have missed the factors, although they should have included them. Therefore, the factors will still be considered in the next chapter, but with more caution than the other characteristics of the innovation phase.

The role of marketing in the innovation phase is hardly made explicit in literature. The goal of marketing, used marketing methods, its importance. Very little is said about marketing in the innovation phase. A secondary search was needed to gain at least some idea of what marketing could mean during the innovation phase. This confirms the literature’s general focus towards running a project instead of trying to change or create the market where the product is envisioned to fit in.

Because of the broad set of activities that is part of bringing a radically new technology to the market, a company cannot only have an internal focus. Forms of marketing help bringing things in the company to other actors in the market, but literature has not given this attention. Creation of a new market is helped by knowing the current market(s), by envisioning the new market, and by creating a path of change between the current market and the new market. Market knowledge is crucial in formulating and realizing a path of change.

Towards the end of this chapter the inevitable question draws near about the translation of characteristics of the innovation phase to factors in the innovation phase. How will this chapter contribute to a model that describes factors in the innovation phase? Or in other words, at what level is an innovation system created? The poor supply of information on market creation suggests either incomplete literature, or that the elements are included already without calling it ‘creation of a new market’, or a combination. The level of detail of factors in the innovation phase is vital to find the balance between detailed and actionable factors, and less-detailed and high-level factors that cannot be influenced so easily.

4.5.2. Answering sub-question 2: What are characteristics of the innovation phase?

At the project-level, most topics that come up from literature concern the start of a project and the conditions around it that shape the project. It starts from an opportunity and expectations that fuel the start of the projects and continues to proliferation and selection of ideas, and the planning of the project in different roles in and around a project team. The actual content of the project is mentioned shortly as technical refinement that should lead to meeting user needs (better) and decreasing the price.

The place of such a project in a company is still fuelled by expectations and subsequently by top-management support. Expectations are created and nurtured, and used for giving the project a place in strategic directions and ensuring the project 'gets what it needs'. Examples are resources, skills, collaborations if beneficial, and a fitting organizational structure. Risks are high and therefore managed continually through accepting the risk, or attempting to lower the risk. Lowering risk is possible through sharing it through collaboration, but finding organizations that wish to collaborate on such a risky technology is not easy. The support of a company to a development project is also influenced by the dependency on research and development activities, research is often necessary to enable further developments. And last, but maybe most important for keeping a project going, are the financial resources. The search for capital is a continuous one and the Valley of Death between fundamental research and commercialization is hard to cross.

The sociotechnical system then includes all forces outside the innovating company. A government and the regulatory authorities that carry the government's mandate carry the power both to hamper and to support developments of the radically new technology at hand. Subsidies, networking, and pilot projects can support developments, where laws and regulations can create problems. Then again, solving those barriers is another possible form of support. Research was found to be important to the company, and now the strategic aspects around research come into view: supply and demand of researchers and research funds are the central topic, influenced by the government that (partly) finances the research institutes. Other organizations can go two ways. Change leads to risk and change leads to opportunities. In the early stages of development, little competition is found. Users are in a status quo and do not have the knowledge of the technology unless it is brought to them. Knowledge of the existence of a technology in itself is not enough for switching to a new technology. Some convincing is necessary, there must be an advantage and switching costs must be overcome.

But a market does not exist for a technology that is new to the world. The project-, company-, and market-level provided static insights of how developments of a radically new technology can be helped or hindered. Market creation deals with characteristics of creation of a new market, which is less static in nature. Market creation aims to influence and create the three levels. In the search for how a market is created or how it emerges, resources that are needed for realising change in an existing market are not described. Competition is unclear at the start. Not every organization tries to develop a product from the radically new technology and the ones that do will not necessarily go in the same development direction. The closer the technology comes to an actual application, the more clear competition becomes. What an organization can do, which processes are started to create a new market, comes mainly from the field of SNM. They suggest three processes: coupling of expectations, articulation processes, and network formation. But what has to change? What are the elements that must be worked on? The technology must increase performance and decrease price, the market needs an entirely new supply and demand side with new combinations of actors and alliances, possible new infrastructures, new procedures and complementary product and services that add value to the product.

The upcoming of a radically new technology means great challenges at each level that was analysed. The project-level and company-level are vulnerable, the market-level and market creation are slow and hard to influence, and yet they are also vital. If one thing has become clear, it would be that every level is of vital importance to the survival of development efforts, but also that there are many ways to proceed with development efforts at each level. There is no one-size-fits-all model or strategy possible, there is too much variation in the technologies, their applications, the markets they influence, the actors in those markets, and in the way that developments can be helped.

5. Conceptual framework

A deeper understanding of factors is needed to translate lessons from the innovation models in chapter 3 and characteristics of the innovation phase in Chapter 4 to a conceptual model. Chapter 5 starts with an explanation of what is meant with the word ‘factor’, how factors are not static by nature, even though the conceptual model is a static model, how every factor contains sub-factors, and how factors can play different roles in different situations.

The development of the conceptual model is an answer to both sub-question 3 and the main research question. The model in which factors are presented (main research question) is strongly connected to formulation of the list of factors (sub-question 3), the level of detail of factors is an example of this. A model that contains three factors asks for a different list than a model with twenty factors. That is why the two are developed in parallel: they depend on each other.

A trial-and-error approach starts at the existing model that is most related to what this research is looking for: the conditions for large-scale diffusion are the inspiration for the first suggestions for a conceptual model. The conditions for large-scale diffusion serve as a benchmark, a model that is somehow related to the conceptual model for the innovation phase. Each next model in this trial-and-error approach is reviewed, both problems and opportunities are found and they serve as improvement steps for the next attempt. This iterative approach continues until there is a model that solves all problems and makes use of all opportunities: the conceptual model incorporates all that was that was learned and contemplated.

5.1. What are factors?

The three phases of the pattern of development and diffusion are inherently different. That is why the definition of factors helps giving aim to the kind of factors that this research is looking for. Although differences between factors of different phases are expected, the notion that there are factors for each phase suggests that there is a degree of similarity between the sets of factors. How do factors change between phases? Some insight in this dynamic gives insights towards a new model. The levels of detail were pointed to in both Chapter 3 and Chapter 4 and adds to finding factors that are practical and actionable with a fitting degree of abstractness. Also, factors can sometimes take on a specific role as shown by the conditions for large-scale diffusion, where factors can act as conditions. Perhaps more roles exist. Those topics together form a context of what factors are and what they can be, this shapes the search for a model for factors for the innovation phase.

5.1.1. Definition of factors

The ultimate goal is to describe everything that a technology needs to become a sold product. But how does one describe the world in which a technology is introduced, with applications in multiple markets, while different governments can support and oppose its introduction, where every customer has his or her own use for the product, or objections against its use? In a strictly logical sense, it is impossible to describe everything, to develop sufficient conditions for large-scale diffusion. The authors of the conditions for large-scale diffusion realized that this positive formulation (reaching large-scale diffusion) was impossible to prove and changed perspective to combat the negative formulation (removing barriers for large-scale diffusion). Solving barriers for large-scale diffusion may not guarantee that large-scale diffusion is reached, but it is more certain than claiming to understand how the world works and when exactly large-scale diffusion will be reached. The authors first resorted to seven ‘core factors’. Those seven core factors all need to be satisfied to the extent that they do not form a barrier for large-scale diffusion before the radically new technology is able to reach large-scale diffusion. From that provable basis of necessary conditions, those seven core factors are barriers to large-scale diffusion. But the core factors themselves do not carry the cause in them. Customers can be lacking because they do not understand the technology, or the product goes against sociocultural beliefs. Product performance can be low due to insufficient knowledge of the technology. To understand the barriers for large-scale diffusion, a wider context of the technology is explored. Another seven factors are added: the ‘influencing factors’. The general model prescribes that one lacking core factor forms a barrier for large-scale diffusion, with the cause lying in one of the influencing factors. This combination of a barrier and its cause leads to a specific niche strategy. However, although the complete set of factors is called ‘conditions’ for large-scale diffusion, the two subsets of seven are both called ‘factors’, leaving room for the unknowable and case-specific part towards sufficient conditions that cannot be described.

Thinking in factors is fitting for the innovation phase, where much room for the unknown is necessary. Working with factors is not aspiring a specific goal and knowing how to reach it, it is working on different aspects of a technology which you see as important factors. Increasing the level of detail increases the number of factors, but also creates confusion. If the ‘core factors’ and the ‘influencing factors’ are split up into further detailed factors, those can again be split, and so on. But this research takes a simpler approach: there are factors that are important for large-scale diffusion and we are now searching for factors that are important for developments in the innovation phase, both technical development and development of the innovation system. **The definition of factors that are important to a phase in the pattern of development and diffusion is: notions that give understanding of what potentially hinders and helps development and diffusion of a radically new technology**. This is the same for each of the three phases. The claim that a factor is ‘important’ does not imply a quantifiable variable. It merely implies an ordinal relation: the factors that are included in the model are expected to and, in principle, proven to be more important than factors that are not included in the model.

But that does not mean that the same factors are important in each phase. Which is exactly why the next paragraphs go further into different aspects of using factors.

5.1.2. How factors change between phases

The close relation between factors in the innovation phase and factors in the market adaptation phase makes the factors of the adaptation phase a good starting point for this research. Let’s start at the basis. How can factors change in or between phases? Or actually, how do the different factors for the innovation phase relate to the different factors for the market adaptation phase?

Keep in mind that the goal of factors that describe factors for a phase in the pattern of development and diffusion is: understanding of what potentially hinders and helps development and diffusion of a radically new technology. When Table 9 speaks of ‘more important’ or ‘less important’, this relates to what is seen as important for reaching that goal, what is important in hindering and helping development and diffusion of a radically new technology. The term of importance remains ambiguous, but that is because the factors are oversimplified and can be seen to contribute to many different processes. A theoretical statement about the importance of one specific factor does not follow from reasoning, it follows from empirical evidence, it follows from case studies.

Table 9 - Theoretical ways in which a factor can change

1.	X → X	A factor does not change.
2.	X → Y	A factor changes (into a different factor).
3.	… → X	A factor that was not important becomes important.
4.	X → …	A factor that was important, becomes unimportant.
5.	X → Z Y → Z	Two factors describe the situation equally well when they are combined.
6.	X → Y X → Z	Part of a factor becomes so important that the factor is split up.

For now some simple examples for each of the options in Table 9 suffice. Like when the need for (absence of) regulation is the same in the innovation phase as in the adaptation phase (1). The focus in the innovation phase is on costs, while market introduction changes that to price (2). Or the view that the product price is not relevant in the innovation phase, because it has not been introduced in the market, but it becomes important in the adaptation phase (3). Expectations can play the opposite role, being important in the innovation phase, but much less so in the adaptation phase (4). Perhaps the expectations stay important, but might they as well fall under sociocultural aspects in the adaptation phase (5). Institutions sometimes start with only a small role, increasing as the technology gets developed further, creating the need of splitting the factor for institutions to different factors for subsidy, tax, and law (6). Options 5 and 6 are ways of splitting and combining factors. A specific case of splitting is when working with different levels of detail, which is the topic of the next paragraph. The case studies will confirm or contradict the existence of the six theoretical options.

5.1.3. Levels of detail

A Technical Innovation System (TIS) is described by Malerba (2002) through a combination of four elements:

1. Technology and related knowledge.
2. Demand side.
3. Institutions.
4. Networks of actors.

This is a system that does not (completely) exist for a newly invented radically new technology. The disrupting nature of such a technology creates the necessity of new combinations of actors on both the supply and demand side of a market (Ortt & Schoormans, 2004). A new market must be created. A technical niche aims to provide a relatively shielded and protected environment until the innovation reaches a stage that it can withstand market forces and landscape developments (Geels, 2002). The creation of a TIS is not a quick and simple process. Why is the creation of a TIS not a quick process? Only the innovation phase itself lasts 10 to 28 years, the length of the market adaptation phase is estimated between 10 and almost 19 years (Ortt & Schoormans, 2004). The estimates are based on a limited set of observations and examples of exceptions are likely to exist, both for shorter and longer phases than the suggested ranges. This proves that the creation of a TIS for radically new technologies is generally not a quick process. Why is the creation of a TIS not a simple process? Keeping to the four suggested elements, creation of a new TIS is not obvious. An example, apart from the sentiment that it cannot be easy to create an entirely new system of actors that are well-tailored to each other's needs, is the starting point of the creation of a new innovation. Technology and related knowledge can lead to a new insight, a new idea. This idea is then developed further, a first application is commercialised, and diffusion increases step by step. A counter-example is the pharmaceutical industry where part of the innovations start at the demand side. There is a problem that needs solving, and that need forms the basis of the search for a new drug or treatment. If such a need has become large enough in the sense that it reaches the political agenda without being addressed by an organization, then institutions become the starting point of the innovation process. Multiple starting points of the innovation process are possible, the number of possible routes towards large-scale diffusion is almost endless. Understanding this process is hard at the level of four elements of a TIS. More detail is needed. Moreover, the TIS has yet to be created, it does not even exist! The place of a radically new technology in the world can be exposed to forces outside of the emerging innovation system that may yet have a significant influence on its diffusion.

The conditions for large-scale diffusion go into more detail than the four elements of the TIS. The fourteen different factors collectively describe much of the upcoming technology and the world in which it is upcoming. They describe the four elements of the TIS and more. This increased level of detail leads to more insight in opportunities and threats for reaching large-scale diffusion. It is a level that helps researchers to point out causes for failure and causes for success and even define niche strategies for the market adaptation phase. It is a level of detail that can be operationalised from theory to strategies.

This research focusses on the innovation phase. From the perspective of the innovation phase, a factor like ‘product performance’ seems a relatively complex factor which is not easily achieved and which should, possibly, be achieved in steps. Like the fourteen factors, the conditions for large-scale diffusion, followed from four elements of a technical innovation system, there is a need for even more detail in the innovation phase. It is not only the level at which factors become understandable and actionable, it is also because not the entire innovation has to be existent from the start. The four elements of the TIS all have to exist to a large extent to reach large-scale diffusion. But in the market adaptation phase, where the product is offered in niche applications, not all four elements of the TIS have to exist yet. An example is the element ‘technology and related knowledge’, of which the knowledge part is represented by ‘knowledge of the technology’ and ‘knowledge of the market’ in the fourteen conditions for large-scale diffusion. To survive as a company in the market adaptation phase, knowledge of only one application of the radically new technology can be sufficient. Not the entire element that Malerba proposed has to exist yet, only part of it may be enough to not block further diffusion. So there are two reasons for looking for further detailed factors in the innovation phase: working at a level that makes a phase understandable and actionable, and because the fourteen factors in the innovation phase do not have to exist fully.

Going further and further into detail in the developments of a new technology would eventually end up with the specific actions and workflows of researchers and developers. **The goal of factors that describe a phase in the pattern of development and diffusion is: understanding of what potentially hinders and helps development and diffusion of a radically new technology.** That understanding can be reached by finding the right balance in the level of detail. Insufficient detail results in unclarity around necessary development steps. Too much detail loses oversight. The right amount of detail must support the goal that is formulated above. To achieve this level of detail, the conditions for-large scale diffusion can be taken as a starting point. Applying those factors to the innovation phase demands an increased level of detail, as we saw with the Malerba’s element ‘technology and related knowledge’, being split up into several factors in the conditions of large-scale diffusion.

5.1.4. Roles of factors

Factors are not equal. There is a difference between regulations that hamper diffusion and the performance of a product. But the nature of the difference is not obvious. This paragraph proposes a number of ways in which factors differ from each other, without claiming that this list is exhaustive.

The first question is whether a factor is even noticed, whether it is even mentioned as a factor in a model or in an analysis. There is a difference between **explicit and latent** factors. An example are the expectations and promises that are deemed important in the innovation phase, according to the previous chapter that describes characteristics of the innovation phase. In the model of the conditions for large-scale diffusion, expectations and promises are not explicitly mentioned as a separate factor. Part of it may be included in the sociocultural aspects or even in macro-economic and strategic aspects, but in this model, expectations and promises play a latent role. Organizational structure is not included in the conditions for large-scale diffusion. But Schroeder et al. (1986) have shown multiple cases in which this factor had been important. This gives us two ways in which a factor can be latent: by being partly implied, spread over multiple factors in a model, or by being fully excluded from a model. This as opposed to the product performance that plays an explicit role in the conditions for large-scale diffusion.

Factors can have multiple levels of detail, as argued above. That means that some factors are grouped in overarching factors and other factors are split in underlying factors. Underlying factors do not disappear when only an overarching factor is used, the factors are merely **combined or not combined**.

Whether factors get combined and whether they are explicit depends on the **importance that is attributed to the factors**. Importance is a subjective and ambiguous term, in need of clarification. The subjective aspect complicates general statements about what is important and what is not. Importance that is attributed to a factor depends at least on the unit of analysis and the perspective. When the unit of analysis is the technology, a company gets a more instrumental role. The company is then expected to do what is needed to support the development and diffusion of the product. When the company itself is the unit of analysis, its actions are scrutinized and the strategy becomes a variable. The change of perspective is partly linked to the unit of analysis. A strategic perspective fits well with the company as unit of analysis. A sociotechnical systems perspective fits well with the market as unit of analysis. A research perspective, like from innovation management, can be combined with any unit of analysis, whatever field the research is trying to add to. Some factors are important from multiple perspectives and units of analysis, some only come to light in one of the models. The conditions for large-scale diffusion show overlap with the seven types of factors from SNM. The company and project perspective from the Minnesota Studies and the FFE contribute completely different factors, because those factors are important from those perspectives.

Factors can take on a **supportive role** in one case and a **hampering role** in the next. Laws and regulations can stop developments, but they can also support developments. Like quality control, which is an issue for 3D printing in construction, while Dubai's regulations support diffusion through the goal of having 25% of all new buildings printed in 2030 (Kaa et al., unpublished). Factors can also change from being hampering to being neutral, for example when autonomous vehicles are forbidden by law, but permits allow for the possibility of testing within certain settings (Ortt & Dees, 2018). Factors can also be **neutral** in this sense.

The extent to which a factor is satisfied builds on thoughts about supportive and hampering roles. The core factors from the conditions for large-scale diffusion have to be satisfied to a certain extent before large-scale diffusion can take off. When setting a certain goal, like reaching the mass market, factors can become **conditions** for reaching the goal. If describing a goal for a milestone is complicated, then all one can do is choose a unit of analysis and a perspective and find factors that describe that perspective. It is not possible to describe one goal for the innovation phase and thus factors cannot be conditions. However, if case studies do suggest that a goal can be formulated, then this assumption is revisited.

Table 10 - Alternative roles of factors

Explicit or latent
Combined or not combined
Attributed importance
Supportive or hampering
Conditions

A factor can have multiple of all the possible roles (Table 10) at the same time and can also change roles as the context changes. One way to look at the changing roles is between the phases of the pattern of development and diffusion. Paragraph 5.1.2 already described how different factors can be included in models for the different phases of the pattern of development and diffusion. But that view is simplistic, when seen in the light of variating importance, supporting and hampering, and other attributes that this paragraph discusses. Going into all possibilities of how factors differ between phases and how the models of the innovation phase and the conditions for large-scale diffusion are related is grounds for future research. The lesson for now is that there are different roles that a factor can take on and that those roles can change between cases and phases.

5.2. Trying different models

The development of the conceptual model is an answer to both sub-question 3 and the main research question. The model in which factors are presented (main research question) is strongly connected to formulation of the list of factors (sub-question 3), the level of detail of factors is an example of this. A model that contains three factors asks for a different list than a model with twenty factors. That is why the two are developed in parallel: they depend on each other.

A trial-and-error approach starts at the existing model that is most related to what this research is looking for: the conditions for large-scale diffusion are the inspiration for the first suggestions for a conceptual model. The conditions for large-scale diffusion serve as a benchmark, a model that is somehow related to the conceptual model for the innovation phase. Each next model in this trial-and-error approach is reviewed, both problems and opportunities are found and they serve as improvement steps for the next attempt. This iterative approach continues until there is a model that solves all problems and makes use of all opportunities: the conceptual model incorporates all that was that was learned and contemplated.

5.2.1. Model A – A changing set of conditions

The factors together constitute a description of the world in which the radically new technology is being developed and aims to be as complete as possible, but with regard to the usability of the model. If the conditions for large-scale diffusion form a fitting model for an innovation that is on the verge of reaching the mass market, then factors for other phases will probably be related to that model.

Table 11 - Model A: Theoretical and plausible ways in which the set of conditions can change

	Innovation phase	**Adaptation phase**	**Stabilization phase**	
a	C	C	C	The set of conditions stays the same across all phases.
b	A	B	C	An entirely different set of conditions is used for each phase.
c	c	c	C	The set of conditions moves from highly detailed to less detailed.
d	C	c	c	The set of conditions moves from less detailed to highly detailed.
e	◠	◜	C	A subset of the conditions is used in the innovation phase, a larger subset in the next, and the complete set in the stabilization phase.
f	◜	◡	C	A subset of the conditions is used in the innovation phase, a different subset in the next, and the complete set in the stabilization phase.
g	◌	◌	C	Several factors of certain groups are used in the innovation phase, larger groups in the next, and the complete set in the final phase.

The basis of changing sets of conditions lies in the ways that factors can change (Table 9: 1 - 6). Applying that logic to the complete sets of conditions gives results in Table 11 (a - g). When all factors stay the same (Table 9: 1), then the complete set of conditions will stay the same (a) across the three phases. When factors change entirely (Table 9: 2), or when all factors stop being used (Table 9: 4) and new factors are taken into use (Table 9: 3), then a complete new set of conditions is used in each phase (b). When all factors can be merged for every next phase (Table 9: 5), then the conditions for the innovation phase are more detailed than for the market adaptation phase, and those are more detailed than the set of conditions for the market stabilization phase (c). And the other way around: when all factors are split up for every next phase (Table 9: 6), then the conditions for the innovation phase are less detailed than the sets of conditions (d).

The above accounts for the options a to d in Table 11, in which the logic of a change in factors is applied to the entire set of conditions. But aggregating conditions in sub-groups gives more options: they don't have to be viewed as one large set, but can also be viewed as a collection of groups of factors. This strongly links back to the levels of detail of factors. The set of conditions can be split many ways, and this split set can also be split in many ways. An almost endless list of levels of detail emerges. The six options of Table 9 apply at each of those levels and a certain subset of the conditions can be used for the innovation phase, a larger subset for the next, and the entire set of conditions in the stabilization phase (e). Instead of choosing one way in which factors change and applying it to the entire set of conditions, splitting the set of conditions in two groups creates many options when the conditions in those groups change in two different ways. Accounting for all possible ways in which factors change two ways can be approached in a strictly theoretical way, but that would lead to (6*5 =) 30 combinations when accounting for only combinations of two ways to translate factors from one phase to another. The options from e and further are therefore not rooted in deduction from Table 9.

If one subset of the conditions is used in the innovation phase, an entirely different subset is used in the next, and the full set of conditions is used in the stabilization phase, then option f emerges. When the conditions are seen as groups of factors, each constituting a crucial part of the system that is to be created (like the four elements of a TIS), then it's possible that one factor is used as a representative of such a group in the innovation phase, larger parts of each group are used in the next, working towards the full set of conditions in the market stabilization phase (g).

Review

This is a very simple approach: there already is a set of factors for one phase, so it will apply in some form to the other phases as well. The roles of factors (5.1.4) describe how some factors that apply to the innovation phase may not be represented in the conditions for large-scale diffusion. Latent factors or factors that are deemed unimportant can be missing. Examples come from Chapter 3, where plenty of other factors are mentioned by other models, and from Chapter 4, where for example marketing and the organizational structure are described to be important in the innovation phase, while the conditions for large-scale diffusion make no mention of them. This chapter is working towards a model for the innovation phase. Many options arise from model A, but actually forming those sets of conditions in a way similar to the conditions for large-scale diffusion happens the other way around. We cannot suggest theoretical ways in which sets of conditions change between phases, choose a plausible option, and present it as a model. **Model A contains three presumptions. First is that the set of conditions can be observed as a whole, second is that the concept of conditions is applicable to the innovation phase, third is that a model can be created in such a top-down fashion.** Although it is possible that the eventual conceptual model bears a relation to this model, Model A is not a fitting start for creating the conceptual model. The next model continues with the concept of conditions, but stops observing them as one large set and therefore also steps away from the top-down approach.

5.2.2. Model B – Conditions for reaching the next phase

This model is a second attempt to use the conditions for large-scale diffusion as a basis for the conceptual model. The most basic of requirements, the necessary conditions, to enter commercialisation or large-scale diffusion is founded more in logic than it is in theory and empirical evidence: practice will often deviate from necessary conditions because some factors may already be developed further than is absolutely required. Although less likely, the contrary is also possible: that a phase is entered with the conditions being developed less than is seen as an necessary condition, pointing either to an exception to the model, a flaw in the model, or an unwise decision from the actor. The factors of the conditions for large-scale diffusion that are expected to form absolute necessities for passing a milestone, are the necessary conditions: the core factors.

Until now, two things have been confused with each other. Conditions for large-scale diffusion have been mentioned both as a group of factors that is important in the market adaptation phase and as a set of conditions for reaching large-scale diffusion, for the transition from the market adaptation phase to the market stabilization phase. The explanation is this. There are no strict conditions for going through a phase, because a phase in itself has no goal. If the innovation phase has the goal to bring a technology to commercialisation, then we make it seem like bringing a product to the market as quick is possible is the best for diffusion of the technology. But that is not the case, early introduction can lead to failure in the market and eventually even to bankruptcy. The goal of the adaptation phase is not to reach large-scale diffusion, some technologies thrive best in a market niche, or at least until additional barriers have been solved. Lastly, the goal of the stabilization phase is definitely not to end that phase, because that would mean substitution by a new product. Then what is the goal in a phase?

There are different perspectives that can answer this question: every actor in a market can have different interests regarding a radically new technology. From the perspective of the technology we can say that a technology in the innovation phase travels from invention until commercialisation. There a certain requirements to the technology before it can be stated that is has been invented. The technology must be available in some rudimentary form (Ortt & Schoormans, 2004). That means that some basic function has to be performed in some way. In other words, the most basic of product performance is present and producing that most basic performance was possible in some way. One institutional addition: it must not be forbidden to have or to make the invention.

Table 12 - Model B: Necessary conditions for passing milestones

	Invention	Commercialisation	Large-scale diffusion
Product performance	Fulfil basic function	Not dangerous	Better than competition
Product price	-	Affordable for niche	Best price/performance ratio
Production system	One-time	Repeatable (manual/series)	Mass production (or series)
Comp. goods & serv.	-	Enough to deliver value to niche	Enough to deliver value to market
Network formation	-	Enough to support supply and demand for the niche	Enough to support supply and demand for market
Customers	-	Enough to survive	Market saturation
Institutional aspects	Not forbidden to have or make	Not forbidden to sell and use in the niche	Not forbidden to sell and use
Other conditions…	…	…	…

The jump from the innovation phase to the market adaptation phase is made through commercialisation of the product. That does not imply a great product performance: a product can be offered for sale as long as it is not dangerous. Someone has to be willing to pay for it, the product must be produced and it must not be forbidden to sell the product and to use it in at least one niche application. Complementary goods and services and network formation are needed to the extent that the product could otherwise not be sold for a niche application. Some products can be sold stand-alone, but some will need a complementary product. A game-console needs at least one game to be sold. The same goes for the network: products can sometimes be offered for sale without any additional actor involved but the developer of the product. But food products often depend on series of retailers to reach the end-customer, just like additional actors can be needed on the supply side to make production of a product possible.

But are those necessary conditions the only necessities for the decision to move to commercialisation? No, as stated before, the logical minimum requirements deviate from what is perceived to be a good moment to enter commercialisation. The developer of a product aims for more than just a product that is not dangerous. Requirements exist around functionality, ease of use and design of the product, for example.

Review

The challenge with conditional statements is that just one counterexample falsifies the entire claim. The journey to Mars is already being sold (CNN, 2013) while the technology is still in the conceptual stage (Mars One, 2019). So the technology and related knowledge are almost non-existent at the time of market introduction. A secret product development like that of the Segway (Schneider & Hall, 2011) happens with very little network formation and development of the demand side, which is part of the reason that the market for Segways is completely different from what was expected. Commercialising a product or service with non-existent product performance, network, or demand is clearly possible, as shown by the examples. Although the organization that performs the commercialization does take extra risk, and perhaps too much risk, the lack of some elements does not stop them from introducing the product to the market.

Model B shows that the concept of factors in their role as conditions cannot be applied to the innovation phase without further investigation of the relevant factors. A model that relies on necessary conditions that must be fulfilled before the goal can be reached, commercialisation in this case, is prescriptive. It does not speak of importance of factors, nor of their specific roles. It finds minimum requirements that must always be met. Such a model is very helpful when such requirements exist. However, finding such a model in the social sciences is challenging because of its strict definition: one counter-example defies the reliability of the model. **Proving factors in the roles of conditions does not work in the innovation phase**, because the innovating company always has the option to introduce a product against every reasonable objection. The examples above show that a more subtle approach is required.

And are the factors in this model correct? It is easy to come up with more factors, but the question is which factors together form an indication for a successful product, for a product that completely overhauls life as we know it. So not only should we step away from factors in the role of conditions, also **the list of factors must be reviewed**.

5.2.3. Model C – No conditions, but factors

The conditions for large-scale diffusion by Ortt and Kamp (forthcoming) have been designed as a tool to describe conditions for the transition from the market adaptation phase to the market stabilization phase. It is a list of factors that are important for reaching the mass market. An attempt was made in model A and model B to keep viewing them as conditions, but that part of the models failed. This model views the fourteen factors for what they are: factors. They may take on the role of conditions in certain circumstances, but since that is generally not the case, they are now viewed as fourteen factors.

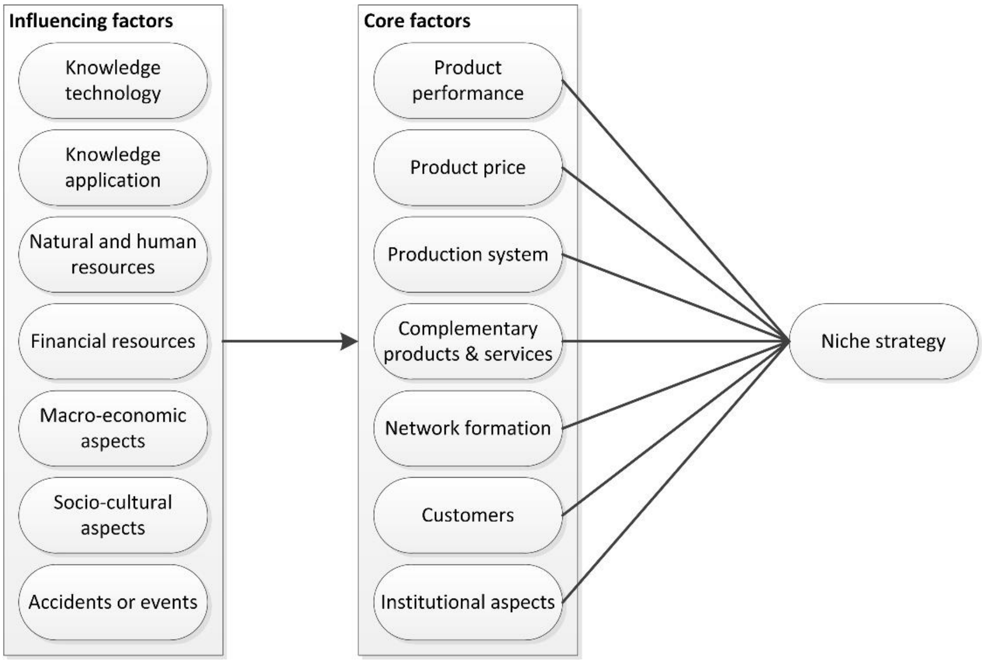


Figure 14 – Conditions for large-scale diffusion of radically new technologies. Based on: Ortt et al. (2013) and Ortt and Kamp (forthcoming).

Important factors for the innovation phase are different from conditions for large-scale diffusion. Technical developments go to the background in the market stabilization phase (Ortt & Schoormans,

2004) and marketing and sales become priority. That transition from the innovation phase to the market adaptation phase is much more subtle: anyone can introduce anything to the market, no matter the chance of success. In that sense, factors are less firm in the innovation phase than the conditions are for transitioning to large-scale diffusion. It is possible to introduce a product to the market for which there are almost no customers. That the product will probably be retracted from the market does not prevent the end of the innovation phase. We will now reflect on the conditions for large-scale diffusion based on the characteristics of the innovation phase from Chapter 4.

The characteristics of the innovation phase, written bottom-up from literature, covers only a selection of the conditions for large-scale diffusion. The focus is on resources, knowledge, and developments leading to an innovation. Network formation is seen as instrumental to realizing needed changes to help bring the innovation to the customers in the shape of an actual product with a specific application instead of a broad technology. Also the role of the government is well-described, mainly as a result of the sociotechnical systems perspective that the SNM framework introduced where they use the theory to do policy recommendations. There is less focus on the role of the production system and (suppliers of) complementary products and services. Also landscape processes, macro- and meso-economic processes, and sociocultural aspects have played a smaller role in the transition from a technology into a product. Lastly, accidents and events were not mentioned by the literature. Figure 15 shows which of the factors is important for the innovation phase and which are not, based on the characteristics of the innovation phase in Chapter 4.

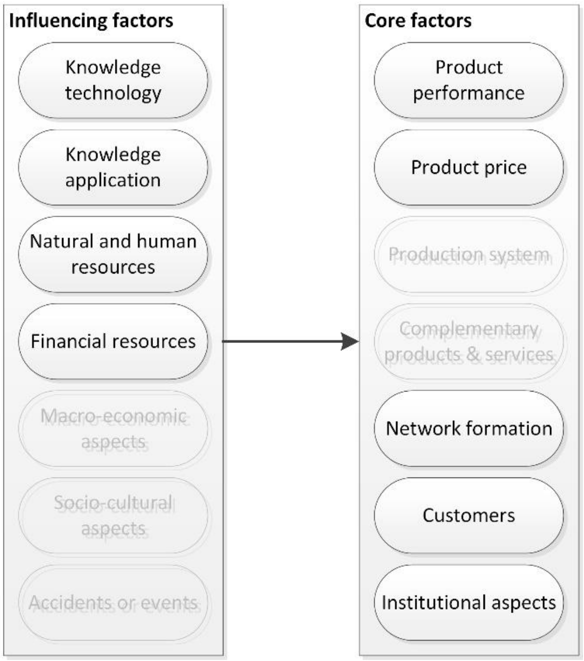


Figure 15 - Most important factors during the innovation phase based on Chapter 4

Can we just neglect factors that are not seen in the innovation phase and delete them? Some factors can form an absolute necessity for reaching the mass market, while the influence during the innovation phase is not that black-and-white. A poor product performance does not prevent commercialization, but it does prevent large-scale diffusion. Do, for example, accidents and events then not influence processes in the innovation phase? Of course they do, they can slow down or speed up the developments. Even after one accident, the fear for more accidents led to revoked permits for the testing of autonomous vehicles (Ortt & Dees, 2018). But only the conditions for large-scale diffusion mention this factor and no literature relates this back to the innovation phase. If the literature does not mention a factor at all, it does not play a central role in the innovation phase. How can accidents not play a central role, while they can stop entire technologies from being developed? Simple: the great value of research is not to show what happens, but to explain why and how things happen and subsequent actions that decrease any negative impact. An accident can de dealt with, but it cannot be prevented and therefore falls outside the scope of most views on innovation management. For that reason, accidents are viewed as an ‘influencing factor’, not being central to the developments in a technology and its sociotechnical system, but still able to stop the entire process.

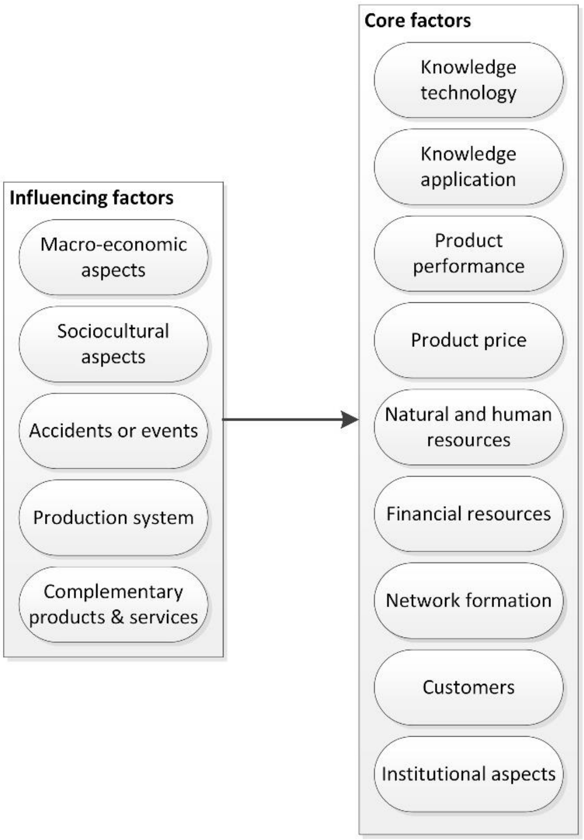


Figure 16 - Restructuring conditions for the innovation phase

A factor that plays a central role is a core factor. Not in the sense that it is a condition, like in the transition towards the market stabilization phase, but in the sense that the factor forms a vital part of the innovation phase. Figure 16 contains the same fourteen conditions, but now restructured. The factors that are central in the innovation phase are now considered core factors and the factors that were not covered by literature became the influencing factors. This logic gives an indication of the importance of factors, and which factors should be included and which should be excluded from the model. The next paragraphs work towards a more refined model through adding logic reasoning to this first step that was only based on literature.

The conditions for large-scale diffusion cannot be completely different from the factors that are important in the innovation phase. Although the market changes considerably in the course of time between those phases, the factors that are important in bringing a product to commercialization must show similarities with factors that are important in entering large-scale diffusion. However, the emphasis is different. Gaining knowledge and translating that to technical developments is absolutely vital in the innovation phase, but that focus is reduced when the product is more mature. A counterexample are complementary products and services. Those are not always vital for commercialization, but are important for delivering more value with the same product and for reaching the mass market. That brings us to the following question: which factors are less important for the transition to large-scale diffusion, but more important in the innovation phase, and may therefore important now while they are not included in the current list of factors? Do we need to add any factors?

Looking back on paragraph 2.3, the conditions for large-scale diffusion do not explicitly cover the company-level elements of the innovation process. The conditions for large-scale diffusion focus on the market and on the radically new technology, and less on the company that is working on the developments. That is reflected in the additional characteristics of the innovation phase that are found in Chapter 4, but not in the conditions for large-scale diffusion. The role of a company as a whole is not central in the conditions for large-scale diffusion, it was seen as part of the 'network of actors' which fits the aim of describing an existing sociotechnical system. This reduces the role of certain factors, including interesting dimensions like the organizational structure surrounding the developments, the shared vision that is needed to aim and focus the developments, the long-term commitment that is needed to develop a technology into a product and to bring that product to the market, and the IP strategy of a company. Moschos (2016) suggested that firm-specific techniques and the culture of values are also important during the innovation phase, although no other literature supports this statement. All those elements can possibly be seen as instrumental in the transition from the market adaptation phase to the market stabilization phase: factors that will change according to what is needed to make a product reach large-scale diffusion. That is different in the innovation phase, where the actions of one single company can be the only actions surrounding a new idea: that one company can make or break the entire potential of the new technology.

A new idea has the potential for change, for example, leading to an improvement or to profit. Expectations and promises about the potential of the technology are important for finding and sustaining support for the project. Expectations and promises are not explicitly part of one of the conditions for large-scale diffusion in the current framework. It can be seen as part of 'sociocultural aspects', but that neglects the more technical side of the advantages, like the expectations a manufacturer of complementary goods has. Those expectations are not entirely formed by underlying sociocultural aspects. The condition 'product performance' considers the improvement or advantage that a technology provides, enhancing the condition to also include the potential product performance would make this a two-tiered condition. The problem with this enhancement are the different dynamics of the expectations and promises about a technology's product performance and the actual product performance. Creating high expectations by making promises makes actors more inclined to join the development and invest resources. Having a low product performance at the start of development does not lead to increased available resources, but also does not have to hamper that as long as the potential is high enough. And a product with a high performance can be sold to customers, but a low performing product with a high potential cannot. Product performance is a more technical dimension which should not be combined with the 'soft', more social expectations and promises. Since expectations and promises can influence many actors, it is also impossible to integrate this aspect with conditions like the 'production system' or 'customers'. Adding expectations and promises as a new condition is then the best option, with the explicit remark that this is an addition for factors that are relevant during the innovation phase. It cannot be concluded that the factors 'expectations and promises' must be added to the list of conditions for large-scale diffusion on the basis of this research because of the scope that is limited to only the innovation phase.

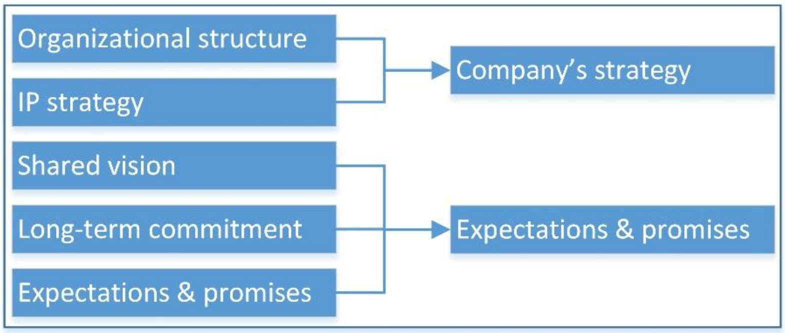


Figure 17 – Two new factors.

All five suggestions from the previous paragraphs that are added to the factors that are relevant to the innovation phase are more detailed than other factors on that list. Combining the five suggestions into common themes makes them more fitting for the current list of factors. The expectations and promises that surround a new-found technology can be translated to a shared vision in which actors find a common goal, a common direction in developing the technology into a product. The opposite direction happens as well, although probably more in incremental than in radically new innovations. When a shared vision is formulated, expectations and promises are created to achieve the vision. The suggestion is to add the condition 'Expectations' as an influencing factor. Organizational structure, long-term commitment and the IP strategy are all strategic decisions from the innovating company. The suggestion is to add the condition 'Strategy' as an influencing factor, including all those aspects in this one condition (Figure 17). Other important strategic decisions can then also be included easily in the analysis of a certain technology. Examples are the decision to aim for a niche market or the mass market, or the timing of the first product launch.

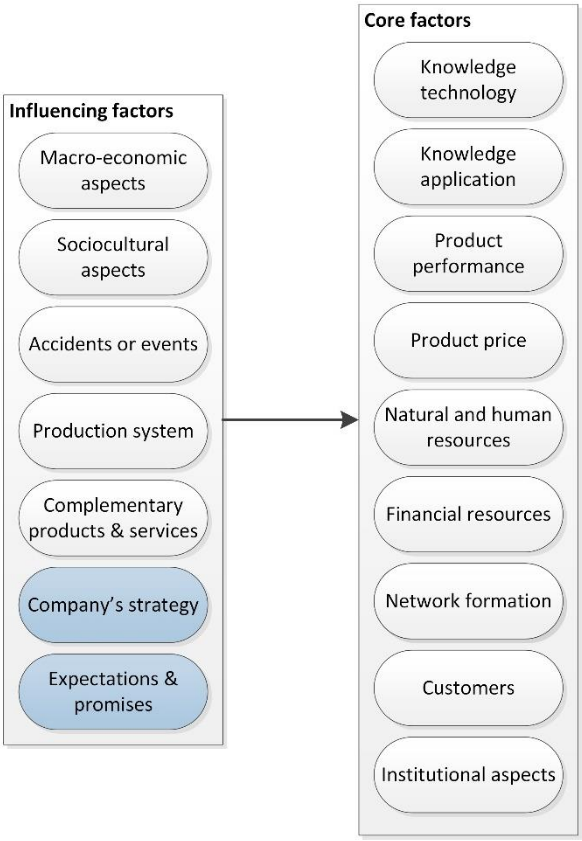


Figure 18 – Model C: Important factors during the innovation phase

The two new factors now create a list of factors that is tailored to the innovation phase, based on the way of thinking that was started in the conditions for large-scale diffusion and what was found in literature about characteristics of the innovation phase Figure 18.

Review

Staying close to the model of the conditions for large-scale diffusion has its advantages. Thinking in a list of most important factors and a list of more contextual or indirect factors creates a structure that helps to include all that is relevant, while the there is also a clear focus on a limited set of factors. However, it is not at all certain if this structure is most fitting for the innovation phase and the next model will **try a new structure**.

Another downside of staying so close to the conditions for large-scale diffusion is that no factors are deleted from the model. It is virtually impossible to claim to a factor that is important around large-scale diffusion would carry no meaning at all in the innovation phase. However, **deleting factors helps** to make a model more concise and possibly more practical.

Model C is based on the conditions for large-scale diffusion and the characteristics of the innovation phase according to Chapter 4. However, other **theories from Chapter 3 have not been included**, while they carry considerable weight through all performed research in each field of study that the models are based on. Including those factors is a step for the next model.

Figure 17 plays with the levels of detail of observations to fit factors together in one model. **Exploring the levels of detail of factors** delivers new insights. Another suggestion for the next model.

5.2.4. Model D – All factors from all models

Three suggestions from Model C lead to a new model. This model. The three suggestions are to try a new structure, use all theory from previous chapters, and explore levels of detail of factors. This model combines the fourteen conditions for large-scale diffusion, the seven types of factors of SNM, the six observations from the Minnesota studies, the five key elements of the FFE, and the characteristics of the innovation phase. Other suggestions along throughout the literature reviews that are included are: considering to add ‘firm-specific techniques’ and ‘organizational culture and values’ as factors, give marketing a role, include market knowledge, include characteristics of the technology itself, include technological developments and review the role of the company and its representation in the factors for the innovation phase. It is a long list of factors and they are bound to show overlap, have different perspectives, different levels of detail, and different levels of importance to the innovation phase. And all that is different between cases.

The method of combining all those factors in one model is simple. All are combined in groups that became apparent in factors mentioned by at least one source. There is no new terminology added to create groups. There is a maximum of three levels of detail to keep the model understandable. This is the creation of one long list of factors, with three levels of detail (Table 13).

Table 13 - Model D: all factors combined

Knowledge

- Market
- Application
- Technology
- (Dependency on) research
  - Central role
  - Partly funded by government
  - Supply and demand of researchers
  - Supply and demand of research funds
  - High risk leads to collaborations

Product (technological factors)

- Product performance
- Product price
- Characteristics of the technology
- Invention and technical developments / dependency on development
  - Opportunity identification / shock
  - Opportunity analysis
  - Idea genesis / proliferation
  - Idea selection
  - Concept and technology development
  - Dependency on research
  - Increase product performance
  - Linking old and new
  - Setback, terminate, integrate

Company

- Firm-specific techniques
- Organizational culture and values
- Top management
- Planning
- Roles
- Competing technologies
- Production system / production factors
- Strategic decisions
  - Organizational structure
  - Secrecy
  - Marketing
  - Establish collaborations / network formation

Resources

- Natural
- Human
- Financial / Valley of Death
  - Subsidies
  - Search for capital
- Development efforts and changing the market

Expectations

- High expectations
- Promises
- Reluctance to change
- Share enthusiasm

Sociotechnical system

- Change
  - Collaborations (to spread risk) / combinations of actors / alliances
  - Infrastructure and maintenance
  - Procedures
  - Change supply and demand side
  - Time and resistance
  - Niches are instrumental
- Development directions
- Macro-economic aspects
- Sociocultural aspects / cultural and psychological factors
- Complementary product and services
- Production system
- Government
  - Subsidies
  - Network
  - Pilot project
  - Need for technologies
  - Laws and regulations
  - Local/regional/international
- Industry dependent
- Existing companies
  - Supply incumbent technology
  - Little competition in early stages
  - Change leads to risk and opportunity / Harm/no effect/opportunity
- Users
  - Status quo
  - Switching costs
  - Knowledge of technology
  - Demand factors
- Network formation

Accidents and events / undesirable societal and environmental effects

This model is not a categorization of the factors. It is merely a grouping. Many factors could have been placed in multiple groups. Only the most obvious factors are included on more than one place, like the production system, which is a part of the company and a part of the market. It is the interconnectivity between all of the factors that makes one exact model impossible. Many different actors influence the same factors and the role of factors is highly dependent on the case that is analysed.

Review

This model is the most theoretically complete model until now, and probably also the least useful for companies and other actors. Since working from the conditions for large-scale diffusion left the models A, B, and C with too many flaws, this model should solve some of those problems. However, similar concerns still remain. The first of which is that **no factors have been deleted**. This creates a lack of oversight and makes practical use limited. There must be room in the model for the fundamental differences between markets and between technologies, but leaving too much room creates too little guidance. Working with this many factors at once is not practical.

This long list of factors makes abundantly clear that some guidance, some **basic idea of the dynamics** would help understanding how factors relate. That would then also help in understanding what is more important and what is less important for going through the innovation phase.

A Technical Innovation System (TIS) is described by Malerba (2002) through a combination of four elements:

1. Technology and related knowledge.
2. Demand side.
3. Institutions.
4. Networks of actors.

Comparing the main topics of Model D to those four elements is a simple test for (over)completeness. ‘Knowledge’ and ‘Product’ together are almost identical to ‘technology and related knowledge’. The demand side, institutions, and network of actors do not yet exist in the innovation phase. All of them are collected in the group of factors called ‘market’. This difference suggests that **‘market’ can be split in smaller groups of factors**. Both ‘resources’ and ‘expectations’ are not elements in Malerba’s framework, which makes sense because of all sources in Chapter 4 that describe how the fragile early stage of a technology is strongly dependent on resources and expectations from just a few actors sometimes. Those factors are more important when a TIS must be built than when it already exists. Also the company had no separate place in Malerba’s elements, but came forward in the factors. That difference can also be explained. The role of one specific company is much more important when it is perhaps the only actor that knows the invention. That company can make or break the innovation, while the story is entirely different when an entire system is working with a product. This comparison of Model D with Malerba’s elements shows but one suggestion for Model D, which is to split ‘market’ into smaller groups of factors.

Lastly, **the level of completeness that this model suggests is not realistic**. By showing three levels of detail, the suggestion is created that this model contains all important factors at three levels of detail. However, the model only contains factors that are found in the literature reviews. It is easy to find other factors. Product performance, for example, can easily be split further in safety, ease of use, and design. But that has not happened because those factors were not found. This matter must be resolved in the conceptual model that this chapter eventually proposes.

5.2.5. Model E – Basic dynamics between factors

The influence of important factors during the innovation phase on each other is complex. Most factors can influence each other, often both in a positive and a negative way, and many of those relationships get reinforced or weakened by other factors as well. This paragraph does not describe all dynamics, it merely summarizes the most important dynamics during the innovation phase, according to what was found in the literature, especially in Chapter 4. This is therefore based on findings in literature, but those models and frameworks that form the basis are all static and not dynamic. The dynamics that are proposed below should therefore be treated as hypothetical.

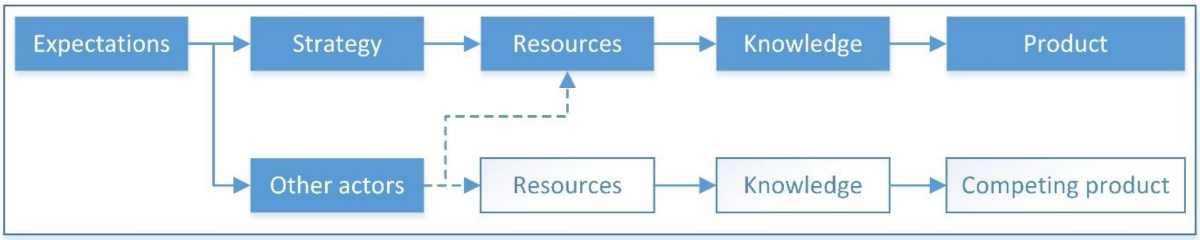


Figure 19 – Model E: basic dynamics between factors.

The elements in Figure 19 are closely related to the highest level of detail of factors in Model D. 'Expectations' and 'resources' are the same, so are 'knowledge' and 'product'. 'Company' is summarized to only its 'strategy', 'market' is summarized to just 'other actors'.

Based on Chapter 4, an idea is only acted upon when there are at least some expectations. The inventor does not have to recognize the full potential of a ground-breaking idea to keep working on it, the expectations can be as simple as 'working on something fun' or 'learning by tinkering with an idea'. That idea gets the shape of a project and is in need of direction. A company, or even a group of organizations, acts on ideas through its strategy and can start large-scale development projects in a formalized setting. A hobbyist may keep on tinkering until interest is lost, which can function as the only underlying strategy. The term 'strategy' is therefore a bit of a stretch in this context, as it refers to any sense of direction or planning that is put in the development of the product. The strategy at the company-level makes resources available to reach strategic goals. A project team starts on the basis of available resources, the hobbyist makes time to work on his or her idea. The developments lead to increased knowledge and subsequently to an improved product. This stream continues as long as possible, with the final goal being a commercialized product. It is well possible that other actors in the market caught wind of the same developments. That does not necessarily lead to available resources, there may be no ambition to enter developments. If that ambition does exist, the newly available resources can either be used for strengthening the existing development efforts, but a competing product or a development direction that works on a different application for the technology are possible too.

Review

The steps from expectations until a product are close to what happens in a project in a company. One sidestep is made to other actors and their influence on the road towards a product, but the rest of the dynamics around a company are left out of the model. The main focus of this model is the project-level, only keeping track of the most important factors. Those dynamics in themselves may be correct, but **the innovation phase consists of more than what is proposed here**. In fact, it was already suggested in Chapter 4 that a model should look beyond a project, towards the full development efforts.

The biggest problem with proposing dynamics is the immense complexity of factors in the innovation phase. The art is to find dynamics in a way that the model is correct, usable, and allows for application to many different radically new technologies. Exclusively proving such a model is impossible, but it is **strengthened and illustrated through case studies** and also through its roots in the literature that shaped Chapter 4.

5.2.6. Model F – The survival perspective

It is literature that forms the basis of the characteristics of the innovation phase. That bottom-up approach to describing the innovation phase gives insight in the content of the literature and the interpretation of the literature. And both are lacking. All of the levels, from project to market, describe a number of building blocks and continue to how those blocks can be used to build the end product. It is a structured description of found characteristics of the innovation phase, and a step-by-step approach from an idea to an implemented innovation. The same approach is used when metaphorically building a house. It starts with an idea, an ambition and that ambition has to be realised in a market environment, the ground on which the house is going to be built, and maybe there are some surrounding buildings as well. Then many parts are bought and combined. Which part comes where is not always easy, so some struggle may be involved, but even during struggles it is still clear how far the process has come along. It is clear whether a wall or a ceiling is being built, and where most specific parts belong in the end-product. This metaphor can be felt throughout the entire chapter. Until now. Because the innovation phase is not structured.

Papers that describe some model of the innovation phase try to find recurring observations. There is a search for patterns and all elements are presented, the one after the other, to form a model of (a part of) the innovation phase. Those models show a form of structure by nature. Even the Minnesota Studies show six elements of an inherently chaotic phase of innovations, all shown consecutively in one graph, the one following the other. Although this orderly presentation of a such a disorderly process is not necessarily wrong, it can give wrong ideas and it can result in a poor interpretation. People are prone to finding structure and order, even when it is not truly there. Then how can a reader truly understand that a phase is chaotic when all characteristics are presented so well-structured?

Perhaps a more fitting metaphor for the innovation phase is the evolution from single-celled (unicellular) organisms to multicellular organisms and their place in an ecosystem. It is a process where survival is central, together with adaptation of both the organism and its environment to become well-adapted to each other. This metaphor is not a scientifically based theory, it is simply an alternative perspective to literature that is at the basis of this research. All coming paragraphs in *italic* describe known processes in evolution, and more specifically, the evolution from prokaryotes to eukaryotes and their place in an ecosystem. Also the introduction of a strange species in an existing ecosystem is used as part of the metaphor. The non-italic paragraphs apply the metaphor to radically new innovations.

Copying errors – waiting, shock, and proliferation

Change in an existing ecosystem is often subtle and incremental. Species evolve only through copying errors which turn out to be a slightly better or slightly worse fit in the environment. Better adaptation to the environment leads to increased chances of survival and reproduction, giving the organism the chance to spread the new-found copying error to its offspring. It takes a long time until every member of a large population possesses the new trait. The first organisms on earth were the prokaryotes. Prokaryotes are simple cells that normally execute only one function, with a metabolic system of one input and one output. (CrashCourse, 2014).

Most of the markets evolve slowly. Many small alterations of the status quo (the copying errors), lead to small, incremental changes. Organizations that are best at this process continuously improve their position by trying to change in an efficient way: spending few resources on the most profitable ideas.

Where evolution changes genomes through copying errors, an organization can change much more quickly. An organization is able to actively influence all of its processes in a matter of months or years, instead of many generations.

The shock of an entirely new species entering a well-balanced ecosystem is not easy for the newcomer. Such an invasion will generally end in the death of the newcomer because it lacks adaptation to the environment where it is placed. An ecosystem is a large system of different organisms, providing long chains of inputs and outputs that reinforce chances of survival for all organisms that take part in this process. All organisms in that ecosystem are well-adapted to the conditions surrounding them, with many interdependencies between species. The newcomer is a prokaryote, a single-celled organism. It will be hard for the prokaryote to survive: to intervene in the existing interdependencies. All the cell wants is to survive, and if it happens to evolve into a eukaryotic cell its chances will be much better already. A eukaryote is a larger cell, containing different organelles and executing several different functions, often with multiple inputs and outputs for its metabolic system. But the evolution from prokaryotes into eukaryotes took a very long time and took many generations. It is not possible for a single-celled organism to contain all energy for all the generations that it takes to become a eukaryote. The metabolism of prokaryotes is specialized, with few inputs and outputs. (CrashCourse, 2014).

When a new idea is created, there is no guarantee for its survival. Many ideas are created by many people, every single day again. Moreover, the same idea can be created in multiple places at the same time. Any idea can enter the innovation phase, the challenge is to survive the phase. Most ideas will not even enter the phase. Ideas are not always shared. Once forgotten, nobody will search for it. There are long periods of time in which a specific radical change simply does not happen.

The first step after the creation of an idea is to work further on the idea, to create a prokaryote, to get development efforts going. One and the same idea can take very different shapes. The prokaryote stands model for all forms of working on an idea, from one individual thinking about it every once in a while, until formalized projects. This does not mean that one idea will result in one 'prokaryote'. The idea can already be created by multiple (groups of) people in multiple locations. And each of those can proliferate in many ways of bringing the idea further in either similar or different directions. Many parallel efforts are trying in similar or different ways to become profitable, like different prokaryotes entering one ecosystem at the same time. The same way that a highly specialized prokaryote will have a hard time to survive in a strange environment, development efforts are vulnerable and have a low chance of survival. When efforts stop, and they often do, the efforts can disappear without leaving a trace, but some remainders can stay stored. Maybe the idea is not forgotten when development efforts stop, many ideas linger in memories, in long-forgotten projects, in research reports, in published work, in shelved patents, in stored prototypes. But leaving trails of development efforts is not a guarantee that work on those remainders will be used for future endeavours. Or that the idea will ever be pursued again.

Survival – setbacks and termination

Just like with any organism, a prokaryote can survive when conditions match its needs. The input for its metabolic system has to be available. The output of the metabolic system is not necessarily used, it can also dissipate to the environment. (CrashCourse, 2014).

Development efforts need resources. Someone must work on the developments. In a sense, all developments are dying out continuously, until resources are replenished. Once resources run out, the development will once again be stopped and enter the uncertainty whether efforts will ever be resumed, and if so, whether they will continue on earlier efforts or start over.

Eukaryote – restructuring, top-management support

The more complex eukaryote is still a single cell, but it contains organelles, subsystems with different functions within the cell. Those organelles have the potential to make the cell more versatile in the sense that multiple processes are working next to each other, reinforcing each other and broadening the functions that the cell can perform. (CrashCourse, 2014).

When development efforts enter the company, the number of inputs and outputs of the efforts increase. Many companies will expect developments to take the shape of a formalized project. Expectations are raised and promises are made. The project is expected to deliver on its promise within agreed upon boundaries. There are advantages: a company performs many parallel activities, like other products from which income is gained. Such parallel activities increase the survival chances of the project. The company can deliver physical resources, financial resources, and the right skills and knowledge through human resources. This increased complexity does improve chances for the project. Its speed of development and chances on survival make a big leap. Metaphorically, we are still considering a single cell with a new-to-the-world function in a large ecosystem. The support from a company will often not be enough and many projects stop nevertheless. Then another period of waiting dawns, and whether the project will ever be resumed remains to be seen. If it is resumed, it does not necessarily use the remainders of this previous project. Another possibility is that another cell, another company, sees potential in the ideas behind the project and takes over the project.

Symbiosis in the ecosystem – integrate, linking old & new

Sex is one of the greatest 'inventions' of the eukaryotes. Prokaryotes sustained themselves by splitting or cloning themselves. Eukaryotes transitioned to using half of the DNA of one cell and half of the DNA of another cell and combine those into one new cell. Sex increases the diversity of a population, thus enhancing its evolutionary options and potential. Another important process is that of symbiosis. During their evolution, cells started helping each other in the sense that the waste product of one cell is used as food by another cell, and possibly vice versa. This reinforcement of both cells helps the survival of both. Later in the evolutionary tale, the processes of cells became so much intertwined that both cells depended on the other for survival. This was a step towards multicellular organisms. (CrashCourse, 2014).

Again, development efforts do not follow the incremental steps of evolution in the case of radically new technologies. We should view this radically new technology as a new species entering an existing ecosystem. Chances for survival of development efforts can increase through interaction with other technological developments (prokaryotes) or organizations (eukaryotes). Interaction is also a way to combine the best of different projects and companies into the one development direction, improving performance of a technology or the system around it.

The variation between cells originated in copying errors, making the variation entirely random. Selection, however, is not random. A copying error, a trait of a cell, can enhance its ability to survive in the one environment while it decreases its ability to survive in another environment, thus changing a population of a certain species slowly to become more and more adapted to its environment. (CrashCourse, 2014).

The selection of ideas is, at least partly, a conscious process. But also the selection environment of a new product can be observed, and interpreted to be applied to a specific product, while keeping in mind that if a market has to undergo severe changes before adoption, the current selection environment does not represent the eventual selection environment. However, what happens when a cell that has been living in a cold, underwater environment with almost no oxygen is placed in an environment that is warm, dry, and in the open air? How can a cell in that warm environment predict what would have to change to the environment to make it suitable for the new cell? A radically new technology starts out with a similar discrepancy. If we thought that evolutionary chances on success were low, then how much lower will the chances be in an unsuitable environment? But technology is introduced by people that have the ability to aim for certain changes, execute change, monitor change, and adapt to what is monitored.

Keeping an idea alive in an environment where it does not fit will either require a continuous supply of everything it needs (resources), or a change in the environment (market), or a change in the idea (technology). The development efforts either end as a result of drying up of resources or survive until enough of the environment has changed to support the new product in a new, changed ecosystem.

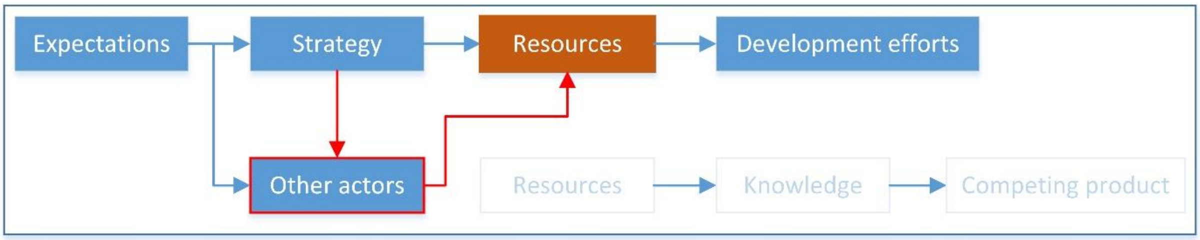


Figure 20 – Model F: Survival of the development efforts

When emphasis shifts from running a project to keeping development efforts alive, having a reliable stream of resources becomes a central goal. When the emphasis shifts from commercializing a product to changing both the product and the market to make them need each other, the other actors in the market get a central role. The challenge is to view the network as a resource of knowledge, financial input through subsidy/collaboration, and human resource/skills.

Review

Resources form the basis on which work is done. No developments can happen if nobody devotes time and effort, let alone money. Many development efforts stop as a result of a lack of resources. Model F therefore places the resources at a central place. However, they resources form just the beginning. Without resources, nothing happens. But once resources have been allocated, work can go on. They take the role of a condition that must be fulfilled, but the actual work happens after that. The focus of model F on the resources brings an additional perspective to previous models, but a strong focus on resources is a narrow view. **The role of the rest of the content of the development efforts and the market should become more visible**.

In comparison with Model E, the factors 'knowledge' and 'product' have been replaced with 'development efforts'. The rationale is that bringing a radically new technology to the market encompasses more than product development, a market has to be created, an entire system must be changed. However, the steps from resources to knowledge to a product is not untrue. In that sense, development efforts should not replace this step, but the parts that constitute development efforts should be represented. Development efforts consist of two parts: product development and market creation. **The different parts of the development efforts should not be merged** together like in this model.

The factors miss detail, they miss explanation of their parts. A way to keep the model simple, but also add more detail is by adding **a table that explains each factor** and what it consists of.

The factor 'other actors' is oversimplified. The many types of actors and their respective interests and power are more complex than the possibility for them to invest or not invest resources in existing developments. Attention for different actors must be increased.

5.3. Answering sub-question 3a and the main research question: Conceptual model for important factors in the innovation phase

This paragraph presents the final conceptual model of this research, taking the lessons of all previous models into account (Table 14). Not all information from the reviews on the model in represented in this table, for the simple reason that some suggestions for improvement were already included in subsequent models. The challenge in this paragraph is to combine models and lessons into one usable and well-supported conceptual model.

Table 14 - Implications of previous models towards factors in the innovation phase

#	Suggestion
Model B	Proving factors in the roles of conditions does not work in the innovation phase
Model B	The list of factors must be reviewed
Model C	Try a new structure
Models C and D	Delete some factors
Model C	Explore the levels of detail of factors
Model D	Create a basic idea of the dynamics
Model D	‘Market’ can be split in smaller groups of factors
Model D	The level of completeness that having three levels of detail suggests is not realistic
Model E	The basic dynamics are too simple
Model F	The role of the rest of the content of the development efforts and the market should become more visible
Model F	The different parts of the development efforts should not be merged
Model F	Add a table that explains each factor

The dynamics are a good way of giving a quick understanding of the basis on which innovations are built. The further an innovation moves towards large-scale diffusion, the more of the system around it has been built, the more of the market is created. But innovations develop in very different ways, focussing on different aspects first. Listing those aspects next to showing the dynamics together creates a concise model that has room for many different routes. One clarification is needed before using dynamics as part of the conceptual model: the arrows. What does an arrow mean? The arrows do not constitute a causal effect, nor do they represent a fixed, exclusive relationship between factors. The meaning of the arrows very much relates back to the definition of the factors: notions that give understanding of what potentially hinders and helps development and diffusion of a radically new technology. The arrows show a relation in which one factors hinders or helps fulfilment of another factor, while leaving room for many more arrows between the factors in the model or even new factors that are especially important to a specific case.

The level of detail of factors and the number of levels of detail that is shown is an important decision. The list of factors in model D was too long and suggested a level of completeness which is not realistic within the scope of this research. Full extension of the list to a third level of detail requires much more research in the factors at the second level than has been performed within this report. Therefore, the third-level factors are not represented in the conceptual model, with exception of changes that bring factors to another level than where they were proposed in Model D (see next paragraph). Supplementing the dynamics with a list of explanations that reaches until the second level of detail is a combination of the simplicity of the basic dynamics and the rigorousness of the list of factors.

The factor ‘market’ in Model D was too large, attempting to include too many sub-factors in one group. It is proposed that the factor ‘market’ is dissolved, bringing all underlying factors to the highest level of detail. Important (groups of) actors like the government, users and other companies are then represented well. Suppliers of complementary products and services and the production system are then brought under the other companies as well, as they form a subset of this group. The macro-economic and sociocultural aspects are combined with accidents and events under the broad environment. Although their differences, they share some traits. All can be very important, or not important at all. All can have strong influence or no influence at all. They all together form part of the broad environment in which an innovation is brought to the market, an environment in which a developing company can change very little.

Some other changes are needed in the list of factors. ‘Existing companies’ is the term that is used in the literature reviews, but those roles can also be fulfilled by newcomers, making the new name ‘other companies’. This could have been called ‘network’, but there are two reasons not to make that change. The first is that not all of the companies in an industry will become part of the innovating company’s network. The second is that a network does not necessarily exist in this stage of development, and the network that does exist is simple and in need of further development. The factor ‘change’ is instrumental, it is more a description of what has to change in factors then that it is a factor itself. In that sense it is a different type of factor and it is removed from the conceptual model for serving the coherence of the model. The factor ‘industry dependent’ is inherent to the entire model, to all factors. Mentioning it separately is therefore not necessary and it is removed from the list of factors. Governments are represented by many organizations that fulfil (part of) the governmental tasks and sometimes more, grouping them under the term ‘institutions’ prevents leaving out crucial aspects of sub-factors like the subsidies that are coming from a national government, but are not managed by the government itself. ‘Users’ is a very specific term for the demand side and seems to imply a direct relation between the innovating company and the end-users. Changing this to ‘demand’ summarizes the entire demand side, including retailers, resellers, and other parties.

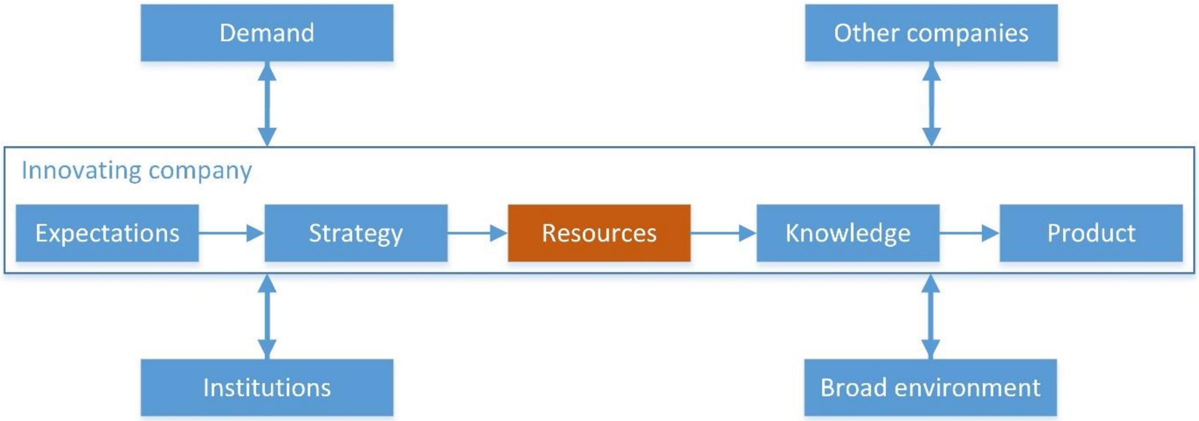


Figure 21 - The conceptual model.

The conceptual model in Figure 21 incorporates many aspects of Chapter 3, Chapter 4 and all that was learned throughout Chapter 5. Let’s point out several of the features. In the middle we find a box that represents the innovating company. It represents the shielded environment where an innovation is started and therefore also its vulnerability. If the process in this box stops, or if the box disappears through bankruptcy, the innovation stops as well. The company works from expectations to a strategy to resources to knowledge to a product. Raising and managing expectations are in the box, again showing the vulnerability of it because it is only carried by such a limited number of organizations and individuals. The resources are absolutely vital and are a focus point. The process is helped or hampered through interactions with different groups: the demand side, other companies, institutions, and the broad environment. All have their own interests and sub-groups and sub-factors within themselves.

This is specified in The place of the four different groups around the process that the innovator owns, only has a meaning in the sense that they are outside the process and that they influence, and are influenced by the process. There is no further meaning to their positioning left or right, or top or bottom.

Table 15. The place of the four different groups around the process that the innovator owns, only has a meaning in the sense that they are outside the process and that they influence, and are influenced by the process. There is no further meaning to their positioning left or right, or top or bottom.

Table 15 - Factors of the conceptual model.

Factor	**Explanation**
Expectations	Having and creating **high expectations** creates movement and willingness to change. **Sharing enthusiasm** and **making promises** should help to overcome **reluctance to change**.
Strategy	Each company has its **organizational culture and values** and **firm-specific techniques**. The **suppliers**, the **production system** and suppliers of **complementary products and services** are either sourced inside the company or through other companies. **Top-management support** to the developments is vital and steers strategic decisions that surround the innovation: deciding on **secrecy**, **planning** of efforts, fulfilling different **roles** around the innovation, getting the word out through **marketing**, and establishing the **organizational structure** through **collaborations** when needed.
Resources	Resources are needed for **development efforts** and for **changing the market**. This can take **natural resources**, **human resources**, and **financial resources**. A particular challenge is to cross the **Valley of Death**.
Knowledge	**Knowledge of the technology** helps further development, **knowledge of the application** helps reaching the market, and **knowledge of the market** helps creating a path of change in the market. Innovations start with a **dependency on research**: **supply and demand of researchers and research funds** is important, which is often **partly funded by a government**. **High risk of the research leads to collaborations** to spread the risk of failure.
Product	The **characteristics of the technology** themselves determine much of the needed development efforts. There is a **dependency on development** to **increase product performance** and **decrease the (future) product price**.
Institutions	Institutions give support through providing **subsidies**, **network**, and **pilot projects** and this can be found at **local, regional, national and international** level. The **need for a technology** is not always communicated clearly. **Laws and regulations** can both help or hamper developments.
Other companies	There is a status quo, a **supply of incumbent technology**. A new technology faces **little competition in early stages** in most markets because of different **development directions**. Change of the market results either in **harm, no effect, or opportunity** for incumbent companies. The innovating company will start looking for **suppliers**, for a **production system**, and for suppliers of **complementary products and services**.
Demand	There is a **status quo**, changing that requires overcoming a **reluctance to change** and **switching costs**. A prerequisite for that change is having the **knowledge** to understand the (potential) change.
Broad environment	There are processes outside the innovating company's reach, that do define the environment of the innovation: **macro-economic aspects**, **sociocultural aspects** and **accidents, events, and undesirable effects of the technology**.

This model points innovators to their role as process owners in a larger environment than just a product development product. The model is aimed at supporting their decision-making process and should be used to steer development efforts in the innovation phase. For that to happen, an innovator must first be aware that the new idea concerns a radically new technology and not just an incremental innovation. This realization must lead to the understanding that chances of survival of the idea are small and to a desire to manage the small chance of success. That is the point where this model comes in. With the use of any available information source, both formal and informal, the innovator maps opportunities and problems, factors that will help or hinder his development goals. Preferably, such an analysis is combined with an understanding of the dynamics between factors. This analysis serves as a basis for decision-making. For making use of opportunities and for solving problems.

The conceptual model is an incorporation of all that was learned throughout this research and is now used in the case studies. The case studies illustrate the model with examples and lead to frictions between the model and reality. This friction is ground for reviewing the conceptual model and changing it where necessary.

6. Case studies

There are two goals in this chapter. The goal of the case studies is to help improve the answer to sub-question 3 and subsequently provide improvements for the answer to the main research question. The case studies together result in suggestions or problems that are used for improvement of the conceptual model. Also, the case studies are a start of illustrating and validating the conceptual model of this research.

The case studies start with a search to create a dataset that together gives a comprehensive description of the innovation phase of the radically new technology. A work-report is created to order all material. The work-report is the basis on which the case studies are written and can be found in the appendix: the work-report for the case of 3D printing is found in appendix B, Augmented Reality's work-report is in appendix C. Conclusions, remarks and observations in the case studies are used to improve the conceptual model in paragraph 6.3, in which the final model is presented as well.

6.1. 3D printing

After the definition, the case study itself consists of an overview of the innovation phase: almost every detail of what happened during the innovation phase is found there. Some anecdotes within the innovation phase provide much more detail than others. Some details are left out in the timeline of the innovation phase, but if so, they return in the next step. The next step discusses each of the factors of the conceptual model, this partly repeats and restructures the information from the timeline of the innovation phase, but it also enriches it with more details. Than a review of the case study lists conclusions and remarks towards the conceptual model.

6.1.1. Definition

The definition of 3D printing that Ortt and Dees (2018) propose is adopted for this research. It is a three-part definition, consisting of the functionality, technical principle, and components of the radically new technology.

Definition of 3D printing according to Ortt & Dees (2017).

Functionality
3D printing is a production technique with which an object is made from a 3D model by adding material layer by layer.

Technical principle
The American Society for Testing and Materials (ASTM) defines seven different categories in 3D printing (ASTM, 2015):

1. Binder jetting: binding ink is injected in a pattern onto a powder to bind the layer of powder.
2. Direct energy deposition: thermal energy is used to melt material and then blend it together.
3. Material extrusion: material is added selectively through a nozzle.
4. Material jetting: drops of building material is placed selectively.
5. Powder bed fusion: a layer of powder is melted together selectively with thermal energy.
6. Sheet lamination: sheets of material are joined together to create an object.
7. Vat photopolymerization: a liquid photopolymer is solidified selectively under the influence of light.

Components
To begin with, a basis is needed on which printing can take place, a substrate to which the material sticks, but from which the end product can later be removed. The printing material is placed onto

that substrate, often with the use of a heat source (warmth or light). Around that, the most striking part of the 3D printer is visible: the construction designed to get the substrate and the product, the material and the energy, in the right place and give it the right speed.

Using CAD (Computer-Aided Design) software, a 3D scanner or photogrammetry software, a 3D model can be made, which is then exported via an STL file (Surface Tessellation Language or Standard Tesselation Language) and converted by a so-called slicer into G-code. It is the G-code that controls all the movements of the 3D printer and starts the actual printing process.

6.1.2. The innovation phase

Before the innovation phase

The first patent in photosculpture was filed in 1860, the first topography patent stems from 1890 (Lengua, 2017). Photosculpture, topography, and material deposition together form three roots of 3D printing. The first devices that start to resemble 3D printing were built in 1956 when Munz worked with photosensitive polymers and in 1972 when Ciraud worked on layers from a metal powder. The first use of a laser happened at Battelle Memorial institute in the 1960s, the point of intersection of two lasers solidified a photopolymer resin in that place. DuPont developed the resin. Swainson applied for a patent and founded Formigraphic Engine Co. (Wohlers & Gornet, 2014). More innovators followed in their footsteps and many experiments were performed with different materials and different techniques (David L Bourell, 2016; Wohlers & Gornet, 2014).

George O. Smith wrote about the fictional *Venus Equilateral* universe in 1975. The ‘era of duplication’ renders the entire manufacturing industry moot in just one month time, disrupting and breaking the entire society (Hollow, 2013).

Carl Deckard worked for TRW Mission in the summer of 1981, a manufacturing company that was one of the first to use 3D computer-aided design (CAD) for controlling machine tools. Manufacturing often depended on cast parts and Deckard saw a great potential for automating the creation of casting patterns based on the digital 3D models. This was the beginning of Deckard’s work on 3D printing, but a concrete idea had yet to be born. (University of Texas, 2012).

Another basic system was developed by Alan Herbert of 3M Graphic Technologies Sector Laboratory around 1982. 3M decided not to continue work on the system. (Wohlers & Gornet, 2014).

Kodama of the Nagoya Municipal Industrial Research Institute in Japan published his paper “Three-Dimensional Data Display by Automatic Preparation of a Three-Dimensional Model” in October 1980 and had already applied for a patent in May of that year. That patent was never granted, allegedly as a result of lacking funds for further research and development. A second paper followed in November 1981: “Automatic Method for Fabricating a Three-Dimensional Plastic Model with Photo Hardening” in which three basic techniques are described. Kodama’s work describes key elements of the stereolithography process, in which a fluid resin is solidified by a laser, layer for layer. (Wohlers & Gornet, 2014).

1984

Then, in 1984, a crucial element of 3D printers became available: computers with an intuitive graphical user interface, enough computing power, and CAD software. This was necessary to make commercialization reachable (David L Bourell, 2016) and would therefore boost 3D printing developments. (Wohlers & Gornet, 2014).

Yoji Marutani from the Osaka Prefectural Industrial Research Institute (OPIRI) also worked on the stereolithography process. He seemed aware of developments before 1984, but not of the other efforts parallel to his. A patent was filed in May 1984 under the title "Optical Molding Method" which describe most key elements of the process. His research continued at least until 1987, when another paper was published under his name. (Wohlers & Gornet, 2014).

A patent by Méhauté, André and De Witte was filed on the 16th of July 1984 (André, Mehauté, & Witte, 1984). André worked with the French National Center for Scientific Research (CNRS) (Wohlers & Gornet, 2014). His colleagues were from the French General Electric Company (now Alcatel-Alsthom) and CILAS (The Laser Consortium), but those organizations abandoned the patent application before it was granted. Méhauté kept promoting 3D printing enthusiastically after that failed patent application. (Mendoza, 2015).

Just three weeks later, Charles "Chuck" Hull filed his patent for a stereolithography system, the Stereolithography Apparatus (SLA) (3D Systems, 2019), under the patent title "Apparatus for Production of Three-Dimensional Objects by Stereolithography" (Wohlers & Gornet, 2014). Hull created the STL-file and in that he developed the algorithms that became the standard for slicing digital 3D objects into printable layers (Wilkinson & Cope, 2015).

Carl Deckard, who saw a market for automating the creation of 3D models in his summer job in 1981, came up with an idea: using an energy beam to melt particles together, like a laser melting a powder together, forming a solid shape layer by layer. This is the start of Selective Laser Sintering (SLS). Dr. Joe Beaman saw the potential and agreed to work with Deckard on this idea for his graduate school project and later as a master's student. Because of changes at the University of Texas, there was a window of opportunity to get budget for new equipment, but that window was closing soon. Deckard's first task was to define the needed equipment before it was too late. He succeeded, although he almost requested a 2 Watt laser instead of a 100 Watt laser due to a copying error in his calculations. (University of Texas, 2012).

1985 Helisys is the first ever additive manufacturing company, founded by Michael Feygin. Helisys worked on Laminated object manufacturing (LOM), based on stacking laser-cut paper layers that were glued together. It would take the company until 1991 for their first shipment. (David L Bourell, 2016).

The second company was founded in Japan, it was called Denken. Their first stereolithography machine, the SLP-3000, was introduced in 1993. (Bourell, 2016).

1986 Charles Hull receives the patent that was filed in 1984 (Steenhuis & Pretorius, 2015) and starts 3D Systems Corporation in March, with Raymond Freed as co-founder (Wohlers & Gornet, 2014). It is 3D Systems that would become the first company to commercialize the additive manufacturing process a few years later (Bourell, 2016).

Also Takashi Morihara of Fujitsu Ltd. worked on stereolithography and patented two techniques. One was for levelling the resin, this technique was used by 3D Systems for years after. The other technique concerned dispensing the resin, which was licensed to another company from 1990. (Wohlers & Gornet, 2014).

Itzchak Pomerantz, founder of the Israelian company Cubital, filed a patent titled "Three-Dimensional Mapping and Modeling System". Cubital and 3D Systems would later cross-license some of their intellectual property to prevent legal problems. (Wohlers & Gornet, 2014).

Two months after 3D Systems was founded, Deckard receives his master's degree in May. He decides to keep working on his newfound technology as a Ph.D. student and filed his first patent in October. 1986 is also the year that academic and commercial progress continue side by side. October is also the month that Dr. McClure (Assistant Dean of Engineering) and Harold Blair (business owner) approach Deckard about commercialization of the SLS technology. Nova Automation is founded. The University of Texas is prepared to license the technology to Nova Automation for commercial development if they can raise $300,000 by the end of 1988. (University of Texas, 2012).

Dr. Efrem Fudim of Light Sculpting was the first to offer services with his own rudimentary 3D printer. However, no one took him up on his offer and he did not sell any system or printed part. (Wohlers & Gornet, 2014).

Yehoram Uziel of Operatech in Israel invented a machine that was close to stereolithographic systems. He visited 3D Systems and would join them in 1989, leaving them again in 1991 to start his own company, Solingen Incorporated. (Wohlers & Gornet, 2014).

1987

3D Systems introduces the SLA-1 (Stereolithography Apparatus) (3D Systems, 2019) and beta units are shipped to customer sites in the U.S. (Wohlers & Gornet, 2014).

Deckard develops a machine called Betsy and shows it to potential investors. The parts that their machine produces are now good enough to be used as casting patterns for real parts, even though each new layer of powder is still deposited by hand with a sort of saltshaker. (University of Texas, 2012). Both Bourell (2016) and Bloomberg (2019) claim that DTM Corporation was founded in 1987, but the University of Texas (2012) reports that Nova Automation changed its name to DTM Corporation in 1989. DTM needs until 1992 to ship its first commercial machine, and will operate as a service bureau for laser sintering from 1990 until 1993 (Bourell, 2016).

1988

3D Systems sells its first SLA-1 in April, thus starting commercialization and therefore ending the innovation phase in 1988. This is also the year that 3D Systems cross-licenses patents with Cubital (see 1986). Also in 1988 is the entrance of 3D Systems on the Japanese market through a joint venture with Japan Steel Works (JSW) called JSW-3D Corporation, providing sales, marketing and service to the Japanese market. This joint venture would be terminated one year later, after which 3D Systems Japan was formed. A partnership with Ciba-Geigy leads to development of stereolithography materials and the first acrylate resins (Wohlers & Gornet, 2014).

By 1988, the University of Texas held eleven patents concerning Selective Laser Sintering, Deckard is involved in most of those patents as inventor. (Espacenet, 2019b).

Scott Crump invents a third way of printing 3D objects. Stereolithography makes a fluid resin solid through light and SLS melts a powder which then solidifies as it cools down. Crump feeds a material through a heated nozzle that melts a solid filament, after deposition of the melted material it solidifies again. (Bourell, 2016). This printing technique is cheaper than the previous two (Hu & Yin, 2014). Crump is the inventor of this technique which called Fused Deposition Modelling (FDM) and receives his patent in 1988. In this same year, the company Stratasys is founded by Crump and his wife. (Steenhuis & Pretorius, 2015). It would take Stratasys until 1991 for its first shipment to their first customer Biomed (Bourell, 2016). Biomed makes custom hips and knees (Lorek, 2014).

Helisys (see 1985) receives two patents in this year (Espacenet, 2019a).

DuPont enters the market with its Somos stereolithography machine, they also develop their own materials. DuPont challenges Charles Hull's 1986 patent at the U.S. Patent Office in September of this year, pointing to work of Kodama and others. Their protest would lead to rejection of all the claims in the patent in 1989. This decision was reversed later that year after 3D Systems delivered proof of the patent's claims (Wohlers & Gornet, 2014).

Loctite starts developing resins for stereolithography but will only stay in the market until 1993 (Wohlers & Gornet, 2014).

OPIRI (see 1984) is part of the Ministry of International Trade and Industry (MITI) in Japan, they license their stereolithography technology to a group of at least five companies (Mitsubishi Heavy Industries, NTT Data Communications, Asahi Denka Kogyo, Toyo Denki Seizo, and YAC) who together formed Computer Modelling and Engineering Technology (CMET). Mitsubishi announced to work on a stereolithography machine in July 1988, suggesting that developments started around that moment. Asahi Denka Kogyo is known to have developed an epoxy resin for the machine. This system was called SOUP (Solid Object Ultraviolet Plotter) and was based on an invention of OPIRI. It would later be introduced 1990. (Wohlers & Gornet, 2014).

After the innovation phase

A number of companies introduced products and filed patents soon after 1988, suggesting that their developments already began during the innovation phase. DuPont filed at least four patents in 1989. D-MEC, a joint venture between Sony and Japan Synthetic Rubber (JSR) was founded and introduced its Solid Creation System (SCS) in 1989 as well. Electro Optical Systems (EOS) was founded in 1989 and sold its first system in 1990. Quadrax brought their system Mark 1000 SL to the market in 1990. (Wohlers & Gornet, 2014).

D-MEC's system was introduced in April or May of 1989 and therefore gives an impression of the state of the art after the innovation phase has ended: "*The system was capable of building urethane acrylate resin parts up to 1000 x 1000 x 750 mm in size from layers at thin as 50 microns.*" (Wohlers & Gornet, 2014).

It would take a long time until many applications for 3D printing arose. The first printers for consumers came on the market on 2006, some printed car parts were presented in 2010 and then many applications followed in 2013 and later. (Ortt & Dees, 2018). An overview is presented in Table 16.

Table 16 - Applications of 3D printing. Based on Ortt & Dees (2018).

Year	Application	Explanation
2006	Printing at home	Complete freedom
2010	Cars	Body
2013	Clothing	Shoes, bikinis, and dresses
2013	Construction	All buildings
2013	Medical	Bone, prosthetics, hearing aids, teeth
2014	Food	Chocolate, candy, pasta, pizza
2014	Cultural heritage	3D models, repairs, souvenirs
2015	Airplane parts	Various parts

Other printing techniques like binder jetting and directed energy deposition were developed in the 1990s. The field was born to decrease development cycle times in the automotive industry and was therefore called rapid prototyping. (Bourell, 2016). Many names came along, and additive manufacturing became the formal name of the group of seven different techniques in 2009 (ASTM, 2015; David L Bourell, 2016). The name 3D printing came up together with small-scale, easy to use printers and co-exists along the more formal 'additive manufacturing'.

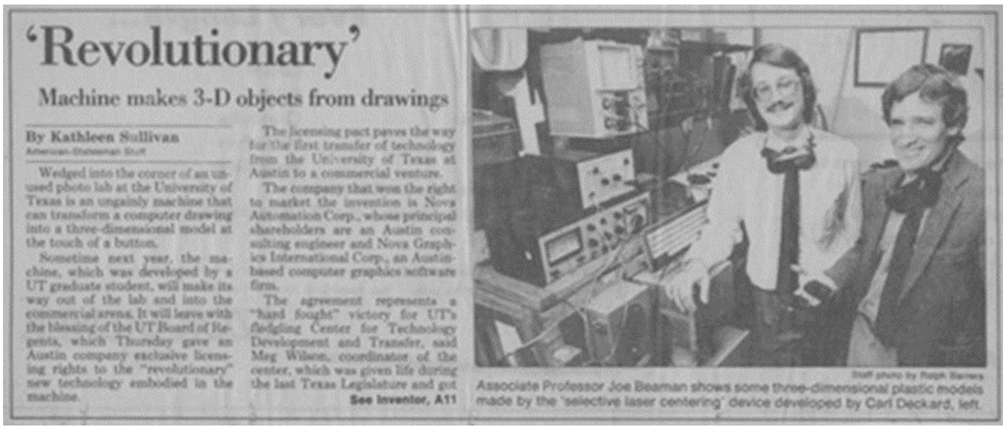
6.1.3. Important factors during the innovation phase

6.1.3.1. Expectations

Kodama worked on stereolithography-like techniques before the innovation phase, in 1980. He was unable to get the scientific community focussed on the potential of his findings, making him stop his project. His work was finally appreciated in 1995 with the Rank Prize. (Lengua, 2017).

Méhauté, De Witte, and André (see 1984) filed their patent three weeks before Charles Hull. Work on the new invention was outside of what would normally be requested in their jobs. They actually worked in an illegal laboratory which became polluted as one of the lasers was leaking. Their commitment followed from "*mathematical order, a passion for transdisciplinary science, and the belief in the explosive commercial potential*". Both financial institutions and the high-tech industry could not see the full potential of their work, ultimately resulting in the abandonment of the patent application by their employers. Nevertheless, Méhauté is proud of what was achieved and still promotes 3D printing with passion. (Mendoza, 2015).

Experiencing and seeing potential improvements in a manufacturing process in 1981 was the starting point for Carl Deckard to start thinking towards 3D printing. He wanted to improve the process of casting for manufacturing. The first step was for Deckard to believe in his own idea enough to present it to an Assistant Professor at his university. The second step was for Joe Beaman, the assistant professor, to see potential in the idea. Which, luckily, he did. It did not take long before several people were working hard on selective laser sintering, defending its potential to everyone else. For McClure and Blair to initiate commercialization of the technology is another sign of great support, as are the license that they received from the University of Texas and the $300,000 investment that was secured in 1988. A 1987 paper called the technology "revolutionary" (Figure 22). Top-figures in Nova Automation (and DTM, as it was called later) are still proud of what was achieved in those days. (University of Texas, 2012).



‘Revolutionary’

Machine makes 3-D objects from drawings

By Kathleen Sullivan
American-Statesman Staff

Wedged into the corner of an unused photo lab at the University of Texas is an ungainly machine that can transform a computer drawing into a three-dimensional model at the touch of a button.

Sometime next year, the machine, which was developed by a UT graduate student, will make its way out of the lab and into the commercial arena. It will leave with the blessing of the UT Board of Regents, which Thursday gave an Austin company exclusive licensing rights to the "revolutionary" new technology embodied in the machine.

The licensing pact paves the way for the first transfer of technology from the University of Texas at Austin to a commercial venture.

The company that won the right to market the invention is Nova Automation Corp., whose principal shareholders are an Austin consulting engineer and Nova Graphics International Corp., an Austin-based computer graphics software firm.

The agreement represents a "hard fought" victory for UT's fledgling Center for Technology Development and Transfer, said Meg Wilson, coordinator of the center, which was given life during the last Texas Legislature and got

See Inventor, A11

Staff photo by Ralph Barrera

Associate Professor Joe Beaman shows some three-dimensional plastic models made by the 'selective laser centering' device developed by Carl Deckard, left.

Figure 22 - A paper calls SLS "Revolutionary" in 1987. Source: University of Texas (2012).

Scott Crump has the ambition to make a toy frog in an automatic way, bringing him to start Stratasys (All3DP, 2019). His printing technique, Fused Deposition Modelling (FDM, is also referred to as plastic jet printing (PJP), fused filament modelling (FFM), fused filament fabrication (FFF), the fused deposition method, and thermoplastic extrusion (Steenhuis & Pretorius, 2015). This spread in terminology points to different visions and ideas across the newly upcoming 3D printing industry.

The generally accepted term for the developments was “rapid prototyping” (Bourell, 2016), a term that seems very narrow and limited in hindsight. The full potential was apparently not known by the entire industry for that name to spread so well. In fact, Hull said: “*it’s a down and dirty industry machine that the general public doesn’t know about.*” (Lorek, 2014).

In conclusion, all kinds of variations show in the expectations during the innovation phase. Expectations have both helped and hindered the development of 3D printing.

6.1.3.2. Strategy

Patents are an important strategic tool for the innovation phase of 3D printing. Charles Hull of 3D Systems, Takashi Morihara, Carl Deckard of Nova Automation (later named DTM), Scott Crump of Stratasys, Itzchak Pomerantz of Cubital. They all patented their inventions before trying to commercialize them. (Espacenet, 2019b; Steenhuis & Pretorius, 2015; Wohlers & Gornet, 2014). The importance of this also becomes visible in DuPont’s efforts to discredit Hull’s patent, in the cross-licensing of technologies between 3D Systems and Cubital to prevent legal issues (Wohlers & Gornet, 2014), and in the crucial defence of a pending patent and the purchase of another patent by Nova Automation (University of Texas, 2012). Licensing happened more, like the license by OPIRI to a group of Japanese companies who together formed CMET (Wohlers & Gornet, 2014) and from the University of Texas to Nova automation. The University of Texas had great success with licenses anyway, as the SLS patent were the generating the highest revenue of all patents that the university held (Lorek, 2014). Stratasys provides another example of the use of intellectual property through the trademark on their own name (Steenhuis & Pretorius, 2015). All this intellectual property must have helped the attractiveness to invest in all the different companies. The negative influence of legal issues around intellectual property were not yet felt much in the innovation phase.

All sorts of collaborations are created and dissolved. 3D Systems enters the Japanese market through a joint venture with Japan Steel Works (JSW), the joint venture is stopped one year later for 3D Systems to start its own subsidiary (Wohlers & Gornet, 2014). Nova Automation already started as a “student/faculty-owned entrepreneurial enterprise”, and its success also followed from a corporate partnership (University of Texas, 2012). CMET, working with OPIRI’s license, also was a collaboration that consisted of five companies, all responsible for a specific part of the developments. D-MEC was a similar joint venture, but then between Sony and Japan Synthetic Rubber (JSR). (Wohlers & Gornet, 2014). Those collaborations to combine skills and knowledge, which in turn helped help developments, it also helped 3D Systems to enter a new market.

OPIRI's development were demonstrated (Wohler & Gornet, 2014), as were Nova Automation's development, with the aim to get investors on board (University of Texas, 2012). However, D-MEC's developments were behind closed doors, kept secret for everyone else. The need for funding, or absence thereof, may well be an important consideration in the decision for secrecy. If a market does not exist, the word must be spread first, expectations have to be created. If the innovation system has already begun to grow, and the first competition emerges, than expectations can possibly be managed in other ways, or are already created by competitors in the market. Whatever the answer to this question, secrecy does not seem to have helped or hindered developments.

The innovation phase ends with the sale of the SLA-1 by 3D Systems (Bourell, 2016). It is unclear which considerations led to their timing of introduction. However, there is a contrast with Nova Automation and Light Sculpting (see 1986). They did not offer printers, they worked as a service bureau instead (Bourell, 2016; Wohlers & Gornet, 2014). The influence of such strategic decisions on developments in general is small, and is also impossible to reconstruct now.

In conclusion, strategies during the innovation phase have helped developments of 3D printing in the innovation phase.

6.1.3.3. Resources

Stereolithography developments required work outside of the normal boundaries of their actual jobs for Méhauté et al., even working in an illegal laboratory with a leaking laser that polluted the room (Mendoza, 2015). Kodama had to stop his efforts due to a lack of funding (Wohlers & Gornet, 2014), also Méhauté et al.'s efforts stopped because support was stopped (Mendoza, 2015). Things worked out better in the case of selective laser sintering.

The moment that Deckard wanted to start working on his idea for SLS was also the moment that Joe Beaman could use funds for new equipment. A $30,000 funding was requested and secured, marking the start of developments. Another $30,000 came in through a grant from the National Science Foundation (NSF), which was used to build a machine called "Betsy". Betsy was later shown to potential investors. Nova Automation was founded and needed an initial investment of $300,000 dollars. The license from the University of Texas was given on the condition that the initial investment would be secured before the end of 1988. Funding from Goodrich Corporation was almost, but not entirely, secured at the end of 1988. A three-month extension from the university saved them and the investment came through in 1989. (University of Texas, 2012). The patents surrounding SLS technology were the highest revenue generating patents of the University of Texas for a number of years (Lorek, 2014).

Indirect accounts of resources are found in the factor Strategy. Joint ventures are a way of spreading costs, spreading risk, and combining knowledge. Those examples include CMET and D-MEC that consisted of five and two companies, respectively. Joint ventures are not seen to have great effect during the innovation phase. The companies that started developments and are close to commercialization of their product at the end of the innovation phase do not report any joint ventures. Of the joint ventures that are found, it is not possible to reliably track their progress during the innovation phase, let alone what the progress would have been without the joint venture.

There is little information available on the topic of resources and the data that is available mainly concerns financial resources. Things turned out well for Nova Automation, but only just, sometimes simply through coincidence. Several other efforts stopped because a lack of support or because of withdrawn support. Resources have the potential to not just hinder, but even to entirely stop development efforts.

6.1.3.4. Knowledge

The invention that starts the innovation phase if not point zero of the available knowledge. Paragraph 6.1.2. shows roots of additive manufacturing in photosculpture, topography, and material deposition. The last mentioned innovator before the innovation phase is Kodama. In fact, he came close to starting the innovation phase himself, if it wasn't for lack of support, lack of funding, and missing an important component of what would later become the first commercialized 3D printer. The increase in knowledge in stereolithography, in 3D printing, also depended on knowledge of other fields. The CAD software that was needed for the translation of a digital file to a physically printed object did not exist before the 1980s, and computing power of computers was also lacking. (Bourell, 2016). The increase in knowledge across the innovation phase of 3D printing is across an industry, it is between organizations, not the general public. Hull said: "*it's a down and dirty industry machine that the general public doesn't know about.*" (Lorek, 2014).

Some innovators worked for research organizations when inventing or developing their variation on 3D printing. The innovators that did not work for a research organization worked for an established, and often well-known company. Marutani was a researcher at OPIRI, Deckard studied and worked at the University of Texas. André worked with the French National Center for Scientific Research (CNRS) (Wohlers & Gornet, 2014). His colleagues De Witte and Méhauté were from the French General Electric Company (now Alcatel-Alsthom) and CILAS (The Laser Consortium) (Mendoza, 2015). Hull worked for UVP, Morihara worked at Fujitsu, Pomerantz was founder of Cubital, Uziel worked for Operatech. (Wohlers & Gornet, 2014). The point is this: ties with research organizations are close, and sometimes form the basis of a company. Knowledge was also shared between innovators and researchers. The patents and licensing of patents is an example of this. The first of three other examples is Sony's mostly secret developments in the joint venture D-MEC that built on knowledge from OPIRI and CMET. Marutani's research at OPIRI built on Kodama's work, but he was probably unaware of Hull's and André's work. (Wohlers & Gornet, 2014). The third and final example is Nova Automation that consulted other researchers, Bourell and Barlow, using their knowledge to improve the SLS technology (University of Texas, 2012).

Indirect accounts of Knowledge are found in the factor Strategy. Joint ventures are a way of spreading costs, spreading risk, and combining knowledge. Those examples include CMET and D-MEC that consisted of five and two companies, respectively. Joint ventures are not seen to have great effect during the innovation phase. The companies that started developments and are close to commercialization of their product at the end of the innovation phase do not report any joint ventures. Of the joint ventures that are found, it is not possible to reliably track their progress during the innovation phase, let alone what the progress would have been without the joint venture.

An organization that worked on 3D printing technology in the innovation phase of that technology could probably come up with more information that is important to this factor and the contribution of knowledge to developments in the innovation phase. Especially in-depth knowledge of the technology and all development steps enriches the analysis of this factor.

The total available knowledge increased steadily across the innovation phase and in that sense it has not hindered developments directly. However, possession of that knowledge was a market on its own, considering all the patenting and licensing. That market stands in the way of the spread of knowledge, but also enforces it because patentability is a consideration for investing in developments in the first place. Also note that the knowledge of 3D printing was only wanted by industrial actors, it was a rapid prototyping machine for them which the general public did not know about. In conclusion, the availability of knowledge did not hinder developments in the innovation phase directly, but the trade of knowledge slowed knowledge diffusion down.

6.1.3.5. Product

The first 3D printers were meant as a way to reduce design cycle times for new vehicles (Bourell, 2016; University of Texas, 2012). The cycle time used to be more than a month, but could now be reduced to days thanks to stereolithography. (Bourell, 2016). Recent research still reports needed improvements in performance, reliability, ease-of-use, user-friendliness (Ortt, 2017), but that is because 3D printing has shifted from rapid prototyping to manufacturing, from only a business-to-business market to including the business-to-consumer market as well. Hull said: "*it's a down and dirty industry machine that the general public doesn't know about.*" (Lorek, 2014). And what's more, the parts were not yet strong enough to be used in production (University of Texas, 2012).

Lorek (2014) reports that the first machine by 3D Systems, the SLA 250, made parts of ten inch by ten inch. There are two problems with this statement. First is that the SLA 250 was not the name of 3D Systems' first product, it was called the SLA-1 according to the company itself (3D Systems, 2019). Second is that it makes no sense to report the printing volume of a 3D printer in only two dimensions; ten inch by ten inch. However, it still gives a suggestion the approximate printing volume around the end of the innovation phase. Another less than perfect reference to get an idea of product performance around that time comes from Wohlers & Gornet (2014): D-MEC's Solid Creation System (SCS) that was introduced in the first half of 1989, had a printing volume of 1000mm by 1000mm by 750 mm with a layer thickness of 50 microns. This printer was introduced soon after the innovation phase and therefore also provides an impression of the state of the art at that time. Products were on the verge of being good and cheap enough to being sold. The stereolithographic process that used masks instead of lasers to direct the light was not automated by Fudim and he never sold any system, Cubital did automate the technology and came further, 3D Systems used lasers did best of the three (Wohlers & Gornet, 2014). Nova Automation machine Betsy was convincing enough to secure $300,000 of investment, while their next design, Godzilla, was "*too big, heavy and expensive*" to ever be built (University of Texas, 2012).

Several techniques were invented and developed further throughout the innovation phase. Stereolithography is the most obvious of those forming the start and end of the innovation phase. Selective Laser Sintering was big in the University of Texas. Laminated Object Manufacturing is not mentioned much, apart from the developments done by Helisys, who did manage to commercialize the technology. Fused Deposition Modelling was perhaps cheaper than stereolithography, but also less accurate. It would later become the way the general public got to know 3D printing (Ortt & Dees, 2018).

3D printing made it possible to create a product, straight from the digital CAD-model (University of Texas, 2012), without needing a mould and therefore needing less engineering knowledge and less equipment (Steenhuis & Pretorius, 2015). Challenges with performance in every sense of the word stay until a product is surpassed by a new, competing product. In that sense, the product did not hold developments of 3D printing back in the innovation phase although the performance was still constraining, leading the maximum speed of development of the innovation system.

6.1.3.6. Demand

3D printing was born in car design, where creating prototypes was expensive and took a long time (Bourell, 2016). That is where it was valuable enough to get customers to accept a rudimentary product with limited quality and strength. The first units were delivered to customers in the U.S. Later development activities would suggest that the demand was also high on the Japanese market, although causes can also lie in other factors like a large Japanese manufacturing industry or an innovative mindset in that country. The first other commercialized application that was found is Stratasys' first customer Biomed which produced custom hips and knees (Lorek, 2014), although it has not been reported whether the machines were used for production or for prototyping.

Both Hull and Deckard started working on their solutions from their experience of a problem. Demand leads the way for developments in their cases, while Kodama worked on stereolithography right before them and was not able to get any interest! It seems that demand, or interest, had been a problem, but was no longer a problem once the innovation phase had started.

6.1.3.7. Other companies

The CAD software that was needed for the translation of a digital file to a physically printed object did not exist before the 1980s, and computing power of computers was also lacking. The change in computers to an intuitive graphical user interface was started by the introduction of Apple's Macintosh in 1984 and Microsoft's Windows in 1985, this made it possible to operate a computer without programming knowledge. (Bourell, 2016). It is the combination of a new way of manufacturing, the easy use of design software, and the connection between those two through Hull's STL-file that makes 3D printing such a ground-breaking technology (Steenhuis & Pretorius, 2015).

Kodama got his photosensitive resin from manufacturer Teijin. Ciba-Geigy worked together with 3D Systems on stereolithography materials in 1988. This resulted in the first types of acrylate resins. Loctite also started to develop resins, but they stopped their activities soon after the innovation phase ended. DuPont announced their machine Somos in 1989 and also applied for four patents regarding photopolymers in that year. It stands to reason that their efforts started before that, during the innovation phase. Asahi Denka Kogyo, one of the companies in joint venture CMET, was the responsible for developing an epoxy resin for CMET's machine. A similar construction is seen in joint venture D-MEC, where JSR is the one who is responsible for the resin, DSM Desotech later also offers resin for D-MEC's machine. The first visible light resin (instead of UV, like the other resins) was introduced by Imperial Chemical Industries in 1990, and therefore possibly developed partly during the innovation phase. (Wohlers & Gornet, 2014).

Much technology in 3D printers is not new. A large part of the innovation is combining existing technologies to create a new functionality. That makes a production system less important: the printers themselves can generally be built with long-existing techniques. 3D printing taps into an existing production system in a new combination, the production system therefore did not hinder development.

Existing organizations often have a role in new companies. The French patent in 1984 was first backed by a research centre and a company. Japan Steel Works helped 3D Systems to get in the Japanese market. (Wohlers & Gornet, 2014). Nova Automation was partly created because of Mr. Blair's involvement, who owned another company Nova Graphics. Hence the name: Nova Automation. Investor were found for getting the company started with the needed investment. (University of Texas, 2012). This research has held the possibility open for individuals to be innovators as well. And they are, looking at Charles Hull and Carl Deckard for example. But the roles of other organizations often start early and grow fast.

In conclusion, there are two points to make. The first is the observation that involved organizations are not always companies. The name of this factor should be changed to allow for research organizations, financers and other organizations to be included to. Second is that the factor has a similar role as the factor 'product'. Very little has hindered development efforts within this factor. The upcoming computers and software and the newly developed materials were important. For both, there is no evidence that they hampered developments, but their development did guide the maximum speed of development efforts. Certain progress was critical to make subsequent development steps.

6.1.3.8. Institutions

One trademark and a great number of patents were reported. Intellectual property was very important for developments in 3D printing and have helped secure knowledge from competition and decrease risks of investments. All the patents slow developments down after the innovation phase, that is the trade-off that institutions make.

OPIRI is an example of a research institute that is operated by a government, by the Ministry of International Trade and Industry (MITI) in Japan (Wohlers & Gornet, 2014). Deckard’s developments received a grant from the National Science Foundation (NSF) (University of Texas, 2012). Institutional support was available to support development efforts, in different ways than the description of this factor proposed.

The influence of institutions can be broader than the examples provided in this paragraph, but no evidence was found regarding phenomena like laws, rules, policies, and habits. The expected cause for this lack of information is simply that those phenomena either do not exist at this development stage or that they are deemed too unimportant to be reported.

In conclusion, institutions helped development efforts. The support was broader than the description of the factor proposes now, which is therefore reviewed.

6.1.3.9. Broad environment

The spread of distributed computing was a precursor for the acceptance of 3D printing (Bourell, 2016). Imagine 3D printers to be offered while computers and their CAD software were both new as well. Operating would seem like a greater challenge and finding people with the knowledge to operate a computer would be harder. Introducing 3D printers when computers are already to beginning to gain widespread traction is much easier.

The story of Deckard and Nova Automation shows the fragility of development efforts. A mathematical error almost ruined his plans. The right people came together, each bringing something crucial for the start and survival of the company. (University of Texas, 2012). Mistakes create a risk for the development efforts to be abandoned completely.

It is tempting to conclude that the broad environment did not hinder development of 3D printing. Computers came up at the exact right time and mistakes did not entirely stop development efforts for Deckard. But what if computing had come up ten years later? Would precursor stereolithography than also have been more successful? And how many innovators are now barely mentioned, who could have had a much greater role when some unreported mistakes had not been made? A believable determination about this factor cannot be made with the current available data.

6.1.4. Concluding remarks

To answer the research question. The factors that helped development efforts of 3D printing are Strategy, Demand, Other Companies, and Institutions. The factors that both helped and hindered the development of 3D printing are Expectations, Resources, Knowledge, and Product. The available information on Broad Environment is deemed insufficient for a determination of that factor’s influence. Product and development of printing materials (included in the factor Other Companies) both proved to have a special role. The developments in those factors are leading for the maximum development of 3D printing. They are dictating the pace, and are hindering in that sense. Not necessarily because they could have gone better of faster, but because they form the limit. Figure 23 shows the model together with the influence of the different factors.

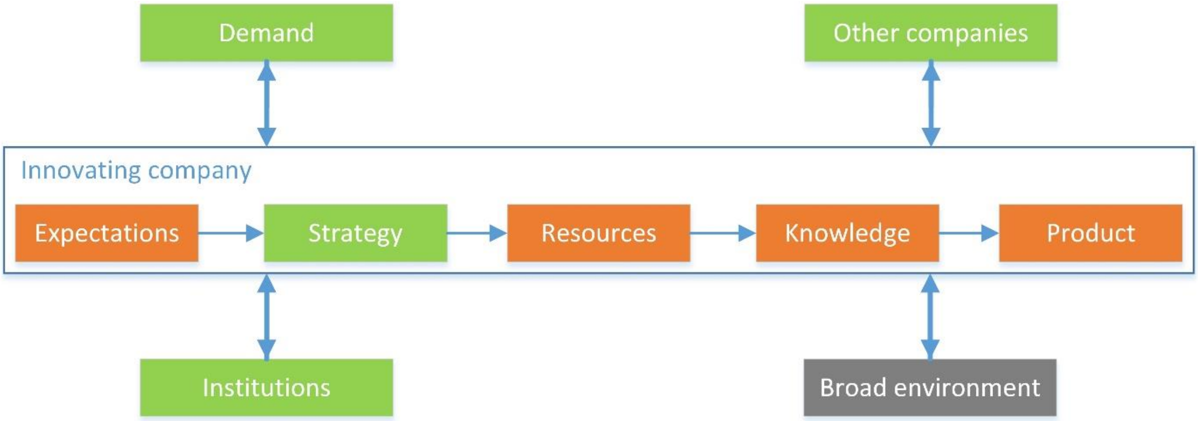


Figure 23 - Factors that help and hinder development efforts of 3D printing in the innovation phase.

When a technology's development efforts are analysed with this model, the view of the technology can be profoundly different from what the technology will later become. 3D printing provides a great example. A crucial and important element of the technology is the connection between digital and physical. Computers with an intuitive graphical interface, CAD software and Hull's STL-file together form this smooth transition from a 3D model to a 3D product. That is part of what made the 3D printers accessible at all, and central to what made 3D printing available and understandable for the general public. But that was not known in the innovation phase! Without this knowledge, Kodama's work could have been the start of the innovation phase, or perhaps even the work of innovators before him. Using the current definition of 3D printing results in a (hindsight) biased definition of the innovation phase.

There is a bias in this research towards elements of each factor that helped development. Negatives will not be reported as thoroughly as positives. Success stories are passed on more often than stories of failures. And more information is helpful in general as well. More detail helps understanding of several factors. Like the interests of other organizations: who fund the research organizations and what are their interests? Little information is available on Knowledge as well, except when diving in the exact technical progress and every little improvement. More information helps this analysis.

Using this model to only analyse the innovation phase misses out on important changes in the innovation system. Perhaps the innovation phase only starts when enough factors are green. Perhaps they hindered developments for a long time. But isolating the innovation phase also gives problems looking forward: the factor Strategy is green because everybody started patenting their inventions, but that created problems later. The great amount of intellectual property slowed the market down in the market adaptation phase. Some observations in the innovation phase can only be explained by taking a wider view.

There was an openness towards new, undiscovered factors for the innovation phase throughout the case study. New nuances and improvement of found factors were plentiful, but only one entirely new factor was found. A natural step in describing the innovation phase is listing all involved actors, all individuals, companies, joint ventures, research organizations, other organizations, governments. Most of those actors fit in a specific factor already, but the innovators themselves have no such place. They are added as a new factor, as one of the three suggestions below.

Lastly, a number of changes in the model are proposed based on this case study. Intellectual property is missing from the factors. Patents report a certain progress in knowledge and institutions enable the possibility of filing patents, but the decision to use that possibility is a strategic decision. Intellectual property is therefore added to the factor Strategy. The factor Product is largely undefined. It suggests that characteristics of the technology are part of that factor, but what are characteristics of a technology? This must at least be discussed when improving the model. Third are the different development directions that are in the description of Other Companies. The Other Companies are meant to be companies that are surrounding the innovation. The different development directions are found in between the innovators, not in the factor Other Companies. And Other Companies can also involve much more than companies. Like banks, funds and investors for money supply for example. Other Companies is therefore changed to Other Organizations. The five central factors are included in the Innovating Company. But there are other innovators as well, like individuals, joint ventures, or perhaps even networks. Changing the name to Innovators will solve this, and also give the possibility to include the different development directions under this new factor. A last advantage to adding the factor Innovators is that it gives the model a place that is designated to listing the involved innovators.

6.2. Augmented Reality

After the definition, the case study itself consists of an overview of the innovation phase: almost every detail of what happened during the innovation phase is found there. Some anecdotes within the innovation phase provide much more detail than others. Some details are left out in the timeline of the innovation phase, but if so, they return in the next step. The next step discusses each of the factors of the conceptual model, this partly repeats and restructures the information from the timeline of the innovation phase, but it also enriches it with more details. Than a review of the case study lists conclusions and remarks towards the conceptual model.

6.2.1. Definition

The definition of Augmented Reality (AR) that Ortt and Dees (2018) propose is adopted for this research. It is a three-part definition, consisting of the functionality, technical principle, and components of the radically new technology.

Definition of Augmented Reality according to Ortt & Dees (2017).

Functionality

Augmented Reality includes multiple functionalities: (1) recording a scene (part of the actual environment); (2) identifying the contents of that environment so that some of it can either be filtered out or highlighted; (3) modifying the selected environment and adding extra information. The added information can be varied: it can be visual, sound, smells, tactile information or combinations of those. In practice, AR often contains sound and vision.

Technical principles

There are various principles for creating AR. The main principle, called ‘video see-through’, consists of the digitization of images from the environment, to which extra information is then added. We take that principle as the basis for our definition. But there are also other principles, like ‘optical see-through’, in which the actual environment is not altered or digitized, but another image information is instead added to that environment, as people see it. You could call that a projection and it is something that people experimented in stage performances even before video cameras were invented.

Components

You need a display for AR (to represent a combination of the actual and added reality) and sensors that indicate where the user is located and in what direction he or she is looking, because the virtual image depends on the position and orientation of the user. Finally, it takes a graphic computer and the associated software.

6.2.2. The innovation phase

Before the innovation phase

The oldest attempt of something that resembles AR is Pepper's ghost in 1862. John Henry Pepper demonstrated his illusion technique in which the crowd could see ghosts on a stage (Peddie, 2017).

L. Frank Baum writes "The Master Key: An Electrical Fairy Tale" in which he features a set of glasses called the "character maker" (Peddie, 2017). The user of the glasses can see people's true character in the shape of a latter on their foreheads (Flanagan, 2018). Also in 1901, Sir Howard Grubb makes an improved version of Pepper's ghost and he files a patent with the title "A New Collimating-Telescope Gun Sight for Large and Small Ordnance" (Peddie, 2017).

The first mention of a head-up display (HUD) comes from 1942 when the Telecommunications Research Establishment (TRE) got radar data projected on the windscreen of a fighter, relieving the pilot of having to look down to find an enemy. Other mentions of similar systems follow in 1953 when the Army-Navy Instrumentation Program (ANIP) got flight data in the pilot's view, in 1961 when Philco made a head-mounted system with a helmet and head-position tracking, in 1962 when Hughes Aircraft made a similar device which they called the Electrocular, in 1963 when Bell Helicopter Company made a remote viewing device that gave the pilot an augmented view of the ground, and in 1967 when Tom Furness developed a head-mounted display for aiming weapons for the Air Force. (Peddie, 2017).

Morton Heilig was a filmmaker who came up with "The Cinema of the Future" in 1955 (Alkhamisi & Monowar, 2013) and patented an "apparatus to stimulate the senses of an individual to simulate an actual experience realistically" (Flanagan, 2018). He patented his Sensorama Machine in 1962. A machine that could "*provide the illusion of reality by using 3-D motion pictures, stereo sound, a vibrating seat, wind in the hair, and even smells.*" The Sensorama Machine is seen as the start of Virtual Reality (AR Unleashed, 2019).

Ivan Sutherland came from MIT (Massachusetts Institute of Technology) to Harvard University in 1962 (Peddie, 2017). He wrote an essay titled "The Ultimate Display" in 1965. He talked about the possibility of augmented reality in this essay (Sutherland, 1965) and started doing experiments in 1966 and 1967 at the MIT Lincoln Laboratory (Sutherland, 1968).

1968

The first Augmented Reality system is created by Ivan Sutherland in 1968 (Alkhamisi & Monowar, 2013). In his function as Associate Professor of Electrical Engineering at Harvard University (AR Unleashed, 2019), he worked with his students on the system that was called 'The Sword of Damocles' (Isberto, 2018). The system showed simple wireframe drawings (Augment, 2016), showing more complex structures was impossible due to the limited processing powers of the computers of that time. The system uses a head-mounted display and two different 6-degrees-of-freedom trackers. (Arth et al., 2015). This was the same display as Bell Helicopter Company used before in their developments. The system was the first Augmented Reality System, but also the first Virtual Reality system (Arth et al,. 2015). A publication in 1968 on this system was called 'A head mounted three dimensional display' (Flanagan, 2018). Sutherland joined the Computer

Science Department of the University of Utah later that year. That department was headed by Dave Evans. Sutherland and Evans knew each other from MIT, and founded Evans & Sutherland Computer Corporation (Peddie, 2017).

1969 Myron Krueger refers to his work as ‘artificial reality’. He works on a Ph.D. in Computer Science at the University of Wisconsin–Madison. His work was on projects like Glowflow, Metaplay, and Psychic Space, in which a responsive computer-generated environment was the careful start of what would later be called telepresence, enabling communication in digital environments over long distances. (Peddie, 2017).

1974 Steve Mann makes an Augmented Reality system wearable with the use of wearable computers (Peddie, 2015). Earlier efforts were not mobile because of the processing power that Augmented Reality requires and the state of the art in the computer industry was not sufficiently powerful at first (Van Krevelen and Poelman, 2010).

Videoplace is founded by Myron Krueger, which he created as an artificial reality laboratory (AR Unleashed, 2019). A combination of projectors and video cameras creates onscreen silhouettes (Augment, 2016). The movements of the participant are projected live on a screen and the digital environment reacts to those movements (Krueger et al., 1985).

1978 It is not easy to determine the fit between some of the developments in head-mounted displays for pilots and the definition of Augmented Reality that is used in this research. Most of the efforts in this direction are excluded because information is placed over reality, not fitted in the reality, which is described in the functionality of AR. However, a new project in 1978 seems to do just what those other developments were missing. An experiment showed that teaching people to land a plane for the first time with the help of an augmented display works far better than without this augmented information. (Lintern & Roscoe, 1978).

1980 Steve Mann creates the Eyetap. This device is wearable and uses an antenna for wireless communication, it gives the user an augmented reality. (AR Unleashed, 2019; Peddie, 2017).

1981 The idea to make weather broadcasts on TV use AR came from Dan Reitan. (Peddie, 2017).

1982 KSDK in St. Louis mixed images for radar systems and satellites with Reitan’s technology (Peddie, 2017). The first time that this happened live on television was in 1982 (AR Unleashed, 2019). Reitan would later go on to develop ReinCloud and file several patents (Peddie, 2017).

1983 Krueger publishes his book ‘Artificial Reality’ (Peddie, 2017).

1985 Furness’ efforts on a head-mounted display that started in 1967 continued and he proposes a virtual retinal display when working at the Armstrong Laboratory at Wright-Patterson Air Force Base: a display that is projected in the eye, directly on the viewer’s retina. This seemingly makes information float before the viewer (Peddie, 2017). This work is probably part of the collaboration between U.S. Air Force’s Armstrong Laboratory, the NASA Ames Research Center, the

Massachusetts Institute of Technology, and the University of North Carolina at Chapel Hill which are reported to work together on AR in the 1970s and 1980s. (Van Krevelen and Poelman, 2010; Peddie, 2017).

1986 Kazuo Yoshinaka works at Nippon Electric and also has the idea to work on a virtual retinal display (Peddie, 2017).

1989 Reflection Technology introduces The Private Eye, which is a head-mounted display that creates the view of a 15 inch screen on a distance of 18 inch. (Peddie, 2017).

A system is proposed for an astronomical telescope. The viewer looks into the eyepiece and sees the normal view, augmented with names of stars and other additional information. (George & Morris, 1989).

1990 Thomas P. Caudell and David Mizell introduce the term "Augmented Reality" in their time as researchers at Boeing Corporation (Peddie, 2017; Van Krevelen and Poelman, 2010).

1991 Furness completes his work on the virtual retinal display together with Joel S. Kollin, when working at the Human Interface Technology Laboratory at the University of Washington (Peddie, 2017).

1992 Furness files a patent concerning his work on the virtual retinal display (Peddie, 2017).

Caudell and Mizell developed onscreen guides (Bensch, 2015) towards an AR system that uses a head-mounted display (Metz, 1994). They demonstrated the system for four different applications: for work on a wiring formboard, a connector assembly, a composite layup, and for maintenance or assembly (Caudell & Mizell, 1992). Their work was part of the Computer Service's Adaptive Neural Systems Research and Development Project at Boeing (Bensch, 2015) and the goal was "*advancing the components of this technology to the point at which the use of AR in manufacturing applications is practical*" (Caudell & Mizell, 1992). However, the system was not responsive enough: it was too slow to properly keep up with the head-movements of the workers due to lacking computing power of the wearable computers and the system did not catch on (Metz, 1994). Caudell and Mizell also discuss AR versus VR (Virtual Reality), AR renders less pixels and therefore requires less computing power. However, some extra computing power is needed for aligning the real and virtual elements. (Arth et al., 2015).fv

Neal Stephenson publishes his novel Snow Crash, in which he describes a Metaverse, a place where real elements and virtual elements basically become one and which people can access with the help of special goggles. He would join Magic Leap in 2015, Magic Leap works on AR developments. (Peddie, 2017).

Louis Rosenberg works on Virtual Fixtures at the Armstrong Laboratory of the U.S. Air Force (also see 1985). The system used an exoskeleton that was worn by the user, the user's movements were replicated by a remote robotic arm. The user was also visually connected with the remote robotic arm, seeing the robot as his own arms. Experiments required users to use the robotic arm for simple peg insertion tasks. The time that it took to perform the tasks was recorded and compared with the times it took when simple Virtual Fixtures were displayed. Virtual Fixtures are overlays that the user sees which guide his movements, like a plane or an arrow that guides the movement or position of the peg. Results showed that performance could be improved with the help of such Virtual Fixtures. (Rosenberg, 1992).

Three AUGSIM (Augmented Simulation) demonstrations were given in 1992 and 1993 where the crew of a combat vehicle could see other virtual vehicles around them. The system also allowed interactions with the virtual vehicles, meaning that the effects of weapons are visible. This makes army training able to be large-scale without the great costs and logistic challenges of such a large training that includes multiple vehicles. (Barrilleaux, 1999). This system and those demonstrations were initiated by Loral WDL and sponsored by STRICOM (Peddie, 2017). STRICOM is the Army Strike Command (Library of Congress, 2019). The idea for those demonstrations was simply born from the idea ‘to do something different’ (Barrilleaux, 1999).

The efforts by Furness (see 1985), by Rosenberg, and by Barrilleaux were all connected to the United States Army in some way. Especially the efforts by Furness and by Rosenberg were performed in the same laboratory. But no connections between the three developments are found. Different organizations were involved, there is no common sponsor found, and the publications do not mention any of the others in their references. Nevertheless, it is likely that Rosenberg had knowledge of Furness’ efforts seven years before him.

Steven Feiner, Blair MacIntyre, and Doree Seligmann present their paper on KARMA (Knowledge-based Augmented Reality for Maintenance Assistance). They develop a system for maintenance and repair instructions, starting with instructions on filling the paper tray of a printer and changing its cartridge. (Feiner et al., 1993).

1993 Rosenberg founded Immersion Corporation which is a Virtual Reality company (Peddie, 2017).

An outdoor navigation system for visually impaired was developed by Loomis et al. It was based on an electronic compass, GPS, a Geographic Information System (GIS), and played audio depending on the location of the user. (Arth et al., 2015; Van Krevelen and Poelman, 2010).

Fitzmaurice creates Chameleon. Although not really an Augmented Reality device, it does have an interesting feature. The user holds a device with a 4 inch screen and navigates through a virtual environment by holding and releasing a button on top of the device, and by moving the device while the button is pressed. (Arth et al., 2015).

1994 Steve Mann has continued his efforts for wearable devices (see 1974 and 1980) and decides to wear a webcam for almost two years, starting in 1994. Online visitors could see what he saw and Mann could see their messages on a mobile display. (Arth et al., 2015). The device was called SixthSense and was developed at MIT. Mann would continue those development with a head worn gestural interface in 1997 and a neck worn version in 1998. (Peddie, 2017).

The first commercial application of AR is in a theatre production called "Dancing in Cyberspace" (Isberto, 2018; Peddie, 2017). The Australian Julie Martin created the show with funding of the Australia Council for the Arts (European Theatre Lab, 2017). Acrobats and dancers would play with virtual objects through real-time interaction (European Theatre Lab, 2017; Peddie, 2017).

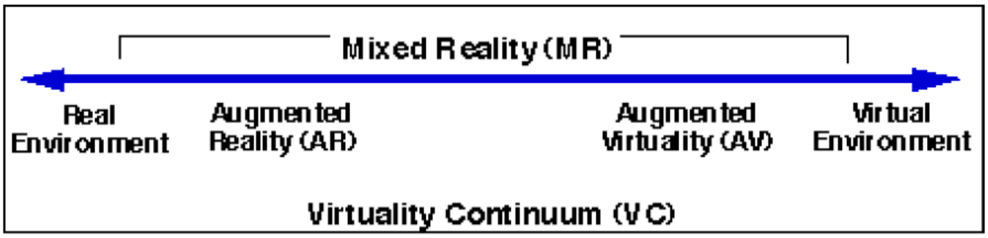


Figure 24 - The Reality-Virtuality Continuum. Source: Milgram and Kishino (1994).

Paul Milgram and Fumio Kishino publish "Taxonomy of Mixed Reality Visual Displays". They propose the Reality-Virtuality Continuum, in which AR is closer to the real environment and Augmented Virtuality (AV) is closer to a fully virtual environment, see Figure 24. (Milgram & Kishino, 1994).

After the innovation phase

A number of developments were presented soon after 1994, suggesting that their developments already began during the innovation phase. Rekimoto and Katshi created the NaviCam in 1995, which was an improved version of the Chameleon (see 1993), it registered markers in the real environment and displayed information that was linked to those markers. Benjamin Bederson introduced Audio Augmented Reality that played specific audio at specific locations, usable as a museum guide. (Arth et al., 2015). Then Sony entered the market with the Glasstron in 1996, Glasstron was a head-mounted display with LCD screens and earphones (Peddie, 2017).

Now towards an impression of what AR could do at the end of the innovation phase. Sutherland's equipment displays 3000 lines at 30 frames per second (Sutherland, 1968), he already talked of area-filling devices that would someday be possible (Sutherland, 1965). However, limited processing power kept AR from becoming truly mobile (Van Krevelen and Poelman, 2010). The NaviCam that was created in 1995 still used a nearby workstation for processing, but it was able to identify markers in the viewed and overlay information according to what the marker's identification related to. The system by Feiner et al. (see 1993) was able to provide a screen resolution of 720 pixels by 280 pixels. Depending on the set focus, the display could be seen at a distance of 10 inch or further. (Feiner et al., 1993).

Table 17 - Applications of Augmented Reality. Based on Ortt & Dees (2018).

Year	**Application**	**Explanation**
1994	Theatre	Dancers with virtual objects
1997	Headset for consumers	Sony introduces Glasstron
2000	Game	AR Quake is the first AR game
2008	Travel guide	Historic information on buildings
2012	Advertising	First large-scale AR advertising
2016	Pokémon	Pokémon GO is played worldwide

It would take decades before Augmented Reality would be applied to larger publics. There is so little information on Sony's Glasstron that it was probably not the breakthrough the company had hoped for. The technology finally reached the mass market with Pokémon GO, a game that was played worldwide by many people. (Ortt & Dees, 2018). An overview of the main applications of AR is presented in Table 17.

6.2.3. Important factors during the innovation phase

6.2.3.1. Expectations

Heilig, who developed the Sensorama Machine in 1962, believed that cinema should be able to draw the watcher into the reality of what happened on the screen (Alkhamisi and Monowar, 2013). He saw opportunities in stimulating multiple senses of the watcher, to make the experience more realistic, possible application are "*for teaching and training in jobs and environments that might otherwise cause the trainees harm, such as military training*" (Flanagan, 2018).

But Heilig still missed crucial elements of what would later become Augmented Reality. The invention of AR is attributed to Sutherland in 1968. His work in this direction started in 1965, expecting to make experiences possible that are impossible in the real world, he compares his envisioned Ultimate Display with the Wonderland that Alice walked in (Sutherland, 1965). The right two-dimensional images create the illusion of a three-dimensional object. Many people contributed to Sutherland's project, their continuous support was vital to the project's survival. (Sutherland, 1968).

Krueger (see 1969, 1974, and 1983) pressed for creativity and radical thinking when he pushed researchers "*not be bound by the constraints of the present*". Videoplace started out as a telecommunication system, but there was a bigger picture. Controlling computers would move away from programming and towards more intuitive methods. An example is the human desire to touch digital objects and the expectation that the object responds to that touch. Krueger sees possibilities in teaching and in creating advantages over touchscreens, but the big goal is to develop an intelligence that makes interaction of the system with a participant almost human. (Krueger et al., 1985).

Caudell and Mizell (see 1990 and 1992) expected Boeing to reduce costs and increase productivity of aircraft manufacturing with the help of AR (Caudell & Mizell, 1992). Fitzmaurice (see 1993) expects applications of AR in 3D information spaces that combines several sources of information (like phonebooks, phone calls, and fax messages), in accessing the content of an office, and in libraries. The information space he proposes is a way of preventing an information overload for the user. The sought information comes up only by looking around in the office and focussing on the phone, on the calendar, or on the bookshelf. (Fitzmaurice, 1993). But the year before, in 1992, Rosenberg discovered something in the opposite direction: virtual fixtures help increase precision and performance of human abilities while reducing the sensory workload, basically reducing the effort that it takes to perform a task, like a ruler guiding a pencil (Rosenberg, 1992). KARMA, presented by Feiner et al. in 1992, showed that AR can be applied for providing guidance in maintenance and repair tasks (Feiner et al., 1993). Milgram and Kishino also mention a telecommunication environment, but they also point to medical imaging as a possible area of application of AR (Milgram & Kishino, 1994).

More and more applications are envisioned as the innovation phase progresses. Steve Mann wears a webcam for two years, being continuously connected to his online visitors (Arth et al., 2015). This demonstrates his vision towards wearables devices and the everyday use of AR. The first development direction was a military one, with heads-up displays that shows pilots information on their windshields or their helmets. Although that started off without actually augmenting the reality, the AUGSIM demonstrations in 1992 and 1993 showed a huge leap forward, although the development were only motivated by the simple goal to do something different at a trade show. The author does, however, provide quite the range of application for AR: "*Training for civil services and disaster teams. Visualization for business, architecture and science. Maintenance and manufacturing tools for industry. Medium for education and collaboration. Games for entertainment and therapy.*" (Barrilleaux, 1999).

All that those statements mean, is that the people who worked on the technology believed in AR and saw many applications. Meanwhile, Sony's Glasstron barely did anything on the consumer market in 1996. Perhaps the cause for the slow spread of AR lies in another factor, perhaps a part can also be found in low expectations. Whether the first is true is reported in the rest of this chapter, whether the second is true is unknown due to lack of such reports. All that is reported points clearly to high hopes and also early promises of certain advantages of AR, helping it through the innovation phase.

6.2.3.2. Strategy

Most innovators work for research organizations, mostly universities. Dan Reitan is the first on the timeline of the innovation phase who is not a researcher, we are then thirteen years after Sutherland's invention in 1968. Most efforts involve researchers. There is a change as time progresses, though, when the U.S. Air Force's Armstrong Laboratory, the NASA Ames Research Center, the Massachusetts Institute of Technology, and the University of North Carolina do research together. This makes developments for military applications go faster, but Barrilleaux (1999) shows that developments for military application do not stand in the way of having a vision on other applications. The researchers need support for their projects. Little is mentioned about this, but Sutherland thanks all the people involved in his 1983 publication. He says that the project would have died if it wasn't for the spirit of those who helped. He also thanks Stewart Ogden for making it possible to do more work and less paperwork, which apparently quite a difference. (Sutherland, 1983).

Heilig filed a patent for his machine, but his development stopped at the prototype (Flanagan, 2018). After that, there is little mention of patents or any other form of intellectual property. There is no mention of any legal issues about intellectual property either. The exception to this is Furness and his work on the virtual retinal display, for which a patent was filed in 1992. The relatively safe conclusion is that intellectual property was not crucial in the innovation phase of AR. There were probably some more patents filed than are reported here, but there is no data to suspect that the protection of intellectual property helped or hindered developments of AR.

Two companies were founded on the basis of AR developments. Sutherland founded Evans & Sutherland Computer Corporation in 1968. Sutherland joined the Computer Science Department of the University of Utah around the end of that year. That department was headed by Dave Evans. Sutherland and Evans knew each other from MIT, and started the company together. They formed the first computer graphics company in the world. Rosenberg founded Immersion Corporation in 1993, which is a virtual reality company. (Peddie, 2017). Two companies is very little for such a promising technology. It is tempting to conclude that researchers and other innovators could have helped AR developments more by starting more companies. It is likely that the risk for starting such companies was too high. An example are Boeing's efforts, which could not become viable (Metz, 1994). The question then remains for other factors: why was it not viable to start an AR company? For now there is another question: if the researchers did not commercialize their ideas, then what did they do to help AR further?

Many development efforts report demonstrations. Sutherland built a demonstration system (Sutherland, 1968), Videoplace was a beautiful demonstration where the digital reality responds to a the participant's movements (Krueger et al., 1985), Caudell and Mizell demonstrated AR in a manufacturing application (Caudell & Mizell, 1992), Loral WDL demonstrated their combat vehicles for manned simulations (Peddie, 2017). Two other demonstrations are by Thad Starner and Steve Mann, both of them started to constantly wear their computer (Arth et al., 2015; Peddie, 2017), demonstrating and basically marketing the technological principles and the possibilities for everyday application.

In conclusion, some elements seem to be missing in the Strategy factor. Especially the absence of start-ups stands out and it suggests that another factor was slowing down development efforts. The innovators did what they could to help development efforts. There was some attention for intellectual property, but the most important aspects was the abundance of demonstrations. The factor Strategy helped development efforts of Augmented Reality in the innovation phase.

6.2.3.3. Resources

Boeing's investment in applying AR to the workspace in an experimental way (Caudell & Mizell, 1992; Van Krevelen and Poelman, 2010) is a rare sight in AR's innovation phase. Sutherland's biggest thanks goes out to the people who contributed to the research and Stewart Ogden who managed to keep the paperwork out of the way (Sutherland, 1968), his main resource are the people around him. This is also illustrated when he starts a company with an old acquaintance (Peddie, 2017). His AR system, however, only shows wireframe drawings due to the limited processing power of computers (Arth et al., 2015). Krueger et al. find that their work is limited by resources and because commercial equipment did not yet have the processing power that was needed. They first circumvented the problem by building their own hardware and could later buy three Silicon Graphics workstations around 1985 (Krueger et al., 1985), undoubtedly after having more resources available. Before that, for the creation of Videoplace, the funding had come from a National Endowment for the arts (Peddie, 2017). Rosenberg's work was sponsored/monitored by a number of organizations: Armstrong Laboratory, Biodynamics and Biocommunications Division, Human Systems Center, Air Force Materiel Command, and the university of Wright-Patterson (Rosenberg, 1992). The AUGSIM system for manned combat vehicle simulations was sponsored by the army's STRICOM (Barrilleaux, 1999). Julie Martin's "Dancing in Cyberspace", the first commercial application of AR, was funded by the Australia Council for the Arts (European Theatre Lab, 2017; Peddie, 2017). Around that time, mobile AR was still impossible because of the limited processing power of devices (Van Krevelen and Poelman, 2010).

It helps to know the right people. It helps to find people that you, as an inventor, want to work with. The fact that most innovators are researchers helps them it accessing a large group of intelligent, knowledgeable, technical people. However, money supply was harder. The projects that are reported did receive sufficient funding to at least work until a demonstration, but often this funding was ad hoc. A grant, a sponsorship, a project. There is little long-term dedication found, keeping AR developments an unattractive field for people who could not rely on their own research budget. The most limiting element of resources was the state of the art of computer hardware during the innovation phase. Limited processing power was a problem, display resolutions were relatively low, mobile services like GPS and Wi-Fi were not available at all, or only very limited. The resources surely hindered developments of AR in the innovation phase.

6.2.3.4. Knowledge

The heads-up display (HUD) is first seen in 1942, a display for fighter pilots that shows information from their dashboard on the windshield of the aircraft, preventing the need to look down (Peddie, 2017). Developments in this direction were more a matter of overlaying information than augmenting the reality. Those developments did, however, provide a well-known and well-developed application of a mixed reality vision. That is probably the reason that AR was picked up so well by researchers in the army. Krueger has an entirely different background, he has more experience with games than with military applications, proven by his statements about the interface of an AR system. The informal and compelling interface of digital systems should become standard, he says. (Krueger et al., 1985).

The factor Strategy concluded that the vast majority of innovators in the innovation phase was a researcher. That is reflected by reports of publications, like the Milgram and Kishino's paper 'Taxonomy of Mixed Reality Visual Displays' in which they define Augmented Reality (Arth et al., 2015), and even Caudell and Mizell's efforts at Boeing were published in 1992. CyberEdge Journal was started by Ben Delaney in 1991 and reported on the virtual reality industry. (Peddie, 2017).

Some advantages that AR can provide were already proven during the innovation phase. Rosenberg (1992) showed that virtual fixtures, guiders in the digital space, could enhance human performance in peg-insertion tasks. He used planes and arrows to guide movements and describes this as the equivalent of a ruler guiding a pencil. Also learning can be greatly improved by using AR. Researchers tracked the progress of subjects who had no flying experience at all during their attempts to learn how to land a plane. Part of the subjects got taught in a simulator that gave augmented feedback as an instruction to the subject. The first real plane-landing was easier for those who learned with augmented feedback than for those who learned without. (Lintern & Roscoe, 1978).

Knowledge was increasing quickly. Demonstrations explored different applications, this experience could be added together will the previous experiences with development of the HUD for pilots. As said, most innovator were researchers, making progress (somewhat) formalized, reported, and shared. With the exception of Kazuo Yoshinaka's invention of the virtual retinal display, parallel to Furness' equal idea (Peddie, 2017), most researchers know of other work: papers often cite prior works. Knowledge helped development of AR in the innovation phase.

6.2.3.5. Product

Sutherland's equipment displays 3000 lines at 30 frames per second (Sutherland, 1968), he already talked of area-filling devices that would someday be possible (Sutherland, 1965). However, limited processing power kept AR from becoming truly mobile (Van Krevelen and Poelman, 2010). The NaviCam that was created in 1995 still used a nearby workstation for processing, but it was able to identify markers in the viewed and overlay information according to what the marker's identification related to. The system by Feiner et al. (see 1993) was able to provide a screen resolution of 720 pixels by 280 pixels. Depending on the set focus, the display could be seen at a distance of 10 inch or further. Also their system still only showed virtual wireframe objects (Feiner et al., 1993).

Most systems suffered from the low processing power of computers, some solved it like the NaviCam, with a cable to a workstation. GPS was new and not combined with mobile devices yet (Arth et al., 2015). Some systems were mobile, some created more than a wireframe, some used GPS, some used more than just vision, some were truly interactive, some were truly augmenting the view by fitting virtual objects to real objects. Many elements of what AR is in 2019 were demonstrated during the innovation phase, but combining them in one affordable product that had a market application, that was not done yet.

There are optical see-through and video see-through systems. The difference is whether you actually see the environment with digital objects projected at specific places, or whether you only see a digitized version of reality with digital objects fitted in it. Optical see-through provides challenges in aligning real and virtual objects in space and time. Also, the optical see-through systems had problems with light intensity, which would supposedly be solved by the introduction of the virtual retinal display. Video see-through creates challenges with the camera position, which has a slight offset from the line of sight because of the camera's placement. (Bensch, 2015).

AR was developed in many directions and new challenges were coming up. If the camera offset is the biggest problem, then you know that many problems before have been solved. Then the technological principle has been developed properly. In that sense, the product did not hold developments of AR back in the innovation phase, although its performance was still constraining, leading the maximum speed of development of the innovation system. Systems needed further development for practical applications to be realized.

6.2.3.6. Demand

The expectations for AR are plentiful and many applications are suggested by researchers. However, such technology push needs some acceptance, it needs customers. The greatest demand in the innovation phase is from military applications. From the HUD in 1942 (Peddie, 2017), to the virtual retinal display in 1985 (Van Krevelen and Poelman, 2010; Peddie, 2017), to the Virtual Fixtures in 1992 (Rosenberg, 1992) and the AUGSIM system in 1992 and 1993 (Barrilleaux, 1999), military developments are plentiful.

Sutherland showed floating wireframe objects (Sutherland, 1968), Krueger created interactions in Videoplace which were close to games (Alkhamisi and Monowar, 2013), Loomis et al. worked on a system for visually impaired persons (Arth et al., 2015). Those are all demonstrations, and any mention of demand for such systems is lacking. Things change when Caudell and Mizell start developing an AR system for manufacturing applications (Caudell & Mizell, 1992). The fact that they got to work on those developments for Boeing is demand in itself. During this project, there was a parallel between developments and demand. There is a similar parallel in the work of Steve Mann: he promotes wearable (AR) devices by developing, demonstrating, and using wearable devices. He too, is his own demand. His influence on the general public is unknown.

Pepper’s ghost shows the interest of the theatre in illusions in 1862 (Peddie, 2017) and Julie Martin’s ‘Dancing in Cyberspace’ confirms this in 1994 (European Theatre Lab, 2017; Peddie, 2017). The role of the interest of arts in illusions and AR on developments? That is unknown, but at least some demand was there throughout the innovation phase.

Researchers point to their limited resources for AR developments, but some resources were available. Increased demand could have helped them get those resources, although this is mere speculation, and again: there were enough resources to continue the work. Resources from institutions like the Armstrong Laboratory of the U.S. Army helped support several development directions. Without this help, things would have progressed much slower. The conclusion is that demand helped the developments of AR in the innovation phase.

6.2.3.7. Other companies

The lacking processing power has been pointed to a number of times before in this case study. The supply system of Augmented Reality was not able to keep up with its demands, to the extent that Krueger’s team even began to create their own hardware for the development of Videoplace (Krueger et al., 1985). Of course, this part of the supply system of AR was actually an autonomous industry: the computer industry. AR depends on computers, but computers do not depend on AR.

Another crucial part of an AR system is its display. Luckily, the development of the Heads-Up Display provided optical see-through head worn devices that displays information in the user’s line of sight (Caudell & Mizell, 1992). When Sutherland started working on his invention, displays just got line-drawing capability (Sutherland, 1965). Resolutions were very low as well (Arth et al., 2015), compared to what displays can do now, in 2019. However, it was the processing power that held developments back, not the displays. Better displays would only lead to a greater need of processing power. Also other developments, like making devices mobile and creating new services such as GPS, enable further

AR applications. They helped in trying new AR applications, but were also still held back by the processing power of devices.

A computer with sufficient processing power to support an AR system is an enabling technology. It is developed by other companies, and it is supplied to those who buy it for developing AR systems and/or applications. While all of this is true, it does not make any company hinder the development of AR. There is a state of the art that is missing, and although it will be developed by 'other companies' it is mainly a resource that AR developers need. That is why the factor resources is hindering the development of AR in the innovation phase and that is also why the factor 'other companies' is not hindering developments. There are no other additional problems reported either, meaning that the supply of the HUD technology had the greatest influence here, providing lots of knowledge and hardware for optical see-through displays. This factor has helped the development of AR in the innovation phase.

6.2.3.8. Institutions

Universities, other research organizations and the army. Together they sum up almost the entire field of AR during its innovation phase. Apart from Sutherland's thanks to Stewart Ogden for keeping the pressures of paperwork low (Sutherland, 1968), there is nothing that suggest the contrary: institutions greatly helped the development of AR in the innovation phase.

The influence of institutions can be broader than the examples provided here, but no evidence was found regarding phenomena like laws, rules, policies, and habits. The expected cause for this lack of information is simply that those phenomena either did not have any influence at this development stage or that they are deemed too unimportant to be reported.

6.2.3.9. Broad environment

Computers, displays, mobile devices, GPS. They are all technologies that greatly change societies. That change is a broad change, a landscape development if you will. But it they are also enabling or even complementary products to AR, which is why it has been discussed on other factors above. From the perspective of AR there is one observation regarding those technologies on the broad environment and that is the development of anything digital. The first mobile phone was introduced in 1973, the first laptop in 1982, and the first smartphone in 1993 (Arth et al., 2015). Smaller devices were introduced as well, like the walkman in 1979 and the digital watches and PDAs (Personal Digital Assistant) around that same time (Van Krevelen and Poelman, 2010). All of those developments helped each other, it helped to familiarize the world with digital devices for companies and consumers. A concrete example of this is at Boeing. Introducing AR in manufacturing is complex in itself, but even more so when there are no digital objects to project. The Boeing 777 was the first fully digitally modelled aircraft at Boeing (Metz, 2014), making it possible to work on an AR application at all. This helped the development of AR in the innovation phase.

6.2.4. Concluding remarks

To answer the research question (Figure 25): the factors that helped development efforts of Augmented Reality are Expectations, Strategy, Knowledge, Demand, Other Companies, Institutions, and Broad Environment. The factor that both helped and hindered the development of Augmented Reality is the Product. The factor that hindered the development of Augmented Reality is Resources. Computers are an enabling technology for Augmented Reality, making them a form of physical resource. However, this type of resource was not included in the description of the factors in the model, this is a suggestion for improvement of the conceptual model. The factor Product also has a special role, the product did not hold developments of AR back in the innovation phase, but its performance was still constraining, leading the maximum speed of development of the innovation system.

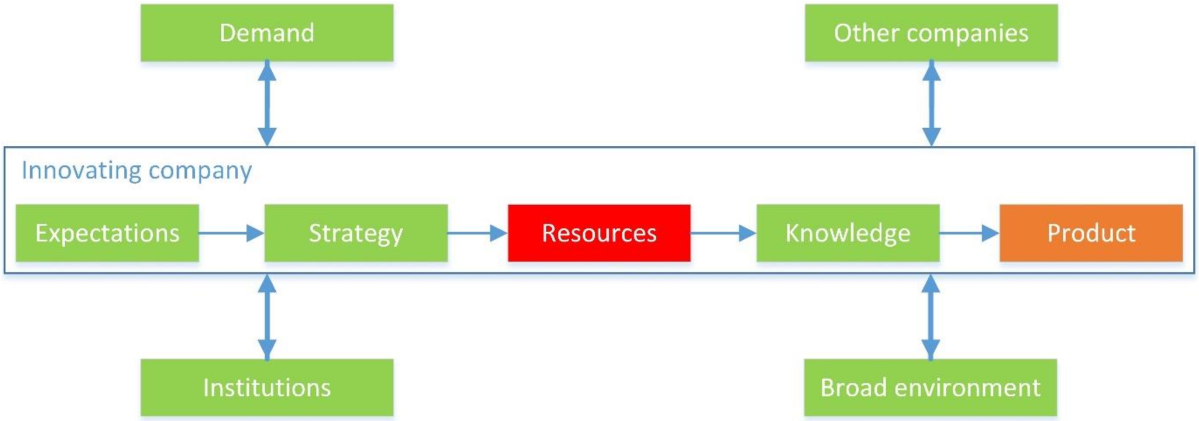


Figure 25 - Factors that help and hinder development efforts of Augmented Reality in the innovation phase.

The first observation is that the innovation phase is different from the innovation phase as it was reported before (Ortt & Dees, 2018). The end of the innovation phase was reported in 1994, with Boeing's developments, led by Caudell. However, those efforts turn out to be performed in 1992 instead of 1994 (Caudell & Mizell, 1992), and they were an experiment which failed (Metz, 1994). However, the new end of the innovation phase, Julie Martin's theatre performance 'Dancing in Cyberspace' also took place in 1994 (European Theatre Lab, 2017; Peddie, 2017), leaving that claim and the total duration of the innovation phase intact.

Some confusion arose during the making of the work-report over technologies that AR needs to be able to work at all. They are enabling technologies, like computers (with sufficient processing power), displays, mobile devices, GPS, and possibly more. Those technologies are a kind of technical resource, they are part of the AR system and therefore part of the product, they are developed by other companies, and together they form this digitalization shift in the broad environment. They where are they included, where are they excluded, and why? A computer with sufficient processing power to support an AR system is an enabling technology. It is developed by other companies, and it is supplied to those who buy it for developing AR systems and/or applications. While all of this is true, it does not make any company help or hinder the development of AR. There is a state of the art that is missing, and although it will be developed by 'other companies' it is mainly a resource that AR developers need. That those technologies, combined with other technologies, are part of a general change towards digital technologies is a different effect. This is a slow, but large change in the landscape environment, if you will. While the state of the art had not progressed far enough to support the full potential of AR, the collective change towards digital technologies did help AR. The problem with enabling technologies was therefore solved by including it in the two factor Resources and Broad Environment.

There was an openness towards new, undiscovered factors for the innovation phase throughout the case study. New nuances and improvement of found factors were plentiful, but only one entirely new factor was found. A natural step in describing the innovation phase is listing all involved actors, all individuals, companies, joint ventures, research organizations, other organizations, governments. Most of those actors fit in a specific factor already, but the innovators themselves have no such place. However, the five central factors form a process that is owned by the 'Innovating Company'. Turning that title into a factor creates a factor where the innovators themselves are described. The newly proposed factor does, however, not necessarily contain companies, also individuals or joint ventures can be innovators. Therefore the name of the new factor should be Innovators.

A second observation in the search for new factors was the role of competing technologies. Augmented Reality is closely related to Virtual Reality, but also has the potential to overtake other technologies like the computer keyboard (Krueger et al., 1985). Competing technologies did not become a separate factor in the case study of AR and is also not a suggestion for a new factor for the model. There are two reasons for this exclusion. One is that the competing product is not part of the innovation system of the radically new technology that is analysed. The second is that the competing technology is represented through the interest of Other Companies in the new developments. A radically new technology is not necessarily a threat for incumbent technologies, it can also be an opportunity and different strategies can be used to reduce the threat or make maximum use of the opportunity. It is through the interests and influence of Other Companies and the Broad Environment that competing technologies have their influence on the development efforts of the radically new technology.

Using the current definition of Augmented Reality results in a (hindsight) biased definition of the innovation phase. When a technology's development efforts are analysed with this model, the view of the technology can be profoundly different from what the technology will later become. The transition from precursory technologies into what will later become AR, into what we now call the innovation phase of AR, is a very fluent process. Simply choosing one moment in time when the milestone of invention took place is one way that our definition of AR limits this analysis. Another is that it is easy to miss important developments in parallel. The development of Virtual Reality and Augmented Reality shows parallels and that is why Virtual Reality is mentioned at a number of points in this case study. Still, choosing a modern-day definition for a technology to analyse its innovation phase creates a bias, both in time and in parallel developments.

Many sources in this case study are academical and much is reported on technical developments, very little on anything else. This suggests that there would have been room during this innovation to put more work in the creation of an innovation system. A keen observer would contradict this by pointing at the non-green factors: Resources and Product. The rest of the factors was green, so why would other efforts be required than to secure more funding and improve the product? Because an under-developed innovation system is slower to respond to improvements in the product than an existing and efficient innovation system. For the innovation phase, Product is orange and Resources is red. But if those problems are solved, then which of the factors is the most constraining? Perhaps other factors could have helped more than they did, or they can be prepared and improved to be of more help in a later stage of development efforts.

6.3. Modelling factors for the innovation phase

The two coming paragraphs take what was learned in the case studies, combines that, develops it a step further, and then implements it in the conceptual model, leading to the final model that this research proposes.

6.3.1. Observations and suggestions

Performing two case studies serves the goals of illustrating the application of the conceptual model and of finding problems and/or possible improvements. Both case studies have led to suggestions in their concluding remarks (Table 18).

Using the model for the very first time and applying it to two technologies begs the question whether desired outcomes have been achieved. As paragraph 5.3 already states, the model is aimed at supporting their decision-making process and should be used to steer development efforts in the innovation phase, but the theoretical case studies of this research did not yet go that far. Also sources were predominantly scientific, and not as informal as the Innovator's knowledge of a specific market, although that was sometimes included in scientific publications as well. Accepting those limitations of the case studies, the first use of this model for two cases was rather successful. It provides a way of structuring information and unclarities to which factor some findings belong could be found in the explanation and sub-factors of the factors themselves. That list of factors is invaluable because it defines boundaries, differences and overlaps between factors. The suggestions and problems that follow from the case studies are only smaller remarks, which suggests that the model fits its purpose well. A beautiful overview is given of the innovation phases of both 3D printing and Augmented Reality.

Table 18 - Suggestions and problems from case studies.

Case	Suggestion / problem	Explanation
3D printing and AR	Insufficient information	The available information on Broad Environment is insufficient for a determination of that factor's influence. The available information on Knowledge is low and mainly technical. The influence of institutions can be broader than what was found in both case studies, but no evidence was found regarding phenomena like laws, rules, policies, and habits. The expected cause for this lack of information is simply that those phenomena either do not exist at this development stage or that they are deemed too unimportant to be reported.
3D printing and AR	Bias towards positives	There is a bias in this research towards elements of each factor that helped development. Negatives will not be reported as thoroughly as positives.
3D printing and AR	Bias in the definition	Using a current definition of a technology provides a bias. A technology can be profoundly different today compared to its state in the innovation phase. Another problem is that it is easy to miss important developments that are parallel to the case at hand.
3D printing and AR	New role of factors	The factor Product and Other Companies did not hinder developments, but they did lead the speed of developments.
AR	Interpreting green factors	Does a green factor suggest that it could have not been improved? Which opportunities remain?
3D printing	Look beyond the innovation phase	Using this model to only analyse the innovation phase, misses out on important changes in the innovation system before and after the innovation phase.
AR	Enabling technologies	Some confusion arose during the making of the work-report over technologies that AR needs to be able to work at all.
3D printing and AR	New factor: Innovators	The five central factors are included in the Innovating Company. But there are other innovators as well, like individuals, joint ventures, or perhaps even networks.
3D printing	Development directions	The different development directions are found in between the innovators, not in the factor Other Companies.
3D printing	Other Organizations	Other Companies can include much more than companies. Like banks, funds and investors for money supply for example.
3D printing	Intellectual property	Add intellectual property to Strategy.

The objective of this research is formulated as follows: '*Develop a model of factors that help or hinder development of radically new technologies in the innovation phase.*' How and where is such a model applied? Working out historic cases brings insight to how technologies can be modelled in hindsight. It is a great method to start illustrating and perhaps even proving a model, but the goal, even for historic cases, is to find applications of such a model for today. To find strategies for innovators who work on a radically new technology and who could improve what they are planning to do in the innovation phase of their technology. The optimal outcome would be a model that is applicable during the innovation phase. A model that is used by organizations that are working on such a radically new technology. Is it then a problem that the broad environment could not be determined for the case of 3D printing? When working on a current case for an organization that is in the innovation phase, much more information is available about the context of the technology. Especially the factor Broad Environment, like global economic developments, is generally not reported when describing the history of a technology like 3D printing. But it is general knowledge for decision-makers in a company who are spotting opportunities and threats for their development efforts. The same goes for the factor Knowledge. This factor is hard now, because the fine improvements are too technically detailed for a research that focusses on the entire innovation system of a technology. This problem would not occur when researching a current development and does therefore important for application of the model, but it does not change the model.

A bias towards positives is created when negatives are not reported. Looking back on innovation phases that started in 1968 for AR and 1984 for 3D printing creates a paradox. It is most reliable to only use sources from during or right after the innovation phase. But it is also more reliable to use much information to create a good view of the innovation phase, forcing use to also use much more recent sources. What is left of a complete account of everything that happened is likely to be more biased towards success stories than publications during the innovation phase. Failing inventors, bankruptcy of companies, a failed government project. Not everything ends up written down. This bias becomes smaller when working on a radically new technology that is currently in the innovation phase.

The problem that a definition of a technology creates a bias in the research is directly applicable to this research. But, like argued above, this problem is automatically solved when the model is applied to an innovation phase that is still on-going. There is no bias from what a technology will eventually become when it is still in its innovation phase. The bias does limit the reliability of this research, but it does not decrease the reliability of research that uses the proposed model for on-going development efforts.

In both cases there was the interesting observation that factors can have a role that is different from the roles that were proposed in paragraph 5.1. Some factors do not exactly hinder developments of the technology in the innovation phase, but the factor is still constraining, leading the maximum speed of development of a part of the innovation system. This does not mean that the developments efforts could have gone better or faster for that particular factor, it simply means that the factor forms a limitation. A metaphor is the critical path of a planning: whatever is improved and changed in a planning, there always is a fastest way to perform a sequence of activities. Even an optimised planning cannot make all activities be performed in one day. This observation also has consequences for interpreting green factors, factors that help developments in the innovation phase of the radically new technology. If a factor is green, if a factor is helping developments of a technology, why try to influence it? However, only working on non-green factors is a too limited view. If other factors do indeed form a certain critical path, if there is always a factor that dictates the speed of development, then that does not mean that other factors do not bear important potential. Imagine that the technical development of the Product is the factor dictating the pace of developments, then lobbying with institutions can have incredible pay-off after market introduction. Still, the factor Institutions would be green within this model. This model still requires the researcher to look beyond the innovation phase and interpret finding accordingly.

The need for looking beyond the timewise borders of the innovation became even clearer for the 3D printing case. Patents were filed by almost every innovator in that technology and it provided security for funders and investors that they would see a result, a return. It helped developments in the innovation phase, making the related factors green. The great amount of intellectual property slowed things down in the market adaptation phase. Some observations in the innovation phase can only be explained by taking a wider view.

New technology often depends on prior technologies. The same goes for AR, which depended on see-through displays, on fast computers, and later on mobile devices and GPS as well. Especially the computers were an absolute necessity, AR is impossible without their processing power. Krueger et al. (1985) devised some hardware of their own, but apart from that it is safe to say that AR developments did not include developing computers further to increase their processing power. It really is a different technology with its own innovation system. Its role is also not that of a complementary product. It does not only add value, it wouldn't even work without it. It is not complementary, it is an enabling technology. It is therefore not part of the factor Other Companies: it stands completely aside from the innovation system of 3D printing. And while the computer is incorporated in AR systems, it is not directly part of the Product. It actually is just a Resource at first. A physical, technical resource that is needed to continue developments. That is the conclusion in the case study, and that is also the conclusion for the conceptual model. The factor Resources currently does not contain any mention of such resource in its description. It does contain natural resources, which are also physical, but different from technical resources. To keep this distinction intact, the term 'technical resources' is added to the description of the factor Resources.

A new factor is proposed, although it has already been worked out for both of the cases. The Innovating Company contains the five central factors, it is the process owner of bringing expectations to a product. But the innovator is not necessarily a company, it can also be an individual, a researcher, a research organization, a joint venture, or perhaps even a network. The name is changed to Innovators, and it is also made a factor. Both of the case studies already show a long list of innovators already in their timeline. The Innovators are an implicit part of the model, but that is now made explicit.

The description of the new factor Innovators contains at least some reference to the skills of the Innovator, like Krueger et al., (1985) who made their own hardware, or any of the innovators for that matter, who were all able to combine knowledge from several fields into one new technology. Their (social) network is also important. Sutherland and Evans knew each other from MIT, and founded Evans & Sutherland Computer Corporation in the same year that Sutherland moved closer to Evans again (Peddie, 2017). That would not have happened so fast if they had not known each other yet. Also the team that Innovators work in is important. That sub-factor in itself can be described in many ways, consisting of many factors, but the description of the factor Innovators stops at this level of detail: the team. The team was, for example, important for Sutherland, who writes that the project would have died many times without his team (Sutherland, 1968). Those sub-factors are added to the description of the factor Innovators.

The development directions for a technology into different products was listed under the factor Other Companies. However, it is the Innovator, the process owner who works on the product itself. The factor Other Companies comprises development right around the main technology. The development direction is therefore a matter for the Innovator, and now that that factor is created, the development direction becomes part of the description of the factor Innovator.

But there are more organizations who play a part in the innovation system of an upcoming technology. It is not just the companies who supply, who produce, and who develop complementary products and services. There are also other organizations involved. Suppliers of funds for example, like banks and investment funds, or a research organization that supports an Innovator's development efforts. This is an obvious change to the model: the factor Other Companies is renamed to Other Organizations.

Intellectual property is missing from the factors. Patents report a certain progress in knowledge and institutions enable the possibility of filing patents, but the decision to use that possibility is a strategic decision. Intellectual property is therefore added as a sub-factor to the factor Strategy.

6.3.2. The final model and improved answers to sub-question 3 and the main research question

The conceptual model is changed and improved after the case studies. This is the final model for important factors in the innovation phase of radically new technologies. This is the answer to sub-question 3: *Which factors help or hinder the development of radically new technologies during the innovation phase?* And to the main research question: *How can factors that help or hinder the development of radically new technologies during the innovation phase be modelled?*

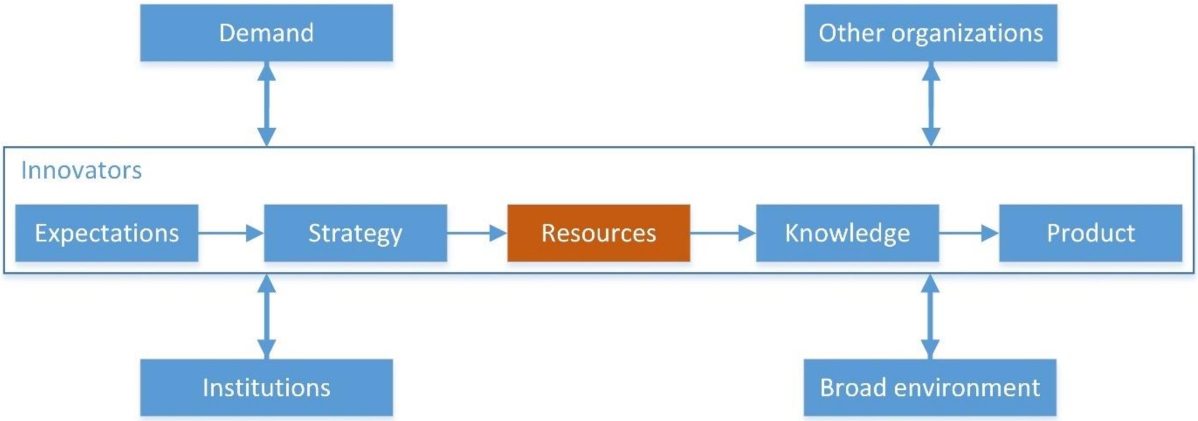


Figure 26 - Model of important factors in the innovation phase.

The centre of the model is formed by a group of five factors. Those five factors go from Expectations to Product. The process of creating a product is supported by all kinds of activities, all kinds of development efforts which all aim to support the new technology, both the product itself and the innovation system that is created around the product. The Innovator is the self-appointed process owner who wants to create the product. The Innovator tries to manage as many influences as possible on those five central factors to maximally improve the technology's chances. There is a special role for the resources, because insufficient focus on this factor results in a complete stop of all development efforts.

The four other factors all have influence on the five central factors. It is up to the Innovators to increase help to the five central factors and to decrease any problems. Examples are to use demonstrations to increase expectations, to secure funding, or to find developers of complementary products. Problems to solve are dealing with a complete lack of demand for the technology, with laws that prohibit the product from commercialization, or with an economic recession.

What does an arrow mean? The arrows do not constitute a causal effect, nor do they represent a fixed, exclusive relationship between factors. The meaning of the arrows very much relates back to the definition of the factors: notions that give understanding of what potentially hinders and helps development and diffusion of a radically new technology. The arrows show a relation in which one factors hinders or helps fulfilment of another factor, while leaving room for many more arrows between the factors in the model or even new factors that are especially important to a specific case. The five central factors form a process of which the Innovator is the process owner. Those factors form a row of consecutive factors, a route from expectations until a product. It is an almost chronological order, with the exception that many more relations exist than the ones pointed out with an arrow. You could even say that the arrows from Expectations until Product show an ambition, a desired direction. This process is influenced by the four other factors, but that influence also goes the other way. New developments have repercussions for other actors and for the broad environment. That is why the arrows to the four outer factors go in to directions.

Each factor can hinder or help the development efforts of the radically new technology. One special role are factors that do not actively hinder the developments, but still dictate its pace by being the 'slowest' factor of all. A product that is not good enough can stop an Innovator from commercializing it, while the production system and the demand are all open to it. All factors contain many levels of detail. The factors of this model can be split up in more detailed factors, which can also be split up to achieve further detail. This model goes one level of detail deeper starting from the factors in Figure 26. The factors and their sub-factors are explained below in Table 19.

Table 19 - List of important factors in the innovation phase.

Factor	**Explanation**
Innovators	The Innovator can be a **company**, an **individual**, a **researcher**, a **research organization**, a **joint venture**, or a **network**. The Innovator possesses certain **skills**, a certain **(social) network**, and work is often with a specific **team**. A new technology faces **little competition in early stages** in most markets because of different **development directions**.
Expectations	Having and creating **high expectations** creates movement and willingness to change. **Sharing enthusiasm** and **making promises** should help to overcome **reluctance to change**.
Strategy	Each organization has its **organizational culture and values** and **firm-specific techniques**. The **suppliers**, the **production system** and suppliers of **complementary products and services** are either sourced inside the company or through other companies. **Top-management support** to the developments is vital and steers strategic decisions that surround the innovation: deciding on **secrecy**, **planning** of efforts, fulfilling different **roles** around the innovation, protection of **intellectual property**, getting the word out through **marketing**, and establishing the **organizational structure** through **collaborations** when needed.
Resources	Resources are needed for **development efforts** and for **changing the market**. This can take **natural resources**, **technical resources, human resources**, and **financial resources**. A particular challenge is to cross the **Valley of Death**.
Knowledge	**Knowledge of the technology** helps further development, **knowledge of the application** helps reaching the market, and **knowledge of the market** helps creating a path of change in the market. Innovations start with a **dependency on research**: **supply and demand of researchers and research funds** is important, which is often **partly funded by a government**. **High risk of the research leads to collaborations** to spread the risk of failure.
Product	The **characteristics of the technology** themselves determine much of the needed development efforts. There is a **dependency on development** to **increase product performance** and **decrease the (future) product price**.
Institutions	Institutions give support through providing **subsidies**, **network**, and **pilot projects** and this can be found on **local, regional, national and international** level. The **need**

	for a technology is not always communicated clearly. **Laws and regulations** can both help or hamper developments.
Other organizations	There is a status quo, a **supply of incumbent technology**. Change of the market results either in **harm, no effect, or opportunity** for incumbent organizations. The Innovator starts looking for **funding**, for **suppliers**, for a **production system**, and for suppliers of **complementary products and services**.
Demand	There is a **status quo**, changing that requires overcoming a **reluctance to change** and **switching costs**. A prerequisite for that change is having the **knowledge** to understand the (potential) change.
Broad environment	There are processes outside the Innovator's reach, that do define the environment of the innovation: **macro-economic aspects**, **sociocultural aspects** and **accidents, events, and undesirable effects of the technology**.

This model is a tool for innovators who work on a radically new technology in the innovation phase. it lists the most important factors and describes which sub-factors can be used to describe them. The Innovator keeps development efforts going, keeps resources from running out, and brings a technology from expectation to product with the help of actors around him, thus building the new innovation system that the radically new technology needs. This model points innovators to their role as process owners in a larger environment than just a product development product. The model is aimed at their decision-making process and is to be used to steer development efforts in the innovation phase. For that to happen, an innovator must first be aware that the new idea concerns a radically new technology and not just an incremental innovation. This realization must lead to the understanding that chances of survival of the idea are small and to a desire to manage the small chance of success. That is the point where this model comes in. with the use of any available information source, both formal and informal, the innovator maps opportunities and problems, factors that will help or hinder his development goals. Preferably, such an analysis is combined with an understanding of the dynamics between factors. This analysis serves as a basis for decision-making. For making use of opportunities and for solving problems.

7. Conclusions

All observations, ideas, and conclusions come together to answer the questions that were asked at the beginning. As introduced at the start of the research, the research questions are answered from the perspective of the problem owner of challenges in the innovation phase: the company that develops a product based on a radically new technology.

Sub-question 1. What is the role of the innovation phase in innovation models?

The innovation phase is the period from invention of a radically new technology and lasts until the first market introduction. Two phases follow after the innovation phase: the market adaptation phase starts at commercialization and lasts until large-scale diffusion – the mass market – is reached, the market stabilization phase starts at large-scale diffusion and ends when the technology is substituted by another technology.

The importance of the conditions for large-scale diffusion during the innovation phase was discussed and is reflected upon when working towards a model for the innovation phase. A condition that is important for reaching large-scale diffusion does not necessarily imply importance of that condition during the innovation phase. The conditions for large-scale diffusion showed a number of factors concerning the innovation itself, like product performance and product price. A number of factors concerns the market environment of the innovation, like customers and suppliers. The company perspective has an implicit place in some factors, but is generally less represented than the innovation and its market. A company culture and values, for example, can have a large influence on its effectiveness and efficiency in working on a technology. Apparently, effectiveness and efficiency is assumed for the market adaptation phase, but it cannot be assumed for the innovation phase, with a low number of organizations working on a technology. The role of the company in the innovation phase and how this role is represented in the factors is therefore reviewed in the development of the conceptual framework. Conditions for large-scale diffusion can influence each other in many different ways, with direct and indirect influences and positive and negative feedback loops. Some basic idea about the most important dynamics between the conditions leads to increased insight and to ways to influence those conditions. The same logic applies to the innovation phase, where some basic dynamics between factors can enable quick insight in characteristics of a specific case.

Strategic Niche Management adds more to the market adaptation phase than to the innovation phase. Their most important notion is that of technological and market niches, which are instrumental in the progression of the technology. The creation of niches starts before commercialization, and therefore in the innovation phase, and the factors in becoming a sociotechnical regime show similarities with the conditions for large-scale diffusion. There are also differences between SNM and the conditions for large-scale diffusion. SNM's technology is split in the conditions product performance and product price, while SNM's culture and symbolic meaning are combined in the conditions sociocultural aspects. There are also more subtle differences. Industry structure and network formation have an overlap, but arguably both factors have parts that are not described in the other factor.

The trial-and-error learning that is observed in many of the cases of the Minnesota Studies leads to the suggestion to continuously monitor the factors in the innovations phase. Continuously monitoring factors is seen as useful for predicting and finding problems in the development and diffusion of the innovation of which an organization is working. It may also present opportunities in solving the problem. The overlap between the innovation phase and the adaptation phase, that becomes explicit through the model of the Minnesota Studies, can result in broader applicability of factors that were designed for one specific phase. In this case, the potential applicability of the conditions for large-scale diffusion to the factors in the innovation phase.

The Fuzzy Front End shows relevance to more than just the innovation phase: each phase contains projects and all projects have a fuzzy beginning. It could therefore be that factors in the innovation that link to the FFE are also relevant in later phases, but in a lower degree. The opposite is also true: factors that relate to a phenomenon that is important in a later phase can also be relevant to the innovation phase to some extent. Even if the same factors are important in different phases, the emphasis on the factors or the roles of the factors can still differ, which is an insight that helps the conceptual framework development.

The innovation phase is an inherently chaotic phase. Any step or factor that is described needs the nuance of deep uncertainty. The project that realizes the transition from a technology to a product is planned in steps, but needs to adapt continuously. The project depends on unexpected ideas and the incidental meetings of problems and solutions, a model for success does not exist and cannot be created. There are specific subjects that often require attention, recurring problems or opportunities that many technologies meet. Finding such subjects requires a deeper knowledge of the innovation phase and its inner workings.

Sub-question 2. What are characteristics of the innovation phase?

Going deeper into the innovation phase brings up all sorts of important elements. Actors, factors, mechanisms, dynamics, and other notable observations and propositions, many of them from different perspectives and from a different unit of analysis. Structure is provided by discerning four levels: project, company, market environment, and market creation and emergence.

At the project-level, most topics that come up concern the start of a project and the conditions around it that shape the project. It starts from an opportunity and expectations that fuel the start of the projects and continues to proliferation and selection of ideas, and the planning of the project in different roles in and around a project team. The actual content of the project is mentioned shortly as technical refinement that should lead to meeting user needs (better) and decreasing the price.

The place of such a project in a company is still fuelled by expectations and subsequently by top-management support. Expectations are created and nurtured, and used for giving the project a place in strategic directions and ensuring the project ‘gets what it needs’. Examples are resources, skills, collaborations if beneficial, and a fitting organizational structure. Risks are high and therefore managed continually through accepting the risk, or attempting to lower the risk. Lowering risk is possible through sharing it through collaboration, but finding organizations that wish to collaborate on such a risky technology is not easy. The support of a company to a development project is also influenced by the dependency on research and development activities, research is often necessary to enable further developments. And last, but maybe most important for keeping a project going, are the financial resources. The search for capital is a continuous one and the Valley of Death between fundamental research and commercialization is hard to cross.

The market environment then includes all forces outside the innovating company. A government and the regulatory authorities that carry the government’s mandate carry the power both to hamper and to support developments of the radically new technology at hand. Subsidies, networking, and pilot projects can support developments, where laws and regulations can create problems. Then again, solving those barriers is another possible form of support. Research was found to be important to the company, and now the strategic aspects around research come into view: supply and demand of researchers and research funds are the central topic, influenced by the government that (partly) finances the research institutes. Other organizations can go two ways. Change leads to risk and change leads to opportunities. In the early stages of development, little competition is found. Users are in a status quo and do not have the knowledge of the technology unless it is brought to them. Knowledge of the existence of a technology in itself is not enough for switching to a new technology. Some convincing is necessary, there must be an advantage and switching costs must be overcome.

But a market does not exist for a technology that is new to the world. The project-, company-, and market-level provided static insights of how developments of a radically new technology can be helped or hindered. Market creation deals with characteristics of creation of a new market, which is less static in nature. Market creation aims to influence and create the three levels. In the search for how a market is created or how it emerges, resources that are needed for realising change in an existing market are not described. Competition is unclear at the start. Not every organization tries to develop a product from the radically new technology and the ones that do will not necessarily go in the same development direction. The closer the technology comes to an actual application, the more clear competition becomes. What an organization can do, which processes are started to create a new market, comes mainly from the field of SNM. They suggest three processes: coupling of expectations, articulation processes, and network formation. But what has to change? What are the elements that must be worked on? The technology must increase performance and decrease price, the market needs an entirely new supply and demand side with new combinations of actors and alliances, possible new infrastructures, new procedures and complementary product and services that add value to the product.

The upcoming of a radically new technology means great challenges at each part that was analysed. The project-level and company-level are vulnerable, the market-level and market creation are slow and hard to influence, and yet they are also vital. If one thing has become clear, it would be that every level is of vital importance to the survival of development efforts, but also that there are many ways to proceed with development efforts at each level. There is no one-size-fits-all model or strategy possible, there is too much variation in the technologies, their applications, the markets they influence, the actors in those markets, and in the way that developments can be helped.

Sub-question 3. Which factors help or hinder the development of radically new technologies during the innovation phase?

a) Based on theory.

b) Based on case studies.

The factors that are important during the innovation phase are defined as **notions that give understanding of what potentially hinders and helps development and diffusion of a radically new technology**. Such a factor can be different between phases. Factors can assume different roles, have a different level of detail, be relevant in one phase but not in another, or be combined with or split from other factors (see paragraph 5.1). The answer to this research question is not found in the conditions for large-scale diffusion. Factors in the innovation phase and conditions for large-scale diffusion are neither the entirely the same, nor completely different: the market adaptation phase and the innovation phase are different from each other, but both still contain developments of one and the same radically new technology.

Table 20 - Important factors in the innovation phase.

Factor	**Explanation**
Innovators	The Innovator can be a **company**, an **individual**, a **researcher**, a **research organization**, a **joint venture**, or a **network**. The Innovator possesses certain **skills**, a certain **(social) network**, and work is often with a specific **team**. A new technology faces **little competition in early stages** in most markets because of different **development directions**.

Expectations	Having and creating **high expectations** creates movement and willingness to change. **Sharing enthusiasm** and **making promises** should help to overcome **reluctance to change**.
Strategy	Each organization has its **organizational culture and values** and **firm-specific techniques**. The **suppliers**, the **production system** and suppliers of **complementary products and services** are either sourced inside the company or through other companies. **Top-management support** to the developments is vital and steers strategic decisions that surround the innovation: deciding on **secrecy**, **planning** of efforts, fulfilling different **roles** around the innovation, protection of **intellectual property**, getting the word out through **marketing**, and establishing the **organizational structure** through **collaborations** when needed.
Resources	Resources are needed for **development efforts** and for **changing the market**. This can take **natural resources**, **technical resources, human resources**, and **financial resources**. A particular challenge is to cross the **Valley of Death**.
Knowledge	**Knowledge of the technology** helps further development, **knowledge of the application** helps reaching the market, and **knowledge of the market** helps creating a path of change in the market. Innovations start with a **dependency on research**: **supply and demand of researchers and research funds** is important, which is often **partly funded by a government**. **High risk of the research leads to collaborations** to spread the risk of failure.
Product	The **characteristics of the technology** themselves determine much of the needed development efforts. There is a **dependency on development** to **increase product performance** and **decrease the (future) product price**.
Institutions	Institutions give support through providing **subsidies**, **network**, and **pilot projects** and this can be found at **local, regional, national and international** level. The **need for a technology** is not always communicated clearly. **Laws and regulations** can both help or hamper developments.
Other Organizations	There is a status quo, a **supply of incumbent technology**. Change of the market results either in **harm, no effect, or opportunity** for incumbent organizations. The Innovator starts looking for **funding**, for **suppliers**, for a **production system**, and for suppliers of **complementary products and services**.
Demand	There is a **status quo**, changing that requires overcoming a **reluctance to change** and **switching costs**. A prerequisite for that change is having the **knowledge** to understand the (potential) change.
Broad Environment	There are processes outside the Innovator's reach, that do define the environment of the innovation: **macro-economic aspects**, **sociocultural aspects** and **accidents, events, and undesirable effects of the technology**.

There are ten important factors in the innovation phase (Table 20): Innovators, Expectations, Strategy, Resources, Knowledge, Product, Institutions, Other Organizations, Demand, and Broad Environment. Each factor is explained through the sub-factors that it contains. Splitting factors in more detailed elements eventually goes on until the specific actions that each individual takes in his or her role in the innovation phase. The list of important factors is a balance between generalizability and specificity, between factors being always applicable and factors giving a sense of strategic direction to development efforts.

Main research question. How can factors that help or hinder the development of radically new technologies during the innovation phase be modelled?

An Innovator is not just an inventor. An Innovator is the process owner of expectations leading to some form of action, that strategy makes resources available for increasing knowledge and incorporating that knowledge in a product, for using new knowledge to make the transition from a technology to a product.

Although the Innovators are the owners of this process, they are not the only ones that have influence on the five central factors. Other organizations, institutions, demand, and the broad environment in general. They all stand to gain or to lose position because of the upcoming radically new technology. They will seek to fulfil their interests by helping or hampering each of the five central factors. This is a two-way relation: they will try to influence the radically new technology to their advantage, and the technology will influence them. For example, demand must often be created, keeping in mind that there are market-pull technologies like blockchain. Customers can help by showing commercial interest, or hamper by opposing development efforts. The innovation system that is created through those interactions has a place in a much larger world, the broad environment. A speech from an influential president or an economic recession, both are outside the influence of the Innovators while there is a profound influence on development efforts.

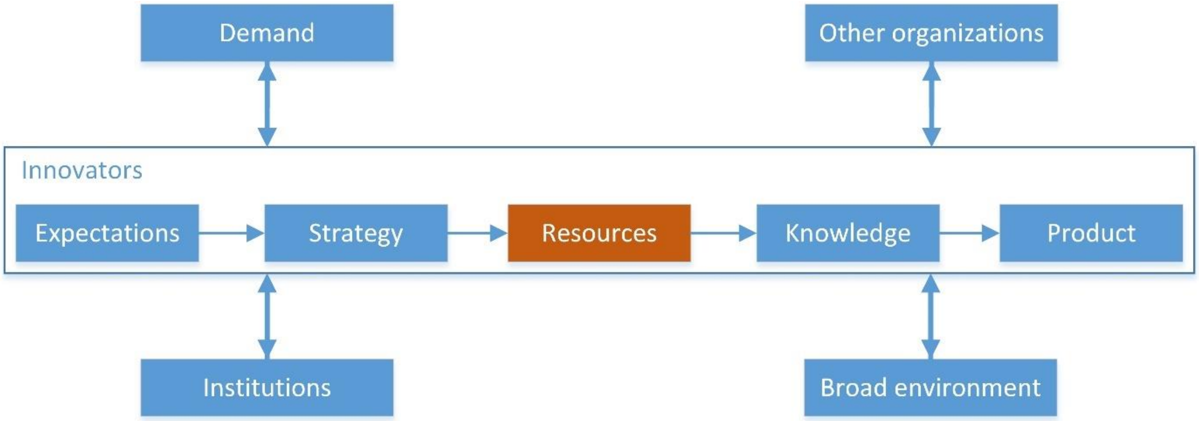


Figure 27 - Model of important factors in the innovation phase.

The creation of a new innovation system is the task of the Innovator. But isn't such a task generally too large for one actor? Yes, that is why the innovator tries to increase his own expectations and those every other actor. The factors of which the innovator is the process owner do not all belong to the innovator. Every actor has expectations, even if the expectation is that the radically new technology will never be commercialized. The same goes for resources. The resources in the model are not just the innovator's resources, they are the resources of every actor that contributes to further developments. But it is the innovator who convinces actors to join in the developments through allocation of resources. The resources do not all belong to the innovator, but the process around the resources does. Owning the process consists of development efforts that entail both working towards a product and improving the necessary factors before and around the product. One important focus of the development efforts is to ensure sufficient resources for its own survival.

8. Discussion and recommendations

The end reflects on the start and on the entire process, it also looks forward. The discussion starts with a review of the research methodology, questioning if the right decisions and assumptions were made in the research design, questioning whether the fit of the methodology throughout the research, and suggesting improvements for all identified struggles. The second part looks forward and gives suggestions for future endeavours that improve research efforts in this field.

8.1. Reflection on the research

This paragraph goes back to the beginning, questioning the steps that this research made. Showing problems that occurred and suggesting ways to solve those problems.

8.1.1. Definition of the radically new technology

Defining a technology on the basis of functionality, technical principle, and components is thorough. It makes clear what is included and excluded, what is part of the technology, what is complementary or optional, and it sheds light on which developments stem from the same radically new technology. The innovation phase, however, is inherently chaotic and unpredictable. Innovators come and innovators go. Developments start and developments stop. Development directions and applications are tried and are cancelled. The technology changes continuously and thoroughly throughout the innovation phase. A radically new technology is not easily caught in a strict definition while it is still developing. For example, Bitcoin was started as a cryptocurrency, but its underlying blockchain technology proves to have much broader applications (Ortt & Dees, 2018). Also, a pattern of development and diffusion is viewed as an isolated pattern, while patterns actually develop in parallel. Many technologies are developed at the same time and their development have an influence on each other. For an example we only have to think back to the parallel between Augmented Reality and Virtual Reality of the case study in this report.

Observing the innovation phase when it has stopped, while using the current product as the definition, creates a bias: a hindsight bias. The exclusion of the heads-up display and Virtual Reality from the case study of Augmented Reality creates a whole other vision on its entire pattern of development and diffusion. The first practical application of the heads-up display was a long time before 1968 and Virtual Reality was partly developed in parallel with Augmented Reality during the innovation phase. Such exclusions create an unrealistic black and white picture of the world. Of course, the goal of the model of the innovation phase is to provide guidance *during* the innovation phase, not after. The case studies themselves are historic cases, not current cases, because although developments are still ongoing for both technologies, the innovation phases have ended decades ago. Using the model for an on-going development at least partly solves the problem of the bias in the definition. But the historic case studies of this research are affected by the bias in the definition and this limits the reliability of these case studies, which in turn weakens the proof of the model. If a bias cannot be prevented, one should look for ways to reduce it. **Working with a hindsight bias can be done in at least eight ways.**

1. First is perhaps the most obvious solution: do not look back, but **prevent the bias entirely by using a current case**. The assumption that a hindsight bias cannot be prevented is an assumption that can be proven wrong in some cases.
2. **Predominantly use sources that were published during the innovation phase itself**. Reports and analyses from later times can already contain a hindsight bias.
3. **Widen the scope of the research**. By researching a wider context than the object of research, more information becomes available. The challenge is to expand the research in a way that delivers new insights, without costing too much extra time on subjects that add very little or nothing at all.

4. **Consider what sources do not report on**. The model of this research proposes a set of factors, following such a model makes the researcher consider factors that otherwise would not have been looked for.
5. **Reflect on the causal relations that are proposed**. Especially when it is not possible to only use sources that were published during the innovation phase, not all conclusions have to be correct, or perhaps they are correct while still missing some extra context.
6. **Explore topics that can lead to contradiction of claims that were already found**. In this research, finding out more about the competing technology Virtual Reality can create more insight in factors that shaped developments of Augmented Reality as well, as a result of similarities between the two technologies.
7. If a hindsight bias exists, and therefore some uncertainty around results and conclusions remains, an option is to **perform more (case) studies to prove the hypothesis that is proposed**. The uncertainty may remain, but reliability of the research rises when multiple case studies lead to the same conclusions.
8. Once all options have been exhausted or rejected and still a hindsight bias exists (or may exist, it is not necessarily known), the **final way to deal with the bias is to account for it in the results**. Make conclusions more careful, less strong, and less generalized.

Those eight strategies are ways to work with a (possible) hindsight bias. It gives ideas on directions of thought which can either reduce the hindsight bias or at least be included in considerations in research designs. Accepting an explicit limitation to reliability or validity of research is better than leaving it implicit.

8.1.2. Definition of the innovation phase

The unit of analysis is the technology, and a clear definition of the technology leads to one unambiguous definition of the innovation phase. This prevents problems with the beginning and end of the innovation phase and creates a clear picture. However, the model is designed for providing help in the innovation phase, perhaps eventually for formulating and improving strategies in the innovation phase, which is something that happens at another level. Most often the company-level, but in some cases also at an individual or network level. Combine that with the criticism on the definition of the previous paragraph and questions rise about the end of the innovation phase as well. The innovation phase ends at the moment of the first market introduction. While that makes for a clear theoretical milestone, practice needs a more refined view. What if innovators are unaware of each other’s activities? And if they are aware of each other, how much influence does a market introduction in one country have on another? And is that influence positive or negative? What about a market introduction of a product that solves an entirely different problem, but is based on the same technology the innovator is developing? And, back to the model, should strategies in all of those cases be based on the factors of the innovation phase or on the conditions for large-scale diffusion? Many questions arise, and none of those have been answered. This research does not touch upon those questions because it is a first exploration that did not go that far and because the unit of analysis is the technology. When thinking towards a company and its strategies, those questions resurface. This point is revisited in the suggestions for future research.

8.1.3. Reflections on the model for the innovation phase

A model for the innovation phase aims to structure reality in a way that problems and opportunities become clear. The problem with this model is that it is impossible to prove its validity in a strictly logical sense. It is impossible to rightly state that the model is the best way to model the innovation phase and that it applies to all radically new technologies. It is also impossible to prove that the set of factors is an exhaustive and complete set. One counterexample disproves such claims. Then, how is such a model made reliable? This research has used a range of different angles to look at this problem and as it progressed, collected several **ways of making a model that is based on factors more plausible, and more likely to be correct and complete**:

1. Comparison with other models.
   The model of the innovation phase is better than other models. The first reason for this is that the model is simply the first model of the innovation phase: the only model that fits the first phase in the pattern of development and diffusion. The second reason is that other perspectives have been used from literature to distil different views of activities in the innovation phase. Mostly complementary and some contradictory views were found, but more importantly, incompleteness was found in most models. Combining the different views and enriching them with case studies makes this model the best current fit for the innovation phase, and makes the model more plausible to be correct.
2. The model is useful for case studies.
   While combining models is largely based on reasoning, illustration works best through simply using the model for what is was designed: showing how factors help and hamper development efforts of a technology in the innovation phase. The two case studies in this research form the second type of proof.
3. The factors can be categorized.
   Layers that exist in an innovation system (thinking back on the multi-level perspective from SNM) must be found in the model for the innovation in some shape or form. Insights from literature were divided in the project-, company-, and market-level and market creation, and that serves two purposes. It prevents different factors from different models with different perspectives to be combined too easily, and it strengthens the basis of the model for the innovation phase.
4. Use a similar model as benchmark.
   The model for the innovation phase is compared with the conditions for large-scale diffusion. Modelling the innovation phase is complex, but continuous comparison with the conditions for large-scale diffusion creates a kind of benchmark. The conditions for large-scale diffusion are much more established than this newly proposed model for the innovation phase. If the two still make sense in comparison to each other, than that increases plausibility. It is an external validation.

This methodology emerged throughout the research and can be used for future research as well. Pushing and pulling the shape of the model for the innovation phase from four different sides still cannot prove it in a strictly logical sense. But if it looks like a duck, swims like a duck, and quacks like a duck… Chances are, it’s a duck!

However, one downside must be mentioned. The first point of the methodology above, creating a model by combining insights from several other models that touch upon the subject of research, creates a problem. As repeated often in all pages that precede this one, the innovation phase is chaotic, unstructured, unplannable, and more of such terms that makes life hard for a researcher. Especially problems and failures have a profound influence on achieving success or not. Combining insights about the innovation phase from different models is basically using theory that tried to find structure, and use those to find more commonalities and structure. Actionable elements and ways to success receive more attention than completely unexpected exception. Understanding of things that can go wrong is lacking. Describing the positive side gives options on what can be done, but the negative side makes clear which option is the best.

Another point of reflection are expectations of actors. The model for the innovation phase puts the factor Expectations in a central box, within the process that is owned and managed mainly by the innovator. That does not mean that the factor only concerns the innovator's expectations. The factor concerns the expectations of all actors with some interest in the technology, even if it is a non-existing expectation with an actor that does not yet realize the potential influence of that technology. **This research assumes that the innovator is the main manager of expectations surrounding a radically new technology.** It is the innovator who tries to really push the technology and to make other organizations join those efforts. Even in the case of market pull, where users face problems that they want solved, the innovator becomes the primary manager of expectations. The innovators assigns himself as problem owner and with that, tries to take control of the expectations of everyone in the innovation system. An important note is that being the manager of expectations does not mean that the innovator also has the largest influence. Nor is the innovator necessarily the actor with the highest interest in the technology. The innovator is simply does the most effort to get everybody's expectations aligned.

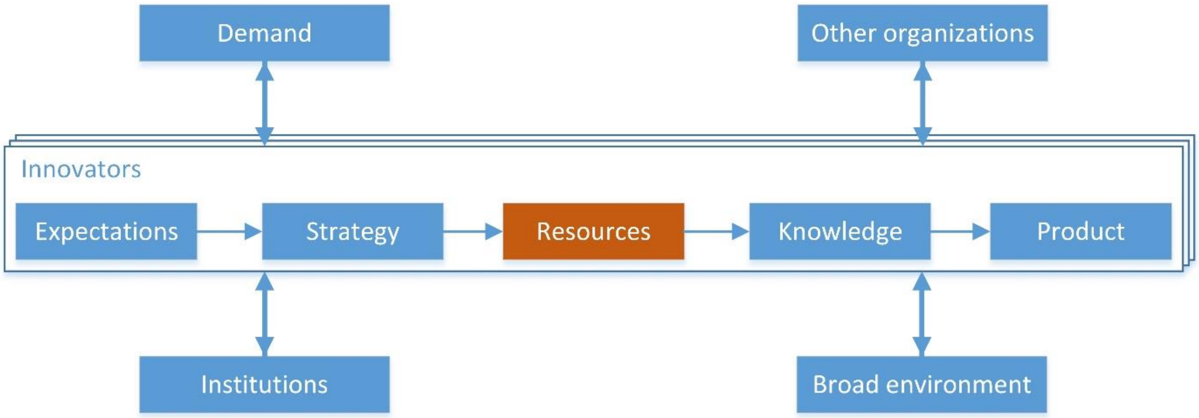


Figure 28 - Adding parallel efforts of different innovators to the model for the innovation phase.

In hindsight, there is not a group of innovators that manages the process from expectations until product. There are multiple innovators who all manage their own process from expectations until product. Those processes can be isolated from each other, for example because of geographic spread, because of different applications for the same technology, or because of different development directions of the same technology. The processes can also become linked and unlinked over time, when innovators start and stop collaborations and joint efforts. That is not visible in the current model, the suggestions is to **make simultaneous and possibly unconnected efforts of different innovators visible in the model for the innovation phase**. An idea and first impression of this is visible in Figure 28.

8.2. Managerial implications

The chaotic and unpredictable nature of the innovation phase makes it hard, if not impossible, to make a dynamic model of that phase. Even the static model that is proposed in this research posed quite the challenge. Working on a radically new technology is not a linear and stepwise endeavour. A model cannot point to specific tasks in predefined succession. The hope is to point managers and other decision-makers that are involved in innovation processes to important factors, and to provide realization as to which other factors surround the factor that needs changing.

The classical view of an inventor that creates machine after machine is not found in this research. Innovators are process owners. The first implication of this position is just a technological vision is insufficient for creation of a new innovation system. Resources are crucial, they are key to survival of development efforts. The role of marketing in the innovation phase must not be underestimated.

All of this starts with the realisation of the innovator he/she/it (or they) is working on a radically new technology and that there are different phases in that work. Understanding the pattern of development and diffusion and determination of the position in that pattern is a first step. Then the position of the innovator in that phase is described through guidance by the important factors in the innovation phase. As suggestions for future research also imply, the innovator must make the step from helping and hampering factors towards strategies to help development efforts around the radically new technology.

The static nature of the model makes continuous updates necessary as factors change and progress. The closer to commercialization, the more important the conditions for large-scale diffusion become. The milestone of commercialization is not an immediate shift. Rather, the transition from the innovation phase to the market adaptation phase is more subtle, more of a grey area than black and white.

8.3. Future research

Looking forward, there are suggestions to improve research that is similar to this by improving the case studies and using more fields of research as literature. There are also suggestions for entirely new research, bringing this research and other research further.

8.3.1. Real-time case studies and actual decision-making

A most obvious suggestion is to perform more case studies and thus increase the reliability (or plausibility actually, assuming the criticism above) of the model for the innovation phase. A more important note is how new case studies can enrich the current work. A historic case study like the ones performed in this research misses out on much data. A profound part of the insights is expected to be lost through reliance on written accounts only. Knowledge about the upcoming innovation system is not necessarily made explicit. Many influences and dynamics are subject to continuous change and are either not formalized and written down, or are reported but can have changed both before and after the moment of creating the record. An easy way out is to use data from longitudinal case studies like the Minnesota Innovation Research Program (see paragraph 3.5). An even better option is to use the model for what it is designed: for on-going developments of a radically new technology that is currently in its innovation phase. Such a **real-time case study** can make use of much more data than the written accounts that were used now: examples are news articles that only loosely connect to the new technology and thus explain more about the industry that the new technology creates or replaces, or first-hand knowledge of innovators themselves. Taking it one step further, is using the model for actual decision-making, using the model for formulation and implementation of strategies is suggested later in this chapter. **Using the model** in an organization gives the ultimate feedback, especially when the outcomes and effect of decisions based on the model are reviewed to improve it. Research should take a step to help use of the model in practice by suggesting strategies. But before diving in that topic, first a few ways to improve the theoretical basis.

8.3.2. Other valuable literature

There are three suggestions that concern the selection of literature. The field of Science and Technology Studies (STS) operates on the edge of technology and society. The field is expected to contain at least some notions about the timeframe that is defined as the innovation phase in the pattern of development and diffusion. The small gap between this research and STS is one of the handbooks of STS (Hackett et al., 2007) in which Malerba's work from 2002 and 2004 is used, just like it is in this research. The role of marketing in the innovation phase was very small in the selected literature of the two literature reviews. All literature that was analysed in the literature reviews should include and review the role of marketing in pre-commercialization stages. Because it has a role, a rather important role if we look at work from researchers like Urban and Hauser (1993) and Moenaert and Souder (1990). Urban and Hauser integrate marketing, R&D, production engineering, and financial aspects for all development phases of new product design. Moenaert and Souder describe how marketing and R&D efforts work together for technologically new products. A third area where theory was lacking is that of market creation and market emergence. Most literature simply describes the place of an upcoming technology in an existing market and never stops to consider that a new market and a new innovation system are created for radically new technologies. The characteristics of the innovation phase in Chapter 4 needed more support on this topic, for which other literature must be found that deals with those topics. **The three suggestions - include STS, include marketing, include market creation/emergence - strengthen the model** both in a general sense and specifically in the areas that support is currently weak.

Not only improvement of the model in this research is an outcome. Lessons from this research must be extended to other theory as well. A larger role for marketing was already suggested above, but the pattern for development and diffusion and the conditions for large-scale diffusion are also reviewed.

8.3.3. Improving the pattern of development and diffusion

The focus on executing a project is very different from the focus on keeping development efforts going, as was proposed in this research. But the two perspectives are not contradicting each other, they are complementary. Trying to commercialize a radically new technology without involvement of any other organization means a higher investment for your company and a higher chance that you have not found the right application. The Segway, the “new car”, was developed in secret with high expectations, but failed to meet expectations of the producer (Schneider & Hall, 2011). When many organizations are involved, but product performance is still low, a large movement may be seen while only a few applications are used. An example is blockchain, of which the underlying technology has a good product performance, but the applications do not. Many organizations work on blockchain, while large-scale functionality is still lacking (Ortt & Dees, 2018). Both monitoring the important factors in the innovation phase and the number of involved innovators during the innovation phase will provide a view of both the development successes and the chances of continuation of development efforts with a sufficient amount of resources. Since the innovators already are one of the factors, **graphing the innovators in the innovation phase of the pattern of development and diffusion** is only a small step.

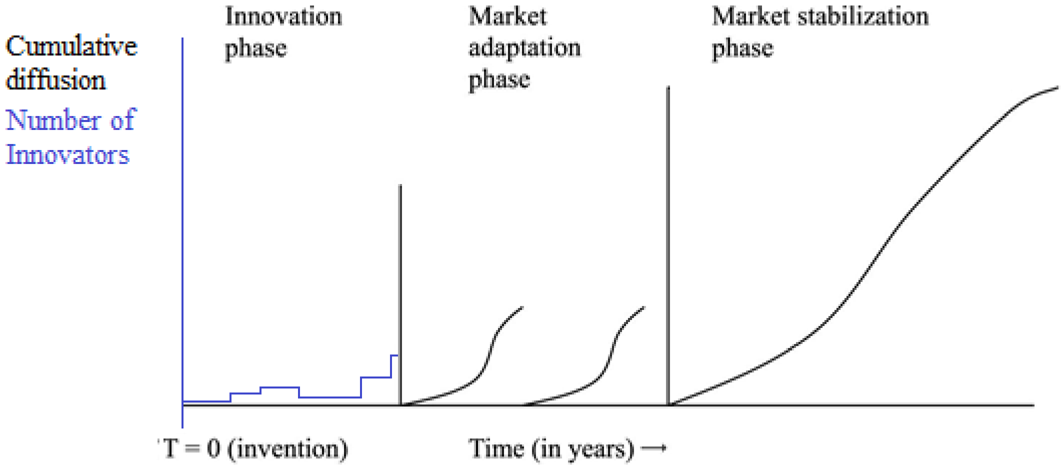


Figure 29 - Example of the pattern of development and diffusion with number of innovators in the innovation phase.

A low number of innovators gives an indication of the fragility of development efforts and can be connected with all sorts of challenges and problems. Low expectations, poor strategy, lacking (marketing) communications, challenges with obtaining resources, lacking knowledge, problems with the product development, or other individuals, groups, or organizations trying to delay developments, they are all examples of reasons that the number of innovators has not increased or has decreased. A high number of innovators is an indication of the opposite: high expectations, good strategy, etcetera. The influence of the number on innovators on the length of phases of the pattern of development and diffusion is an exciting direction of thought. Does a higher number of innovator lead to earlier market introduction? To less different applications in the market adaptation phase before large-scale diffusion is achieved? Or to a shorter market adaptation phase? To ask the questions is one, to answer them is quite something else. There are many variables to consider and proving such relations requires a large number of case studies. Perhaps a more realistic goal is to think towards best practices. What does the amount of innovators mean for the actions of those innovators? A higher number of innovators has more lobbying potential with a government, a lower number of innovators could make it easier to find enough resources to keep working on developments for a longer period of time. All those ideas are hypothetical, they are intuitive directions that can be explored to find a measurement for the innovation phase that helps innovators to understand their situation. To help innovators and their radically new technologies to survive the innovation phase and market adaptation phase.

8.3.4. The transition from the innovation phase to the market adaptation phase

Looking at the conditions for large-scale diffusion, there is the problem of the milestone of commercialization. Factors for the innovation phase and factors for the market adaptation phase are different, they are two different models. But the shift from one model to another is not from one moment to another. Although a dynamic model is probably more complex than it is practical, some explanation is needed as to **how factors change from one phase to the next**. A start on this topic was made in the development of the conceptual model, it was proposed that the focus shifts from one factor to another in different phases, and that factors that become more important get a more prominent role while factors that become less important get a less prominent role in the model of that phase. One example of such change in factors is the focus on company-level factors: there is more attention for the company in the factors for the innovation phase than the conditions for large-scale diffusion provide for the market adaptation phase. Still, the transition can be explained further, especially when working with strategies and when changing from strategies in the innovation phase to the niche strategies of the market adaptation phase.

8.3.5. The goal of the innovation phase

The goal of an organization that works on a radically new technology in the innovation phase has not been described in this research. In fact, many different goals have been proposed or assumed, with little proof, but also with little implications.

- "*The ultimate goal is to describe everything that a technology needs to become a sold product.*" (paragraph 5.1.1).
- "*Working with factors is not aspiring a specific goal and knowing how to reach it, it is working on different aspects of a technology which you see as important factors.*" (paragraph 5.1.1).
- "*The goal of factors that describe a phase in the pattern of development and diffusion is: understanding of what potentially hinders and helps development and diffusion of a radically new technology.*" (paragraph 5.1.3).
- "*A model that relies on necessary conditions that must be fulfilled before the goal can be reached, commercialisation in this case.*" (paragraph 5.2.2).
- "*The expectations and promises that surround a new-found technology can be translated to a shared vision in which actors find a common goal, a common direction in developing the technology into a product.*" (paragraph 5.2.3).

- *“The developments lead to increased knowledge and subsequently to an improved product. This stream continues as long as possible, with the final goal being a commercialized product.”* (paragraph 5.2.5).
- *“When emphasis shifts from running a project to keeping development efforts alive, having a reliable stream of resources becomes a central goal.”*(paragraph 5.2.6).
- *“The goal of the model of the innovation phase is to provide guidance during the innovation phase.”* (paragraph 8.1.1).

What do those statements have in common? Neither of them provides one goal, or a set of possible goals, for the innovation phase. Goals can be formulated at different levels (Figure 30). The corporate strategy is arguably the highest, most general sense of direction a company has internally. The New Product Strategy deals with innovation. Within that, there is perhaps a goal for the innovation phase. This research gave the goal at the last level: *The goal of factors that describe a phase in the pattern of development and diffusion is: understanding of what potentially hinders and helps development and diffusion of a radically new technology.* It was also claimed that working with factors is not aspiring a specific goal and knowing how to reach it, it is working on different aspects of a technology which an organization sees as important factors.

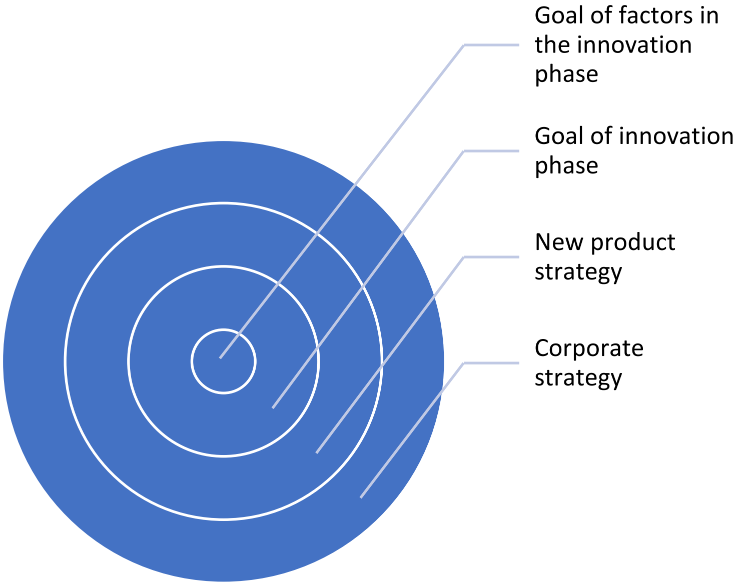


Figure 30 - Different levels at which goals are formulated.

However, there is one problem. Creation of an innovation system requires actors to have a shared vision. That is especially challenging when potential applications of a radically new technology have not been explored. An organization that works on a specific factor because it is an element they think is important to improve upon, can have a hard time convincing other organizations that their focus is the right one. Especially when a shared vision on the innovation phase as a whole is missing. This research bypassed this problem because it does not propose any strategies, it proposes factors. It proposes important elements. **Defining a goal or a set of possible goals for the innovation phase has the potential to steer efforts, and therefore to improve collaboration.**

8.3.6. Influence of an organization

Not every organization has the same amount of influence (Figure 31). Some have great lobbying influence on governments, others have great influence through their networks, and all have the potential to increase their influence. Examples of ways to increase influence are increasing lobbying efforts or marketing efforts, increasing development efforts, or investing in enhancing and strengthening a network.

Figure 31 - Influence of an organization.

The proposal of this research to view innovators as process owners of the process from expectations until a product does not account for the influence, potential influence, or lack of influence on any of the factors. The answer to questions about influence of an organization is not required when a model only points to factors, to elements that should be worked on or developed. However, the questions rise immediately when operationalising the model further: acting on observations that certain factors are lacking must be based on practical considerations, one of which is the limited influence of the organization that is a stakeholder in a particular technology. **Research is needed to form a connection between this research and the conditions for large-scale diffusion on one side, and the limited influence of organizations on the other.**

8.3.7. Dynamics of factors

The ultimate goal is to describe everything that a technology needs to become a sold product on the mass market. But that is arguably impossible. This research proposes a static model of important factors for the innovation phase. Reality is infinitely more complex than a list of factors. Earlier models recognized this same problem and seem to have found two types of solutions. Either minimizing dynamics by proposing a list of factors or allowing for all possible dynamics by suggesting that each element of the model can follow on each other element. Ortt et al. (2013) find the cause of a barrier in an influencing factor to stay one step away from proposing only a list a factors. The Fuzzy Front End’s five key elements can all follow after each other, without a proposed order to it. Assuming that a great potential lies in understanding all dynamics, further opportunities exist in exploring them further. Bruinsma (2015), Vintilă (2015), and Moschos (2016) all touched upon the subject in different ways. Their work amounts to a total of 59 unique dynamics between fourteen different factors of the conditions for large-scale diffusion (Appendix D). Evidently, dynamics become very complicated, very quickly. **The challenge is to explore dynamics and find generic mechanisms that can help organizations** understand not if a factor should be changed, but how it can be changed and how that affects and is affected by other factors. Solving a symptom or solving the cause of a problem are two very different things.

8.3.8. Formulating strategies for the innovation phase

The current model gives a good view on what the technology has and what it needs to go further, to keep development efforts going. But what to do when a problem or opportunity is found? Future research must **identify strategies and outline how those are implemented** in corporate strategies and New Product Development processes. That is the purpose of a model of the innovation phase: to guide decision-making and strategic thinking around radically new technologies.

There are two main parts in such research: formulation of strategies and guiding use of the strategies, the first explores and expands views to find a long list with possible strategies, the second leads to a selection of the strategies to find the best fitting choice for a specific organization in its specific context, working on a specific radically new technology. The first step, finding and designing strategies can be done in several ways:

1. Reasoning and creative thinking.

Several perspectives can be taken: formulate strategies for each factor, for improving it, or to make it less hampering to development efforts. Distinguish if one organization can execute the strategy or if it depends on other organizations.

2. Literature.
   Include the field of Strategic Management and use niche strategies as a benchmark. Especially the niche strategies that are developed for the conditions for large-scale diffusion provide an interesting example. The combination of core factors and influencing factors points to a specific niche strategy. A similar logic can be applied to strategies for the innovation phase. Presumably though, there will not be two different sets of factors like the core and influencing factors. Development efforts in the innovation phase are fragile and small problems can cause a complete stop. This research has struggled with the dynamics between factors, and although the model contains arrows that indicate some relationship, they have been explicitly described as non-exclusive relationships. The possibility for each factor to have an influence on any other factor remains open. What remains after this remark? The suggestion to look at least one step deeper after a problem is found with one of the factors. Looking one step further than the actual problem and searching for the root cause improves the choice for a specific strategy.
3. Case studies.
   The main focus is on strategies that were used, problems that could not be solved, and opportunities that were not fully exploited.
4. Interviews.
   Do not limit research to explicit knowledge. A strategy in practice is better fitting to the situation than a strategy in just theory.

Then the second part of the research gets to focus on making strategies usable, not every possible strategy fits the innovator's purpose. Finding the right strategy: what is that based on? It is at least based on five elements, three of which are formed by the preceding paragraphs. The first is of course the problem or opportunity that arises, which is identified through the model of important factors for the innovation phase. The goal of the innovation phase, the influence of an organization, and the dynamics of factors all shape and steer ways to change and create the world to an innovation system that is tailored to the upcoming radically new technology. Fifth is the implementation. This topic needs further exploration, it encompasses all practicalities within a company that can make it decide on a change of strategy or on a different way of implementing a strategy. Those five elements are all part of the journey from a long list of possible strategies to the selection and implementation of a strategy or multiple strategies.

8.3.9. Final remarks

It is a privilege to work on a complex topic such as the innovation phase. Especially with an exploratory approach that makes all attempts at a linear process futile. This research into the innovation phase resembles the innovation phase itself in the sense that exploring chaos is chaotic in itself. The hope is that this research serves as a basis for future endeavours, some possible directions of which are outlined above. Increased insight into radically new technologies will prove invaluable for any innovator who faces the many choices that the innovation phase presents him or her with.

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Appendix A. Work-report – Characteristics of the innovation phase

Characteristic	**Support**
Determine timing of introduction	Introduction of these technologies is often postponed or, once introduced, they are quickly withdrawn from the market after the first disappointing results. (Ortt, 2004). This release proved premature due to difficulties with stability, impure seed stock, and low seed availability. (Schroeder, 1986, p.8). The concept was very new to the people involved and required a period of time for acceptance. (Schroeder, 1986, p.10) (public schools).
New market emergence / creation	Rather than just substituting technologies in existing markets, new combinations of actors on the supply and the demand side of the market are formed. (Ortt, 2004). Diffusion of these technologies required new infrastructures, new procedures, new alliances between organizations, new customer segments and so on. (Ortt, 2004). In this phase, a good position in the market of supply and demand for research funds and researchers is essential for success. (Ortt, 2004). Initially the company does not have much competition since different companies head in various directions with the product development. (Mannheimer, 2016, p.87) (biopharma). One way to get capital is through government funding, in a pre-competitive stage, where a group of firms can receive money to turn a technology into application. (Mannheimer, 2016, p.88) (biopharma). The biopharma firms need to focus on having the right skills and the right resources throughout the Valley of Death, since the need will change due to the different activities that are carried out in this phase. (Mannheimer, 2016, p.88) (biopharma). A large part of the value in a biopharma firm is from the intellectual property and the in-house talent. (Mannheimer, 2016, p.89) (biopharma). In the case of barcode technology a consultant was active during the innovation phase. The consultant was hired by a company in order to evaluate the commercial potential of a patent that had been developed by an employee of the company. (Moschos, 2016, p.68). Competition hampered the application of RFID concepts that had been developed and demonstrated as prototype. Here, competition refers to the development of alternative technologies by actors that are external to an organization. (Moschos, 2016, p.70). In the organization, new innovations often receive lukewarm support. (Kemp, 1998).

	One important barrier to the introduction and use of new technology is that the new technology does not fit well into the existing transportation system. The use of the new technology may require complementary technologies that are perhaps not available (in short supply) or expensive to use. The introduction of battery-fed electric vehicles, for example, will require the development of an infrastructure for charging batteries. It may also be that the technology itself needs to be further developed. (Kemp, 1998). The manufacturers of existing technologies prefer to avoid risks by building on current consumer preferences. (Kemp, 1998). The introduction of new technologies may require adaptation of the infrastructure. (Kemp, 1998). These elements show that in these technological transitions both the technology and the system in which it is produced and used change through a process of co-evolution and mutual adaptation. (Kemp, 1998). The niches were instrumental in the take-off of a new regime and the further development of a new technology. Apart from demonstrating the viability of a new technology and providing financial means for further development, niches helped to build a constituency behind a new technology, and to set in motion interactive learning processes and institutional adaptations-in management, organization and the institutional context-that are all-important for the wider diffusion and development of the new technology. (Kemp, 1998). (*Niches are instrumental: so trying to skip them might not be smart/possible. This quote states what is being achieved in niches: why not try and start that process in the innovation phase?*) An important finding is that pre-NPD work is not just additional technical development; it also includes significant business development activities. The nature of work described in the valley appears to explain a space between research and NPD in which critical commercial decisions are made. The valley analogy connects the back end of research with the front end of product innovation. (Markham, 2010). By extension, all innovation roles should be expected to change as the project progresses across stages of development. Realizing that roles have multiple tasks and expectations during different phases can help increase innovation effectiveness by allowing for, facilitating, and encouraging these changes to occur. (Markham, 2010). Thus a sectoral system has three building blocks: knowledge and technology; actors and networks; institutions. (Malerba, 2004). In general, demand is quite important, both in affecting innovation in sectors and in the emergence and transformation of sectoral systems. (Malerba, 2004).

Expectations	The successful diffusion of the “old” communication technologies has certainly had its influence on the expectations regarding the diffusion of the “new” technologies, such as broadband mobile communication. (Ortt, 2004). In the organization, new innovations often receive lukewarm support. (Kemp, 1998). The unfamiliarity with the alternatives often leads to scepticism beforehand, because the actors mentioned judge the new technology on the basis of the characteristics of the dominant technology. (Kemp, 1998). The manufacturers think that consumer demands cannot be changed, and therefore they often refer to them as the most important barriers. Their argument is that they cannot manufacture products for which there is no clearly articulated consumer demand. However, the success story of the minivan in the US undermines this argument. (Kemp, 1998). The development from prototype to mass product is quite a long and cumbersome process, but above all it is a risky process. There may be a chance to develop a new market, but the incentive for the automobile industry to introduce a product to the market is not high when it is far from certain that the consumer is interested in buying it, or when there are no external factors such as legislation that require automobile manufacturers to offer the product for sale to consumers. (Kemp, 1998).
Technical developments / Incumbent technology	A lot of technical refinement before the first application. (Ortt, 2004). To attract potential consumers, the reliability and performance of the technology often has to increase whereas the price of the technology has to decrease. (Ortt, 2004). During this same period the conventional wheat yields were also being improved in competition with the hybrid effort. (Schroeder, 1986, p.8). This release proved premature due to difficulties with stability, impure seed stock, and low seed availability. (Schroeder, 1986, p.8). The initial conception of the product has been elaborated into five products involving two phases of technological development. (Schroeder, 1986, p.9). (apheresis). The phase […] contains much uncertainty and risk for a biopharma firm, e.g. regarding developing the right product or getting access to sufficient capital. (Mannheimer, 2016, p.87) (biopharma). In the early phase of their development, new technologies are often ill-developed in terms of user needs and expensive because of low-scale production. They need to be optimized. A related factor is that the new technologies have not yet been tested by consumers on a large scale. (Kemp, 1998).

	The introduction of new technologies may require adaptation of the infrastructure. (Kemp, 1998). Thus a sectoral system has three building blocks: knowledge and technology; actors and networks; institutions. (Malerba, 2004). In general, demand is quite important, both in affecting innovation in sectors and in the emergence and transformation of sectoral systems. (Malerba, 2004).
Pilots / experiments / demonstrations	A pilot in the market without a commercial goal is not considered to be a first application of the technology. (Ortt, 2004). During the most recent year the first product has been undergoing extensive field trials. These took place after the initial FDA approval was received in early 1985. (Schroeder, 1986, p.9). (apheresis). In the early phase of their development, new technologies are often ill-developed in terms of user needs and expensive because of low-scale production. They need to be optimized. A related factor is that the new technologies have not yet been tested by consumers on a large scale. (Kemp, 1998).
Niche or large-scale	Directly after their introduction, most of the communication technologies are used in small-scale specific applications. (Ortt, 2004).
Actors	During the innovation phase, organizations like research institutes and universities, in many cases co-funded by the government, play the central role. (Ortt, 2004). Small companies, which essentially focus on one technology, may be confronted with cash-flow problems during this period. Large companies and governmentally subsidized organizations may be in a better position to survive this period. (Ortt, 2004). By the 1970s major changes had occurred in the innovation participants. Almost all public institutions had dropped out as well as some of the private companies. This was primarily due to the high risk attributed to this research. (Schroeder, 1986, p.8). This release was withdrawn and one of the firms subsequently sold its hybrid program. (Schroeder, 1986, p.8). This program involves joint efforts by researchers and commercial developers. (Schroeder, 1986, p.9). (cochlear implant). During the most recent year the first product has been undergoing extensive field trials. These took place after the initial FDA approval was received in early 1985. (Schroeder, 1986, p.9). (apheresis). Initially the company does not have much competition since different companies head in various directions with the product development. (Mannheimer, 2016, p.87) (biopharma).

	Compared with the discovery and R&D phase, the clinical phase is much more business-oriented, meaning that the R&D focus must shift into focusing towards the launch of the product. (Mannheimer, 2016, p.89) (biopharma). It is a complex process to plan, set up, and execute the trials, including many actors and activities, and the biopharma firm usually seeks support for this. (Mannheimer, 2016, p.89) (biopharma). There is an interaction between the regulatory authorities and the biopharma firm when setting up the trials and to get approval to start the testing. (Mannheimer, 2016, p.89) (biopharma). In the case of barcode technology a consultant was active during the innovation phase. The consultant was hired by a company in order to evaluate the commercial potential of a patent that had been developed by an employee of the company. (Moschos, 2016, p.68). Even though governments are committed to environmental protection and other social goals, they are often not putting out a clear message that there is a need for specific new technologies. (Kemp, 1998). The manufacturers of existing technologies prefer to avoid risks by building on current consumer preferences. (Kemp, 1998). Although our understanding of how technological transitions come about is limited, historical evidence suggests that entrepreneurs/system builders and niches play an important role in the transition process. (Kemp, 1998). Champions make the organization aware of opportunities by conceptualizing the idea and preparing business cases. Sponsors support the development of promising ideas by providing resources to demonstrate the project’s viability. Gatekeepers set criteria and make acceptance decisions. (Markham, 2010). This paper uses three key informal roles commonly found in the innovation literature and notes that their activity sets interact with each other to cross the valley: (1) a champion to adopt and advocate a project; (2) a sponsor to provide project sanctioning and resources; and (3) a gatekeeper to establish criteria and make decisions about the future of the project. (Markham, 2010). By extension, all innovation roles should be expected to change as the project progresses across stages of development. Realizing that roles have multiple tasks and expectations during different phases can help increase innovation effectiveness by allowing for, facilitating, and encouraging these changes to occur. (Markham, 2010). In uncertain and changing environments networks emerge not because agents are similar, but because they are different. (Malerba, 2002).

Applications	Potential applications have to be found and new products and services have to be developed on the basis of the technology before it can be introduced into the market. (Ortt, 2004).
Develop complementary products and services	Potential applications have to be found and new products and services have to be developed on the basis of the technology before it can be introduced into the market. (Ortt, 2004). Therefore, to establish this new market, efforts are united among potential competitors and companies of complementary products and services. An example of this type of cooperation is described by Bijker (1992). The electricity utilities and General Electric, an incandescent light bulb producer, formed an alliance during the 1930s in the USA. In a united effort, both companies tried to develop the market for electric lightning. However, when the market for electric lightning grew, and different types of lightning were developed (e.g. the fluorescent lamp) the cooperation was stopped since the interests of the light bulb producers, i.e. to develop and sell energy efficient lamps, no longer coincided with the interests of the electric utilities that wanted to supply more electricity. So, during the innovation and market adaptation phase many precompetitive alliances are established in an effort to establish a new market. Yet, when the market is there, the goal is to strive for market share at the expense of direct competitors and previous alliances are often abandoned and replaced by other types of alliances. (Ortt, 2004).
Work long-term	The findings indicate that commercializing a breakthrough communication technology is a matter of long endurance. (Ortt, 2004). Small companies, which essentially focus on one technology, may be confronted with cash-flow problems during this period. Large companies and governmentally subsidized organizations may be in a better position to survive this period. (Ortt, 2004). The biopharma firms need to focus on having the right skills and the right resources throughout the Valley of Death, since the need will change due to the different activities that are carried out in this phase. (Mannheimer, 2016, p.88) (biopharma). If an idea makes it through the valley to NPD, there is adequate resource availability to take the idea to market. (Markham, 2010). In the case of barcode technology a consultant was active during the innovation phase. The consultant was hired by a company in order to evaluate the commercial potential of a patent that had been developed by an employee of the company. (Moschos, 2016, p.68). Indeed, considerable long-term investment might be required by companies seeking to survive the innovation phase. (Moschos, 2016, p.74).
Mechanisms	In this phase, a good position in the market of supply and demand for research funds and researchers is essential for success. (Ortt, 2004).

	Such a research and development (R&D) project, which is often mono-disciplinary, is confronted with two intra-company market mechanisms: supply and demand for top researchers and supply and demand for research budgets. (Ortt, 2004). By the 1970s major changes had occurred in the innovation participants. Almost all public institutions had dropped out as well as some of the private companies. This was primarily due to the high risk attributed to this research. (Schroeder, 1986, p.8). This release was withdrawn and one of the firms subsequently sold its hybrid program. (Schroeder, 1986, p.8). Moschos, 2016, p.70: - The role of actors can change in the course of the development of the technology - Actors license out proprietary technology to other actors - Actors communicate market needs and potential solutions with each other - Actors leverage on resources of other actors - Actors collaborate with other actors for production - Actors are hired by other actors to evaluate technologies in terms of their market potential There is not just one barrier to the introduction of alternative vehicles but a whole range of factors that work against the introduction and diffusion. (Kemp, 1998). In such a situation it often takes new enterprises to market the new products. These do not stand much of a chance, however, if they are not backed by sufficient capital. This creates an additional problem, since banks are reluctant to invest in risky projects and governments only grant subsidies for R&D and not for marketing a new product. (Kemp, 1998). Kemp, 1998: - The deep interrelations between technological progress and the social and managerial environment in which they are put to use. - The importance of specialized applications in the early phase of technology development. - These technologies tend to involve 'systems' of related techniques; the economics of the processes thus depend on the costs of particular inputs and availability of complementary technologies. - Social views on the new technology are of considerable importance. In uncertain and changing environments networks emerge not because agents are similar, but because they are different. (Malerba, 2002).
Funds / financials	The invention in many cases heralds a period of new funds. (Ortt, 2004). In late 1985 budgetary reductions caused a change in the program planning. The development effort would not have funds for market entry

	as originally planned. This caused the development of a new program for the marketing of the device. (Schroeder, 1986, p.9). (apheresis). This innovation started when the school district experienced budget cuts and a new superintendent was hired. […] This required a restructuring of the way in which each school was operated. (Schroeder, 1986, p.10) (public schools). This case exemplifies a typical new start-up company with continual problems being encountered in financing the new products and in generating sufficient sales to remain viable. (Schroeder, 1986, p.11) (new organization). The phase […] contains much uncertainty and risk for a biopharma firm, e.g. regarding developing the right product or getting access to sufficient capital. (Mannheimer, 2016, p.87) (biopharma). One way to get capital is through government funding, in a pre-competitive stage, where a group of firms can receive money to turn a technology into application. (Mannheimer, 2016, p.88) (biopharma). For the next financing step, large firms might be able to allocate funds internally (B3), but most smaller firms need to reach out to external investors and prove that the product has enough potential. (Mannheimer, 2016, p.88) (biopharma). There are very few investors with an appetite for these high-risk projects (V2), which is why most investors become interested in investing when the risk profile is more stable, i.e. when more concrete results from the drug development process are established (V2, V4, V5). (Mannheimer, 2016, p.88) (biopharma). In such a situation it often takes new enterprises to market the new products. These do not stand much of a chance, however, if they are not backed by sufficient capital. This creates an additional problem, since banks are reluctant to invest in risky projects and governments only grant subsidies for R&D and not for marketing a new product. (Kemp, 1998). Pinto and Slevin (1987, 1989) and Baker et al. (1983) identify critical resources needed to help innovative projects, including topmanagement support, access to technical resources, marketing advice, and financial resources and analyses. (Markham, 2010).
Switch from research to innovation	Instead of continuing the research activities, a switch is required to start up innovation activities. The latter type of activity usually requires multidisciplinary cooperation among various actors outside the R&D department of a company. For smaller companies, a similar switch of activities is required. In the pharmaceutical industry, for example, many small biotechnology research companies look for an alliance with a large company to commercialize an invention or novel drug. After the invention, project members from more disciplines are required to develop the new drug and to organize the required safety trials before the drug is accepted

	for commercial use. So, after the invention, when the innovation phase begins, a switch is required in the strategy. (Ortt, 2004) Alternative competing technologies are being explored. (Schroeder, 1986, p.9). (cochlear implant). Early development of this product began in the 1950s and 1960s but a concentrated effort did not begin until the early 1970s. (Schroeder, 1986, p.9). (cochlear implant). Compared with the discovery and R&D phase, the clinical phase is much more business-oriented, meaning that the R&D focus must shift into focusing towards the launch of the product. (Mannheimer, 2016, p.89) (biopharma). To develop a new idea into a prototype and product means overcoming resistance both outside and inside the innovating organization. (Kemp, 1998). The Valley of Death is used as a metaphor to describe the relative lack of resources and expertise in this area of development. (Markham, 2010).
Learning process	There is a large risk of betting on the wrong standard when a company starts large-scale production during the market adaptation phase. Rather than striving for scale, in this scenario a company should strive for a quick learning process to establish mainstream applications and dominant product designs in the market and to keep pace with technological developments. A learning strategy requires small-scale and flexible ways of production and marketing, enabling prompt reactions (i.e. new products) to market and technological developments (Sanchez and Sudharshan, 1992; Lynn et al., 1996). (Ortt, 2004) Alternative competing technologies are being explored. (Schroeder, 1986, p.9). (cochlear implant). The biopharma firms need to focus on having the right skills and the right resources throughout the Valley of Death, since the need will change due to the different activities that are carried out in this phase. (Mannheimer, 2016, p.88) (biopharma). The Valley of Death is used as a metaphor to describe the relative lack of resources and expertise in this area of development. (Markham, 2010).
Cooperation	Therefore, to establish this new market, efforts are united among potential competitors and companies of complementary products and services. An example of this type of cooperation is described by Bijker (1992). The electricity utilities and General Electric, an incandescent light bulb producer, formed an alliance during the 1930s in the USA. In a united effort, both companies tried to develop the market for electric lightning. However, when the market for electric lightning grew, and different types of lightning were developed (e.g. the fluorescent lamp) the cooperation was stopped since the interests of the light bulb producers, i.e. to develop

	and sell energy efficient lamps, no longer coincided with the interests of the electric utilities that wanted to supply more electricity. So, during the innovation and market adaptation phase many precompetitive alliances are established in an effort to establish a new market. Yet, when the market is there, the goal is to strive for market share at the expense of direct competitors and previous alliances are often abandoned and replaced by other types of alliances. (Ortt, 2004). By the 1970s major changes had occurred in the innovation participants. Almost all public institutions had dropped out as well as some of the private companies. This was primarily due to the high risk attributed to this research. (Schroeder, 1986, p.8). This program is a joint venture between three firms. (Schroeder, 1986, p.9). (apheresis). Overall risk management is needed, but a firm can also choose to share the risk with partners in collaborative set-ups. (Mannheimer, 2016, p.87) (biopharma). One way to get capital is through government funding, in a pre-competitive stage, where a group of firms can receive money to turn a technology into application. (Mannheimer, 2016, p.88) (biopharma). It is common that a biopharma reaches out to suitable partners that can complement the need of other resources and knowledge. (Mannheimer, 2016, p.89) (biopharma). It is a complex process to plan, set up, and execute the trials, including many actors and activities, and the biopharma firm usually seeks support for this. (Mannheimer, 2016, p.89) (biopharma). There is an interaction between the regulatory authorities and the biopharma firm when setting up the trials and to get approval to start the testing. (Mannheimer, 2016, p.89) (biopharma). Bringing in a partner can potentially increase the speed due to the added capabilities that a partner can offer. (Mannheimer, 2016, p.89) (biopharma). In uncertain and changing environments networks emerge not because agents are similar, but because they are different. (Malerba, 2002).
Organizational structure	The organizational context has also changed for this innovation. In late 1984 the reporting structure for this program was revised when it was placed with a group of other new product ventures. In late 1985 the program manager was changed and a new program manager was brought in from another project. (Schroeder, 1986, p.9). (cochlear implant). The organizational environment was also changing for two of the partners during recent times. In one case there was promotion of the vice president responsible for the innovation to a higher position. On the second case the division president resigned. This has led to other management changes

	including some changes in membership on the innovation management team. (Schroeder, 1986, p.9). (apheresis). The Naval systems innovation started with a major product failure amounting to several million dollars when the company could not deliver a quality product on time. As a result several changes in management occurred, including a change in general manager of the division, and an extensive program of quality improvement was initiated. This resulted in a proliferation of innovative ideas […]. (Schroeder, 1986, p.10) (naval system). The Naval systems innovation has direct involvement of the general manager over an extended period of several years. (Schroeder, 1986, p.10) (naval system). This innovation started when the school district experienced budget cuts and a new superintendent was hired. […] This required a restructuring of the way in which each school was operated. (Schroeder, 1986, p.10) (public schools). Throughout the entire implementation process the superintendent maintained a visible and direct role as leader of the innovation. (Schroeder, 1986, p.10) (public schools). The human resources innovation started with a new vice president of human resources. (Schroeder, 1986, p.10) (HRM). To develop a new idea into a prototype and product means overcoming resistance both outside and inside the innovating organization. It requires a special kind of management: the management of attention, of riding ideas into currency, of managing part-whole relationships (integrating functions, organizational units and resources) and the institutionalization of leadership.4 (Kemp, 1998). In the organization, new innovations often receive lukewarm support. (Kemp, 1998). Radically new technologies require changes in both the supply and demand sides, which usually take time and meet resistance, even inside the organization in which they are produced. (Kemp, 1998). In such a situation it often takes new enterprises to market the new products. These do not stand much of a chance, however, if they are not backed by sufficient capital. This creates an additional problem, since banks are reluctant to invest in risky projects and governments only grant subsidies for R&D and not for marketing a new product. (Kemp, 1998). Champions make the organization aware of opportunities by conceptualizing the idea and preparing business cases. Sponsors support the development of promising ideas by providing resources to demonstrate the project’s viability. Gatekeepers set criteria and make acceptance decisions. (Markham, 2010).

	Some authors counter that formal processes, by default, cannot sufficiently accommodate front-end needs (Nobelius and Trygg, 2002), particularly for discontinuous innovations (Reid and de Brentani, 2004). (Markham, 2010). Therefore, informal role-taking is critical to innovation, especially to get ideas across the Valley of Death. (Markham, 2010). Roberts (2004, p. 9) observes, ‘‘Most large firms are deficient in bringing the marketing vice president and marketing organization . . . into a compatible and parallel role with the CTO . . . .’’ Roberts notes similar gaps between the chief financial officer (CFO) with the R&D business unit. This communication gap between research and commercial business units has also been identified in the fuzzy front end literature (Moenaert et al., 1995). The valley acknowledges the gap between organizational units, and other vital gaps between research and formal NPD. (Markham, 2010). This paper uses three key informal roles commonly found in the innovation literature and notes that their activity sets interact with each other to cross the valley: (1) a champion to adopt and advocate a project; (2) a sponsor to provide project sanctioning and resources; and (3) a gatekeeper to establish criteria and make decisions about the future of the project. (Markham, 2010). Some firms have formal structures established for applying resources to ideas in the early stage; others encourage unofficial skunkworks projects and get resources to them in subtle under-the-radar ways (Cooper et al., 2004; Rich and Janos, 1994). Cooper et al. also found that the best-performing firms provide creative employees with support and time off to work on informal projects. Some case study examples include companies like ABB and 3M. ABB provides one-month funding (opportunity grants) for a selected number of projects (Das, 2002), and 3M dedicates 15% of their researchers’ time resources to developing innovative seed ideas (Kanter, Kao, and Wiersema, 1997, ch. 2). Some firms use incubators to provide support to new ideas outside the regular structure of the organization (Grimaldi and Grandi, 2005; Udell, 1990). (Markham, 2010). In uncertain and changing environments networks emerge not because agents are similar, but because they are different. (Malerba, 2002).
Shorten innovation phase	Once a breakthrough communication technology can be applied in an existing infrastructure and can benefit from prevailing procedures, organizations and so on, it can be hypothesized that the period from invention up to wide-scale diffusion of this technology will be relatively short compared to a breakthrough technology that requires new infrastructures, procedures and organizations. (Ortt, 2004) Bringing in a partner can potentially increase the speed due to the added capabilities that a partner can offer. (Mannheimer, 2016, p.89) (biopharma).

Types of innovations	Utterback and Abernathy [Utterback and Abernathy, 1975], using their experiences in the automotive industry, describe that during the diffusion process, innovations do actually appear. They found that radical product innovations primarily appear early on whereas process innovations and more incremental product innovations appear primarily during the later stages of the life cycle. (Ortt, 2013)
Production system	This release proved premature due to difficulties with stability, impure seed stock, and low seed availability. (Schroeder, 1986, p.8). In the early phase of their development, new technologies are often ill-developed in terms of user needs and expensive because of low-scale production. They need to be optimized. A related factor is that the new technologies have not yet been tested by consumers on a large scale. (Kemp, 1998). Moschos, 2016, p.70: - The role of actors can change in the course of the development of the technology - Actors license out proprietary technology to other actors - Actors communicate market needs and potential solutions with each other - Actors leverage on resources of other actors - Actors collaborate with other actors for production Actors are hired by other actors to evaluate technologies in terms of their market potential There is a large risk of betting on the wrong standard when a company starts large-scale production during the market adaptation phase. Rather than striving for scale, in this scenario a company should strive for a quick learning process to establish mainstream applications and dominant product designs in the market and to keep pace with technological developments. A learning strategy requires small-scale and flexible ways of production and marketing, enabling prompt reactions (i.e. new products) to market and technological developments (Sanchez and Sudharshan, 1992; Lynn et al., 1996). (Ortt, 2004)
Trial and error Failures Uncertainty Risk	This release was withdrawn and one of the firms subsequently sold its hybrid program. (Schroeder, 1986, p.8). The Naval systems innovation started with a major product failure amounting to several million dollars when the company could not deliver a quality product on time. As a result several changes in management occurred, including a change in general manager of the division, and an extensive program of quality improvement was initiated. This resulted in a proliferation of innovative ideas […]. (Schroeder, 1986, p.10) (naval system). By the 1970s major changes had occurred in the innovation participants. Almost all public institutions had dropped out as well as some of the

	private companies. This was primarily due to the high risk attributed to this research. (Schroeder, 1986, p.8). The phase […] contains much uncertainty and risk for a biopharma firm, e.g. regarding developing the right product or getting access to sufficient capital. (Mannheimer, 2016, p.87) (biopharma). It is also important that a biopharma firm dares to take calculated risk in order to get through the Valley of Death with an innovative product as the end-result. (Mannheimer, 2016, p.87) (biopharma). Overall risk management is needed, but a firm can also choose to share the risk with partners in collaborative set-ups. (Mannheimer, 2016, p.87) (biopharma). There are very few investors with an appetite for these high-risk projects (V2), which is why most investors become interested in investing when the risk profile is more stable, i.e. when more concrete results from the drug development process are established (V2, V4, V5). (Mannheimer, 2016, p.88) (biopharma). The manufacturers of existing technologies prefer to avoid risks by building on current consumer preferences. (Kemp, 1998). The development from prototype to mass product is quite a long and cumbersome process, but above all it is a risky process. There may be a chance to develop a new market, but the incentive for the automobile industry to introduce a product to the market is not high when it is far from certain that the consumer is interested in buying it, or when there are no external factors such as legislation that require automobile manufacturers to offer the product for sale to consumers. (Kemp, 1998). In such a situation it often takes new enterprises to market the new products. These do not stand much of a chance, however, if they are not backed by sufficient capital. This creates an additional problem, since banks are reluctant to invest in risky projects and governments only grant subsidies for R&D and not for marketing a new product. (Kemp, 1998). There is a large risk of betting on the wrong standard when a company starts large-scale production during the market adaptation phase. Rather than striving for scale, in this scenario a company should strive for a quick learning process to establish mainstream applications and dominant product designs in the market and to keep pace with technological developments. A learning strategy requires small-scale and flexible ways of production and marketing, enabling prompt reactions (i.e. new products) to market and technological developments (Sanchez and Sudharshan, 1992; Lynn et al., 1996). (Ortt, 2004). In uncertain and changing environments networks emerge not because agents are similar, but because they are different. (Malerba, 2002).

Ethics	Shortly after this new activity began, the chief researcher was censored by colleagues. They contended that it was improper to implant this technology when newer ones were expected to be developed soon. This controversy over choice of technology still remains with the current development. (Schroeder, 1986, p.9). (cochlear implant).
Competition	Initially the company does not have much competition since different companies head in various directions with the product development. (Mannheimer, 2016, p.87) (biopharma). Competition hampered the application of RFID concepts that had been developed and demonstrated as prototype. Here, competition refers to the development of alternative technologies by actors that are external to an organization. (Moschos, 2016, p.70).
Resources	Pursuing clinical trials is an incredibly difficult and expensive part of the Valley of Death, and sometimes it is underestimated how much resources are required for this in comparison with doing discovery and R&D activities. (Mannheimer, 2016, p.87) (biopharma). The biopharma firms need to focus on having the right skills and the right resources throughout the Valley of Death, since the need will change due to the different activities that are carried out in this phase. (Mannheimer, 2016, p.88) (biopharma). It is common that a biopharma reaches out to suitable partners that can complement the need of other resources and knowledge. (Mannheimer, 2016, p.89) (biopharma). A large part of the value in a biopharma firm is from the intellectual property and the in-house talent. (Mannheimer, 2016, p.89) (biopharma). The Valley of Death is used as a metaphor to describe the relative lack of resources and expertise in this area of development. (Markham, 2010). If an idea makes it through the valley to NPD, there is adequate resource availability to take the idea to market. (Markham, 2010). Pinto and Slevin (1987, 1989) and Baker et al. (1983) identify critical resources needed to help innovative projects, including topmanagement support, access to technical resources, marketing advice, and financial resources and analyses. (Markham, 2010). Some firms have formal structures established for applying resources to ideas in the early stage; others encourage unofficial skunkworks projects and get resources to them in subtle under-the-radar ways (Cooper et al., 2004; Rich and Janos, 1994). Cooper et al. also found that the best-performing firms provide creative employees with support and time off to work on informal projects. Some case study examples include companies like ABB and 3M. ABB provides one-month funding (opportunity grants) for a selected number of projects (Das, 2002), and 3M dedicates 15% of their researchers' time resources to developing innovative seed ideas (Kanter,

	Kao, and Wiersema, 1997, ch. 2). Some firms use incubators to provide support to new ideas outside the regular structure of the organization (Grimaldi and Grandi, 2005; Udell, 1990). (Markham, 2010).
Strategy	Most innovations do not start out as a strategic activity but as a peripheral activity of a small team of developers, as most of the research and development (R&D) work in the organization is geared towards improving existing products and reducing their production costs. (Kemp, 1998). Most of the innovations are incremental and development efforts are started top-down in a company by including concrete goals in the company's strategic goals. (Reid & de Brentani, 2004).
Government	Even though governments are committed to environmental protection and other social goals, they are often not putting out a clear message that there is a need for specific new technologies. (Kemp, 1998). Moreover, the existing regulatory framework may actually form a barrier to the development of new technologies. (Kemp, 1998). Three strategies (Kemp, 1998): - The first strategy is to change the structure of incentives in which market forces play. - The second strategy is to plan for the creation and building of a new socio-technical regime. - The third and last strategy is to build on the on-going dynamics of socio-technical change and to exert pressures so as to modulate the dynamics of socio-technical change into desirable directions. - (*those strategies are formulated for policy-makers, not for companies themselves*). Thus a sectoral system has three building blocks: knowledge and technology; actors and networks; institutions. (Malerba, 2004).
Permits / approvals / regulations	During the most recent year the first product has been undergoing extensive field trials. These took place after the initial FDA approval was received in early 1985. (Schroeder, 1986, p.9). (apheresis). The phase is very strictly regulated. (Mannheimer, 2016, p.87) (biopharma). There is an interaction between the regulatory authorities and the biopharma firm when setting up the trials and to get approval to start the testing. (Mannheimer, 2016, p.89) (biopharma). Moreover, the existing regulatory framework may actually form a barrier to the development of new technologies. (Kemp, 1998).

Appendix B. Work-report – Case study on 3D printing

B.1. Search

Primary sources are Bourell (2016), Hu & Yin (2014), Steenhuis & Pretorius (2015), and Wilkinson & Cope (2015). Below are the keywords from each of those sources that are important for the innovation phase.

Bourell (2016)

Chuck Hull, Raymond Freed, 3D Systems founded in 1984 or 1986, stereolithography.

Michael Feygin, Helisys founded in 1985, laminated object manufacturing.

Denken founded in 1985.

DTM founded in 1987.

Stratasys founded in 1988, Crump.

Figure 1 shows historical data, from 'Wohlers associates'. They are searched for more data, as the graph only goes back to 1993, years after the first commercialization.

Rapid prototyping.

Hu & Yin (2014)

Charles Hull, 3D Systems, STL file format.

Scott Crump, FDM (Fused Deposition Modelling), Stratasys.

C.R. Dechard, University of Texas at Austin, invent SLS in 1989.

Steenhuis & Pretorius (2015)

Star Trek replicator.

Chuck Hull, 3D systems corporation, stereolithography, patent in 1986, acquisition strategy.

Scott Crump, wife, invent FDM, Stratasys founded in 1988, patent in 1988, acquisitions.

Rapid prototyping.

Trademark of FDM (Fused Deposition Modelling) by Stratsys.

Use Wohlers associates as source for describing the market growth.

Wilkinson & Cope (2015)

Chuck Hull, 3D systems corporation, stereolithography. STL file.

1984: developments for selective laser sintering (SLS) and direct metal laser sintering and extrusion.

B.1.1. Results

The keywords from the sources above are used for the further search. Results are only *included* when something new is added or when it is a reliable source that confirms something in the work-report. For example: it is known that 3D systems was founded by mister Hull, but reading it from their own website is stronger proof then other sources, which is why it will then still be included. Other search results are *excluded* from the work-report, like confirmation of known information which is not any more reliable and has already been shown in at least two sources. However, the most important reason for exclusion is when the information is relevant only after 1988 and when it also does not imply any development before 1988. The market introduction of a new 3D printer in 1989 would, as a counterexample, imply developments in 1988. In that case the source is not excluded.

The 3D systems website shows a timeline of their history (3D Systems, 2019). *Included*. The Wikipedia page on 3D systems points to a website with the most important people in additive manufacturing (https://www.tctmagazine.com/TCTTop20). This list doesn't add anything new to the known actors. *Excluded*.

Helisys changed to Cubic Technologies (https://www.livescience.com/40310-laminated-object-manufacturing.html, *excluded*). History of both companies is hard to find, but some patents are found. Espacenet reports two patents in 1988. (Espacenet, 2019a). *Included*.

Information on the Denken venture proves hard to find. The search led to a document from Wohlers Associates. *Included.* (Wohlers & Gornet, 2014).

DTM was founded in 1987 and acquired by 3D systems in 2001. (Bloomberg, 2019). *Included*. Little history can be found on the history. Therefore a search to the patents. Espacenet reports patents of DTM Corporation from 1990, but other sources say earlier. So a search on the inventor follows: Carl Deckard. The results shows 11 patents that are owned by the University of Texas in Austin and are filed no later than 1988, all of which concern selective sintering. (Espacenet, 2019b) *included*. Mentioned names in those patents are from Carl Deckard, but also Marcus Harris, David Bourell, and Joseph Beaman. That is where Selective Laser Sintering started (Lorek, 2014; University of Texas, 2012) . *Included*.

A search on the history of Stratasys gave no results on the company's page, but another page. (All3DP, 2019), *included*.

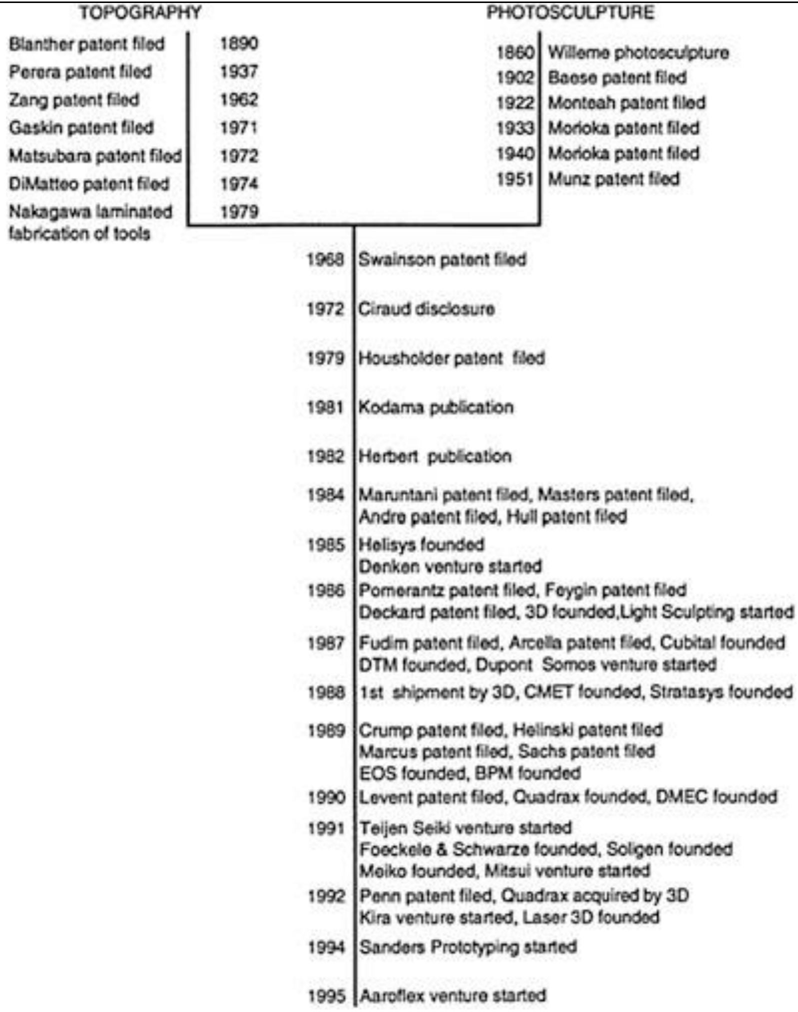
Wohlers Associates is leading in market knowledge on 3D printing. Doing what they do, most documents have to be paid for, but the chapter on the history of 3D printing of the 2014 report is published. (Wohlers & Gornet, 2014), *included*.

Wikipedia mentions a number of people who had a certain amount of influence or a specific vision. Larry Summers turns out to have written his piece in 2014, much later than 1988, and is therefore *excluded*. The same goes for Michael Spence and Naomi Wu. Another writer is George O. Smith, who wrote Venus Equilateral. He speculated about replicating technology in the series that was published in 1942 and 1945. (Hollow, 2013), *included*. "*On 16 July 1984, Alain Le Méhauté, Olivier de Witte, and Jean Claude André filed their patent for the stereolithography process.[9] The application of the French inventors was abandoned by the French General Electric Company (now Alcatel-Alsthom) and CILAS (The Laser Consortium).[10] The claimed reason was "for lack of business perspective".[11]*" An interview with MéHauté on 3dprint.com confirms this story (Mendoza, 2015). *Included*. The patent was also found (André et al., 1984). *Included*.

Netflix documentary "Print the legend" starts in the 2000s, a long time after the innovation phase. *Excluded*.

A Google search on "history rapid prototyping" points to a book in which the first chapter is dedicated to this subject (Lengua, 2017), *included*.

B.2. Timeline

Year	Hallmarks	Remarks
1860	Start of first features of AM	 (Lengua, 2017). Three prehistorical threads of AM include photosculpture, topography, and material deposition, which date back to the 1860s. (D. L. Bourell, 2016). Photosculpture, topography, and material deposition are three technologies that use toolless manufacturing approaches to construct parts in an additive fashion. Because these approaches peaked long before the invention of the computer, they relied on manual labour to form layers or subcomponents that were then assembled by hand. (D. L. Bourell, 2016). The earliest precursor process was a process similar to stereolithography and was invented by Munz (23) in 1956. Included in his system was a method for layer-wise exposure of photosensitive polymer emulsion, including a piston that was lowered between layers. Ciraud (46) disclosed in France in 1972 a powder process that is essentially directed energy deposition. Metal powder was directed into a localized heat source (laser, electron beam, plasma source) and melted to build up the part (Figure 8). Swainson (47) patented a process involving crossed lasers for part creation. The part was created at the intersection of the lasers by either photochemical crosslinking or chemical degradation. This approach was never reduced to practice. Kodama (24) published the first

		functional photopolymer AM system based on photopolymers. Included were three approaches: a top-down masking approach, a bottom-up masking approach, and a moving light source on an x-y gantry. Herbert (25) developed a similar photopolymer approach at 3M. He used a laser point source with optics mounted on an x-y gantry. The photopolymer was exposed in a container at ∼1-mm-layer thicknesses. Housholder (48) described several approaches for freeformed creation of molds, including a process of laser sintering. One embodiment involved selectively scanning a powder bed surface with a laser beam. The powder could be plastic or sand mixed/coated with plastic. The laser system could be computer controlled, and successive layers were added, with the process repeated to build up the part. (D. L. Bourell, 2016).
1950 - 1980	George O. Smith Precursor AM technologies	[…] George O. Smith's imagined 'era of duplication' was a relatively brief affair. Indeed, in Smith's fictional universe, it only takes thirty days for the entire interplanetary manufacturing sector to be rendered obsolete by the emergence of affordable, mass-produced duplication machines. Yet, whilst the technical conversion from production-line manufacturing to industrial duplication was portrayed by Smith as a relatively seamless process, the socio-economic and cultural effects of the so-called 'era of duplication' were imagined to be far more problematical. In particular, Smith worried a great deal about whether the emergence of duplicating technology might serve to disrupt the social fabric of the *Venus Equilateral* universe, 'weeding all ambition out and leaving the race decadent' (Smith (1975b: 134). Likewise, he also hypothesised that the emergence of fully-fledged duplicating technology would erode social and familial relations and might potentially result in the breakdown of civic society (114-115). (Hollow, 2013). Precursor AM technologies are defined to be those techniques invented in the 1950s to 1980s, none of which were commercialized and all of which predated the widespread availability of distributed computers with intuitive graphical interfaces. (D. L. Bourell, 2016). The first attempt to create solid objects using photopolymers using a laser took place in the late 1960s at Battelle Memorial Institute. The experiment involved intersecting two laser beams of differing wave length in the middle of a vat of resin, attempting to polymerize (solidify) the material at the point of intersection. The photopolymer resin used in the process was invented in the 1950s by DuPont. In 1967, Wyn K. Swainson of Denmark applied for a patent titled Method of Producing a 3D Figure by Holography on a similar dual laser beam approach. Subsequently, Swainson launched Formigraphic Engine Co. (Bolinas, California) in hopes to further develop and eventually commercialize his technology. Reportedly, work was still underway in 1994, although it never led to a commercially available system. In the early 1970s, Formigraphic Engine Co. used the dual-laser approach in the first commercial laser-prototyping project, a process it called photochemical machining. In 1974, Formigraphic demonstrated the generation of a 3D object using a rudimentary system. Later, Formigraphic became Omtec Replication, apparently at a time when an alliance was formed with Battelle (Columbus, Ohio). Dr. Robert Schwerzel, then with Battelle, led the development of similar techniques with the help of DARPA funding. Co-developer Dr. Vincent McGinniss was one of the team members employed by Battelle. In the late 1970s, Dynell Electronics Corp. was assigned a series of patents on solid photography. The invention involved the cutting of cross sections by computer control, using either a milling machine or laser, and

		stacking them in register to form a 3D object. Dynell merged with United Technologies Corp. in late 1977. As a result, an independent company called Solid Photography was formed and an affiliated retail outlet named Sculpture by Solid Photography was opened. In mid-1981, Sculpture by Solid Photography changed its name to Robotic Vision. Solid Photography and another company, Solid Copier, operated as subsidiaries of Robotic Vision at least until mid-1989. (Wohlers & Gornet, 2014).
?	Mention in sci-fi	It is often described in terms of the Star Trek replicator. (Steenhuis & Pretorius, 2015). Hollow (2013): George O. Smith's Venus Equilateral.
1980s	Start of AM	The AM field was born in the automotive industry as a means of rapid prototyping (e.g., Reference 11). In fact, the field was referred to as rapid prototyping until the early 1990s. (D. L. Bourell, 2016).
1980	Paper by Kodama	In October 1980, Kodama published a paper titled Three-Dimensional Data Display by Automatic Preparation of a Three-Dimensional Model that outlined his work in detail. His experiments consisted of projecting UV rays using a Toshiba mercury lamp and a photosensitive resin called Tevistar manufactured by Teijin. The method involved black and white film used to mask and control the region of exposure, corresponding to each cross section. The paper also discusses the use of an x-y plotter device and optical fiber to deliver a spot of UV light. CMET used a version of this technique in its SOUP 530, 600, and 850 machines. (Wohlers & Gornet, 2014).
1980s	Start of material extrusion Founding of Stratasys	The technology was first developed and marketed by Stratasys, founded by Scott and Lisa Crump in the late 1980s. (Bourell, 2016).
1981	Deckard	The summer of 1981, after his freshman year of college, Deckard worked for TRW Mission, a machine-shop-based manufacturing facility in Houston that made parts for the oil fields. 3D computer-aided design (CAD) was still fairly new and TRW was on the cutting edge by using 3D CAD in programs that controlled machine tools. However, many of the raw parts started out as castings, and the shapes of those castings came from handcrafted casting patterns. During his time at TRW Mission, Deckard saw that there would be a big market for an automated method for creating casting patterns out of CAD models. He spent the next two and a half years thinking about how to develop such a method. (University of Texas, 2012).
1981	Invention of stereolith.?	In 1981, Hideo Kodama of Nagoya Municipal Industrial Research Institute invented two additive methods for fabricating three-dimensional plastic models with photo-hardening thermoset polymer, where the UV exposure area is controlled by a mask pattern or a scanning fiber transmitter.[7][8] https://en.wikipedia.org/wiki/3D_printing (2018-01-24) Hideo Kodama of the Nagoya Municipal Industrial Research Institute (Nagoya, Japan) was among the first to invent the single-beam laser curing approach, according to several sources. In May 1980, he applied for a patent in Japan, which later expired without proceeding to the examination stage, a requirement of the Japanese patent application process. Kodama claimed to have difficulty in

		securing funds for additional research and development. (Wohlers & Gornet, 2014). Kodama published a second paper in November 1981, titled Automatic Method for Fabricating a Three-Dimensional Plastic Model with Photo Hardening. In Review of Scientific Instruments, Kodama describes three basic techniques he used to create plastic parts by solidifying thin, consecutive layers of photopolymer. In the paper, Kodama claims, “If the solidified layer is immersed into the liquid with the top at a depth equal to the thickness of the layer to be solidified, its top surface is covered with unsolidified liquid polymer,” essentially describing a key element of the stereolithography process. Kodama’s experiments with the three techniques were perhaps the first evidence of working additive manufacturing (AM) techniques in the world. (Wohlers & Gornet, 2014).
1982	Alan Herbert at 3M Graphic Technologies	In August 1982, Alan Herbert of 3M Graphic Technologies Sector Laboratory published a paper titled Solid Object Generation in the Journal of Applied Photographic Engineering. In this paper, Herbert described a system that directs an Argon Ion laser beam onto the surface of photopolymer by means of a mirror system attached to an x-y pen plotter device. With the system, Herbert was able to create several small, basic shapes. The primary purpose of the work, however, was to develop an understanding of the requirements of a real system, according to Herbert. In 1989–1990 timeframe, Wohlers Associates received a handwritten note from Alan Herbert, attached to a copy of his 1982 paper, saying that, unfortunately, his company elected not to commercialize his work. He was apparently very disappointed with 3M’s decision. His interest in the development of AM techniques continued, as indicated by his August 1989 paper titled “A Review of 3D Solid Object Generation” published in the Journal of Imaging Technology. (Wohlers & Gornet, 2014).
1983	First 3D printed part	Chuck Hull creates the first-ever 3D printed part, inventing Stereolithography. (3D Systems, 2019).
1984	Intuitive user interface	The AM precursors are processes that included most, if not all, of the features of AM processes but that, being invented before widespread societal acceptance of distributed computing (circa 1984), were never commercialized. (D. L. Bourell, 2016). The key date of transition from precursor to modern AM processes was 1984, the year Apple released the Macintosh (Mac), the first PC with an intuitive graphical user interface. Over an astonishingly short period of time—a few years—personal computing became ubiquitous in developed societies worldwide. Prior to this, PCs had already existed. In fact, IBM had $4 billion in sales in the PC market in 1984. The Mac, though, was intuitive and operated graphically without the need to learn a programming language. IBM followed suit in 1985 with the introduction of its Windows operating system. (D. L. Bourell, 2016).
1984	Patents stereolith. Andre, Méhauté	On 16 July 1984, Alain Le Méhauté, Olivier de Witte, and Jean Claude André filed their patent for the stereolithography process.[9] The application of the French inventors was abandoned by the French General Electric Company (now Alcatel-Alsthom) and CILAS (The Laser Consortium).[10] The claimed reason was "for lack

	Charles Hull	of business perspective".[11] https://en.wikipedia.org/wiki/3D_printing (2018-01-24) In July 1984, Jean-Claude Andre, now with the French National Center for Scientific Research (CNRS) in Nancy, France, and colleagues working for the French Cilas Alcatel Industrial Laser Company, filed a patent titled Apparatus for Fabricating a Model of an Industrial Part, involving a singlebeam laser approach. The French patent was granted in January 1986. Laser 3D, also of Nancy, France, tried to commercialize the technique outlined in the patent on a service basis with no plans to sell systems. (Wohlers & Gornet, 2014). The patent by Méhauté, André and De Witte was filed on the 16th of July 1984. (André et al., 1984). Alain Le Méhauté, Olivier de Witte, and Jean Claude André filed their patents for the stereolithography process three weeks before Chuck Hull but their applications were abandoned by the French General Electric Company (now Alcatel-Alsthom) and CILAS (The Laser Consortium). However, far from seeming bitter, the grand duke of 3D printing is as proud as ever of their innovative work and he passionately advocates for the value of the technology. (Mendoza, 2015). Three weeks later in 1984, Chuck Hull of 3D Systems Corporation[12] filed his own patent for a stereolithography fabrication system, in which layers are added by curing photopolymers with ultraviolet light lasers. Hull defined the process as a "system for generating three-dimensional objects by creating a cross-sectional pattern of the object to be formed,".[13][14] Hull's contribution was the STL (Stereolithography) file format and the digital slicing and infill strategies common to many processes today. https://en.wikipedia.org/wiki/3D_printing (2018-01-24) Chuck Hull files his patent for Stereolithography Apparatus (SLA). (3D Systems, 2019). In August 1984, Charles Hull, co-founder and chief technical officer of 3D Systems (at that time, in Valencia, California), applied for a U.S. patent titled Apparatus for Production of Three-Dimensional Objects by Stereolithography, which was granted in March 1986. At the time of the patent application, Hull was working for UVP, Inc. (San Gabriel, California) as vice president of engineering. (Wohlers & Gornet, 2014).
	Marutani	In 1984, Yoji Marutani of the Osaka Prefectural Industrial Research Institute (OPIRI), also referred to as the Osaka Institute of Industrial Technology, developed and demonstrated a stereolithography process. It's not clear whether his work was connected with Kodama's early work, although there's a very good chance that Marutani at least studied Kodama's May 1980 patent application and his October 1980 and November 1981 technical papers. It's also possible that Marutani obtained a copy of Herbert's 1982 paper, but it's doubtful that Marutani knew about Hull's and Andre's work in 1984. Marutani's patent document, titled Optical Molding Method, dated May 23, 1984, describes his invention in detail. The document describes many key elements of stereolithography, including the use of photocurable liquid material, focusing rays of light onto the surface of the liquid resin and presenting a fresh layer of

		material on top of the hardened layer. Marutani continued his research and development of stereolithography, at least until mid-1987. In a paper dated August 7, 1987, Takashi Nakai and Yoji Marutani explained that they had developed a new type of system for constructing 3D models using a UV laser and liquid polymer. Rather than discussing the development of a new type of system, however, the paper discusses refinements to already known processes—refinements that increase speed and dimensional accuracy. At the time of publication, both Nakai and Marutani were working in the Department of Electronics at the OPIRI. Kodama's 1981 paper and Herbert's 1982 paper were included as references. It is believed that Marutani is still involved with AM today. (Wohlers & Gornet, 2014).
1984	Creation of first commercial 3D printer	The first commercial 3D printer was created in 1984 when Chuck Hull, working for the US company 3D Systems Corp, developed the stereolithography (STL) process using lasers to selectively cure liquid photopolymers. At the same time, Hull defined the STL file format that is now the de facto standard for the exchange and printing of 3D models. The development of this first 3D printer established the slicing and filling algorithms present in many devices today. During this period, alternative technologies (i.e., selective laser sintering (SLS) and direct metal laser sintering and extrusion) were also under development. (Wilkinson & Cope, 2015).
1984	Deckard	By the end of his senior year in 1984, Deckard had come up with the idea of using a directed energy beam (such as a laser or electron beam) to melt particles of powder together to make a part. Realizing he had more than just another of his previous thought experiments and in need of a graduate school project, Deckard approached one of his professors, Dr. Joe Beaman, then a young assistant professor who saw value in the idea. Beaman agreed to work with Deckard on the project and took him in as a master's student later that year. (University of Texas, 2012). At the time that Deckard was transitioning into graduate school, the UT ME Department was moving to a new building and had a budget to spend on new equipment. The window of time to request money was closing, so Beaman had Deckard spend his first semester of graduate school specifying the equipment he would need to begin working on his project. Deckard specified a 2-watt laser and a fast scanner and came up with a budget of $30,000, but something seemed wrong. He kept looking over his calculations trying to find an error, but all of his calculations were correct. It wasn't until after submitting his $30,000 budget request that Deckard finally realized he had incorrectly copied a physical constant from one page to the next, off by three orders of magnitude, which led him to think he needed a much smaller laser than he actually did. Fortunately, the correct laser was still within his budget, so Deckard ordered the right one: a 100 watt YAG laser. (University of Texas, 2012).
1985	Start of sheet lamination Founding of Helisys	In 1985 Michael Feygin founded the first AM company, Helisys. Laminated object manufacturing (LOM) was based on a stack-and-cut approach wherein paper was glued to a previous layer followed by laser cutting. (Bourell, 2016). As mentioned above, the first modern AM company was Helisys, founded by Feygin in 1985 (26, pp. 6–19). The primary product of Helisys was LOM, a sheet lamination process. The first LOM machine shipment was in 1991, and the company closed in 2000. The Denken venture in Japan started in 1985, but it did

		not introduce its first stereolithography machine, the SLP-3000, until 1993 (D. L. Bourell, 2016).
1985	Founding of Denken	As mentioned above, the first modern AM company was Helisys, founded by Feygin in 1985 (26, pp. 6–19). The primary product of Helisys was LOM, a sheet lamination process. The first LOM machine shipment was in 1991, and the company closed in 2000. The Denken venture in Japan started in 1985, but it did not introduce its first stereolithography machine, the SLP-3000, until 1993 (D. L. Bourell, 2016).
1986	Founding of 3D Systems	Chuck Hull cofounded 3D Systems with Raymond Freed in 1986, with a focus on stereolithography (22). Several versions of stereolithography had been separately published earlier by Munz (23), Kodama (24), and Herbert (25). The first modern commercial AM machine was the SLA-1, introduced in 1987, with the first machine sold in 1988. (Bourell, 2016). Charles Hull was the inventor of stereolithography for which he received a patent in 1986 which is also the year that he formed 3D Systems Corporation (Barnatt, 2013). (Steenhuis & Pretorius, 2015). In 1986, Charles Hull set up the first 3D printing company, 3D Systems, and developed a standard file format, STL. (Hu & Yin, 2014). 3D Systems is co-founded by Chuck Hull and becomes the first 3D printing company in the world. (3D Systems, 2019). In March 1986, Hull and Raymond Freed co-founded 3D Systems Inc. According to Alan Herbert, published illustrations show impressive detailed parts produced by Hull's early system, much more so than those shown by Kodama or himself. (Wohlers & Gornet, 2014).
1986	Founding of Nova Automation	From 1986-89, academic and commercial progress were going on concurrently. Deckard was involved in both ventures. (University of Texas, 2012). May 1986, Deckard receives master's. October 1986, Deckard filed first patent. (University of Texas, 2012). After completing his master's in 1986, Deckard decided to stay at UT as a Ph.D. student to continue working on the project. He and Dr. Beaman, who was the Principal Investigator (PI), received a $30,000 grant from the National Science Foundation (NSF) to advance the technology, building another academic machine nicknamed "Betsy." They improved the system by enclosing it in an electrical box and adding a counter-rotating roller for more even powder deposition, which Deckard had previously been controlling by hand using a device similar to a saltshaker. By this point, the parts coming out of Deckard's machine were good enough to use as casting patterns for real parts. (University of Texas, 2012). With the SLS process showing improvement, it was time to pair up with a private corporation to continue improving the technology. In October 1986, Dr. Paul F. McClure (LinkedIn profile), then an Assistant Dean of Engineering and occasional adjunct professor, and Harold Blair, an Austin business owner, approached Deckard about commercializing the technology. The UT research team formed the first SLS company named Nova Automation after Blair's existing company,

		Nova Graphics Intl. Corp. Although Deckard originally estimated that they would only need $75,000 to start their company, Beaman doubled the number to $150,000, and McClure doubled the number again to $300,000. UT agreed with that figure and licensed Nova Automation to commercially develop SLS under the condition that they raise $300,000 by the end of 1988. (University of Texas, 2012). End of 1986, Deckard meets Blair and McClure and form Nova Automation. (University of Texas, 2012).
1986	Patents by Takashi Morihara	In 1986, Hull was not the only one with patent activity on his mind. The same year, Takashi Morihara of Fujitsu Ltd. patented two elements of stereolithography. One of them involved passing a blade over the surface of a new layer of resin to speed the leveling of the layer. This technique is especially important when the resin is viscous. For many years, 3D Systems used this leveling technique in its SLA family of stereolithography products. Another approach developed by Morihara involved the dispensing of the resin from a slot moving above the surface of the resin. From early 1990 to early 1992, Quadrax Laser Technologies (Portsmouth, Rhode Island) used this resin deposition technique in its fast resin applicator, a feature contained in its Mark 1000 stereolithography machine. (Wohlers & Gornet, 2014).
1986	Patent Pomerantz	In June 1986, Itzchak Pomerantz, founder and former president of Cubital (Raanana, Israel), filed for an Israeli patent. At the time, Pomerantz was working for Scitex Corporation, an Israeli company that owned a small percentage of Cubital. Pomerantz' patent, titled Three-Dimensional Mapping and Modeling System, laid the ground work for the Solider 5600, which Cubital introduced in July 1987. In May 1988, Cubital and 3D Systems cross-licensed certain parts of their technologies to minimize the possibility of subsequent legal conflicts. (Wohlers & Gornet, 2014).
1986	Fudim, first commercial service	In 1986, Russian immigrant Dr. Efrem Fudim of Light Sculpting (Milwaukee, WI) offered one of the first commercially available partbuilding services using an AM technology he invented. His system projects a flood of light from a UV lamp through a mask onto the surface of photopolymer. This mask approach was similar to Cubital's photo mask, although Cubital had automated the process. With Fudim's system, individual masks were produced on a Gerber photoplotter and manually positioned over the build chamber for each new layer. This labor intensive, time-consuming approach did not win the hearts of buyers. Consequently, Fudim did not sell a single system. (Wohlers & Gornet, 2014).
1986	Patent Deckard	October 1986, Deckard filed first patent. (University of Texas, 2012).
1986	Uziel	Hull's 1986 patent describes a process of photo-hardening a series of cross sections using a computer-controlled beam of light. Also in 1986, Yehoram Uziel, then of Operatech (Israel) had invented a basic machine resembling stereolithography. Uziel had read about Hull's work, so he traveled to the U.S. to visit him and Ray Freed. In January 1989, he joined 3D Systems as vice president of engineering. (Wohlers & Gornet, 2014).
1987	License Nova Automation	Going into 1987 with their license signed, Nova Automation began trying to raise money for their new business. (University of Texas, 2012). […] in early 1989 they had finally gotten an investment. Around the same time, McClure became President of the company and it was renamed DTM Corp. (University of Texas, 2012).

	Founding of DTM	DTM was founded in 1987 and shipped the first commercial laser sintering machine in 1992. From 1990 to 1993, DTM operated as a service bureau for laser sintering. (Bourell, 2016). The process was first commercialized by Deckard (21) and Beaman through DTM Corporation (Bourell, 2016). The company was founded in 1987 and is based in Austin, Texas. (Bloomberg, 2019). Carl Deckard. The results shows 11 patents that are owned by the University of Texas in Austin and are filed no later than 1988, all of which concern selective sintering. (Espacenet, 2019b). 1987, Deckard develops Betsy machine and shows it to potential investors. (University of Texas, 2012).
1987	Intro-duction of the SLA-1	Hull and Freed formed 3D Systems in 1986, and the first modern AM machine, the SLA-1, was introduced in 1987, with the first sale occurring in 1988. (Bourell, 2016). 3D Systems commercializes the first 3D printer, the SLA-1 Stereolithography (SLA) printer. (3D Systems, 2019). Additive manufacturing first emerged in 1987 with stereolithography (SL) from 3D Systems, a process that solidifies thin layers of ultraviolet (UV) light-sensitive liquid polymer using a laser. The SLA-1, the first commercially available AM system in the world, was the precursor of the once popular SLA 250 machine. (SLA stands for StereoLithography Apparatus.) The Viper SLA product from 3D Systems replaced the SLA 250 many years ago. (Wohlers & Gornet, 2014). In late 1987, 3D shipped its first beta units to customer sites in the U.S., followed by production systems in April 1988. These were the first commercial additive-manufacturing system installations in the world. (Wohlers & Gornet, 2014).
1988	Commer-Cialization of first stereolith. 3D systems in Japan	The first modern commercial AM machine was the SLA-1, introduced in 1987, with the first machine sold in 1988. (Bourell, 2016). Modern AM, or 3D printing, began with the sale of the first modern machine by 3D Systems in 1987 (D. L. Bourell, 2016). In 1988, the first industrial level 3D printer, SLA-250, based on the stereo lithography molding technique, was released by 3D Systems. (Hu & Yin, 2014). 3D Systems began to establish a presence in Japan in early 1988 when the company formed a joint venture with Japan Steel Works, Ltd. (JSW), a Mitsui company. 3D executives signed the agreement with JSW in March 1988. The new company, JSW-3D Co., Ltd. (Tokyo), served as a sales, marketing, and service organization for 3D Systems in Japan. SLA machines were made available to the Japanese by the third or fourth quarter of 1988. Near the end of 1989, 3D terminated the agreement and formed a wholly owned subsidiary, 3D Systems Japan. (Wohlers & Gornet, 2014).

		In May 1988, Cubital and 3D Systems cross-licensed certain parts of their technologies to minimize the possibility of subsequent legal conflicts. (Wohlers & Gornet, 2014).
1988	Founding of Stratasys	Crump founded Stratasys in 1988, with the first shipment of a fused deposition modeling (FDM) fabricator in 1991 (26, pp. 6–19). (Bourell, 2016). Stratasys' first customer, Biomed, made custom hips and knees. (Lorek, 2014).
	Invention and patent for FDM	In 1988, the first industrial level 3D printer, SLA-250, based on the stereo lithography molding technique, was released by 3D Systems. At the same year, Scott Crump invented a new cheaper printing technique, FDM, and established another company, Stratasys. (Hu & Yin, 2014). Scott Crump was the inventor of fused deposition modelling for which he received a patent in 1988, which is also the year that he formed Stratasys with his wife (Barnatt, 2013). (Steenhuis & Pretorius, 2015).
	Patents of Helisys	Two of the four patents of Helisys have a priority date in 1988. (Espacenet, 2019a).
	Material DuPont Loctite	In 1988, 3D Systems and Ciba-Geigy partnered in SL materials development and commercialized the first-generation acrylate resins. DuPont's Somos stereolithography machine and materials were developed the same year. Loctite also entered the SL resin business in the late 1980s, but remained in the industry only until 1993. (Wohlers & Gornet, 2014).
	NTT Data CMET Sony/ D-MEC Asahi Denka Kogyo / JSR / DSM	After 3D Systems commercialized SL in the U.S., Japan's NTT Data CMET and Sony/D-MEC commercialized versions of stereolithography in 1988 and 1989, respectively. NTT Data CMET (now a part of Teijin Seiki, a subsidiary of Nabtesco) called its system Solid Object Ultraviolet Plotter (SOUP), while Sony/D-MEC (now D-MEC) called its product Solid Creation System (SCS). Sony stopped manufacturing SL systems for D-MEC in 2007. In 1988, Asahi Denka Kogyo introduced the first epoxy resin for the CMET SL machine. The following year, Japan Synthetic Rubber (now JSR Corp.) and DSM Desotech began to offer resins for the Sony/D-MEC machines. (Wohlers & Gornet, 2014). OPIRI, operated by the Ministry of International Trade and Industry (MITI), licensed its stereolithography technology to a group of Japanese companies, including Mitsubishi Heavy Industries, NTT Data Communications, Asahi Denka Kogyo, Toyo Denki Seizo, and YAC. Together they formed Computer Modeling and Engineering Technology (CMET) to develop, manufacture, and sell AM systems. The exact licensing date is not known, although Mitsubishi announced in July 1988 that it would sell a stereolithography machine developed jointly with OPIRI. It has been documented that these five companies supported the development and commercialization of the technology in 1989, leading to the introduction of the SOUP system in 1990. A dated SOUP product brochure, published by CMET, states that the "product had been developed on the invention of Osaka Prefectural Industrial Research Institute." (Wohlers & Gornet, 2014).

		DuPont petitioned the U.S. Patent Office in September 1988 for a reexamination of Hull's 1986 patent. DuPont made the Patent Office aware of Kodama's publications, as well as those of others. (Wohlers & Gornet, 2014).
1988	SLS patents	Carl Deckard. The results shows 11 patents that are owned by the University of Texas in Austin and are filed no later than 1988, all of which concern selective sintering. (Espacenet, 2019b).
1989	Invention of SLS	Also in 1989, C.R.Dechard, a researcher at University of Texas at Austin, invented a new process, SLS. Multi-materials, such as nylon, ceramics and metal, could be used in this 3D printer. (Hu & Yin, 2014). Selective Laser Sintering (SLS) patent issued. (3D Systems, 2019).
	Uziel joins 3D Systems	Hull's 1986 patent describes a process of photo-hardening a series of cross sections using a computer-controlled beam of light. Also in 1986, Yehoram Uziel, then of Operatech (Israel) had invented a basic machine resembling stereolithography. Uziel had read about Hull's work, so he traveled to the U.S. to visit him and Ray Freed. In January 1989, he joined 3D Systems as vice president of engineering. (Wohlers & Gornet, 2014).
	DuPont Reexamination patent Hull	In 1989, DuPont announced the development of its Somos 1000 Solid Imaging System, a technology similar to 3D Systems' SLA. Because of their similarities, DuPont petitioned the U.S. Patent Office in September 1988 for a reexamination of Hull's 1986 patent. DuPont made the Patent Office aware of Kodama's publications, as well as those of others. Seven months later, the Patent Office told 3D Systems that it had rejected all claims in Hull's patent. This was about the time DuPont chose to go public with its Somos system, which occurred around June 1989. In late 1989, the U.S. Patent Office reversed its decision after 3D Systems produced strong evidence to support the claims in Hull's patent, but required the addition of new language that narrowed its scope. This was a turning point for DuPont. (Wohlers & Gornet, 2014). In 1989, DuPont filed several patent applications related to stereolithography. Four of them concentrated on photopolymer developments. In the mid 1990s, DuPont supplied resins to Teijin Seiki, Electro Optical Systems (Germany), and users of 3D Systems' SLA 250 and SLA 500 models. (Wohlers & Gornet, 2014). In early 1989, Hans J. Langer, formally of General Scanning (German branch), and a few associates started Electro Optical Systems (EOS). By mid-1990, BMW ordered its first system from EOS, and later a second for about DM 1 million. European Technology Holding, a venture capital company in Amsterdam, provided the basic financial support for Langer to go into business. Langer also secured DM 1 million from the German Federal Government's program for young technology entrepreneurs. Between mid-1991 and July 1993, EOS had shipped 15 STEREOS stereolithography systems to sites in Europe and Japan. Another customer, Hitachi Zosen Information Systems, had begun to market the EOS system in Japan. (Wohlers & Gornet, 2014).
1989	D-MEC	In 1989, Design-Model and Engineering Center (D-MEC) was launched as a joint venture between Sony and Japan Synthetic Rubber (JSR). In April/May 1989, D-MEC introduced its Solid Creation System (SCS) for 53 million yen. The system was capable of building urethane acrylate resin parts up to 1000 x 1000 x 750 mm in size from layers at thin as 50 microns (0.002 inch). According to one

	Sony/D-MEC	reliable source, the system was developed behind closed doors and details about its origins have been kept quiet. Clearly, Sony had knowledge of OPIRI and CMET's technology, as well as the technology developed by 3D Systems. (Wohlers & Gornet, 2014). After 3D Systems commercialized SL in the U.S., Japan's NTT Data CMET and Sony/D-MEC commercialized versions of stereolithography in 1988 and 1989, respectively. NTT Data CMET (now a part of Teijin Seiki, a subsidiary of Nabtesco) called its system Solid Object Ultraviolet Plotter (SOUP), while Sony/D-MEC (now D-MEC) called its product Solid Creation System (SCS). Sony stopped manufacturing SL systems for D-MEC in 2007.
Late 1980s	Start of material extrusion	The technology was first developed and marketed by Stratasys, founded by Scott and Lisa Crump in the late 1980s. (Bourell, 2016).
Until early 1990s	Rapid prototyping in automotive industry	The AM field was born in the automotive industry as a means of rapid prototyping (e.g., Reference 11). In fact, the field was referred to as rapid prototyping until the early 1990s. The main benefit was accelerated generation of form-and-feel objects that reduced the design cycle for new vehicles. The day or two required for rapid prototyping was in contrast with the time interval between submission of a prototype request to a model shop and receiving the part, often 1–2 months if there was a backlog (12). One might then conclude that, presently, AM is extremely fast for prototyping but extremely slow for manufacturing. (Bourell, 2016).
1990 1991	EOS Quadrax ICI	In 1990, Electro Optical Systems (EOS) of Germany sold its first Stereos stereolithography system. The same year, Quadrax introduced the Mark 1000 SL system, which used visible light resin. The following year, Imperial Chemical Industries introduced a visible light resin product for use with the Mark 1000. ICI stopped selling its resin about one year later when Quadrax dissolved due to a legal conflict with 3D Systems. (Wohlers & Gornet, 2014). In 1991, three AM technologies were commercialized, including fused deposition modeling (FDM) from Stratasys, solid ground curing (SGC) from Cubital, and laminated object manufacturing (LOM) from Helisys. (Wohlers & Gornet, 2014).
1991	Commercialization LOM	As mentioned above, the first modern AM company was Helisys, founded by Feygin in 1985 (26, pp. 6–19). The primary product of Helisys was LOM, a sheet lamination process. The first LOM machine shipment was in 1991, and the company closed in 2000. The Denken venture in Japan started in 1985, but it did not introduce its first stereolithography machine, the SLP-3000, until 1993 (D. L. Bourell, 2016).
1991	Commercialization FDM	Crump founded Stratasys in 1988, with the first shipment of a fused deposition modeling (FDM) fabricator in 1991 (26, pp. 6–19). (Bourell, 2016). […] the very first product (the 3D Modeler, created in 1992) […]. (All3DP, 2019).
1991	Founding of Soligen	Soligen was the first company based on binder jetting and operated as a service bureau. It was founded in 1991, with the first parts shipped in 1993. (Bourell, 2016). Uziel left 3D Systems in 1991 to form Soligen, Inc. (Northridge, California). Around the time Uziel founded Soligen, he licensed MIT's ink jet printing technique for exclusive use in the metal-casting industry. Soligen used MIT's technology in its Direct Shell Production Casting, a process that created ceramic

		investment casting shells (molds) by adhering together thin layers of ceramic powder material using droplets of liquid binder. Soligen went out of business in 2006. (Wohlers & Gornet, 2014).
1991	License from DuPont	Teijin Seiki acquired DuPont’s Somos stereolithography technology through a licensing agreement in late 1991. In March 1992, at the Optomechatronics Show ’92, Teijin Seiki announced the availability of its Soliform AM system for 50 million yen. The machine was an enhanced version of DuPont’s original Somos system, according to Teijin Seiki. With its impressive laser draw speed of up to 2,400 cm (945 inches) per second, the company considered it a second-generation AM system. Teijin Seiki had introduced two versions of its Somos technology, the Soliform 300 (300-mm build chamber) and the Soliform 500 (500-mm), and had made them available for sale in Asia. (Wohlers & Gornet, 2014).
1992	Commer-cializaton laser sintering	DTM was founded in 1987 and shipped the first commercial laser sintering machine in 1992. From 1990 to 1993, DTM operated as a service bureau for laser sintering. (Bourell, 2016).
Late 1990s	Commer-cialization of first directed energy deposition	The earliest commercialization was the LENS®process developed at Sandia National Laboratories in the late 1990s. (Bourell, 2016). With respect to directed energy deposition, LENS® technology was initiated at Sandia Labs in the early 1990s and was later transferred to Optomec. The first machine shipment was in 1998. (Bourell, 2016).

B.3. Factors

B.3.1. Expectations

“Fused Deposition Modeling (FDM) […] Other companies subsequently refer to this type of technology as plastic jet printing (PJP), fused filament modelling (FFM), fused filament fabrication (FFF), the fused deposition method, or simply thermoplastic extrusion.” (Barnatt, 2013: 225). (Steenhuis & Pretorius, 2015).

The AM field was born in the automotive industry as a means of rapid prototyping (e.g., Reference 11). In fact, the field was referred to as rapid prototyping until the early 1990s. (D. L. Bourell, 2016).

Efforts in 3D printing date back to the 1950s but the machines needed Computer Aided Design software that didn’t exist until the 1980s. And the computing power wasn’t sufficient back then either. Faster computers, better software and cheaper storage make 3D printing accessible to more people now, said Bourell with UT. (Lorek, 2014).

This is the story of the birth of an industry that began here in the 1980s. A mechanical engineering undergraduate, with an idea hatched while working a summer job, asked for the help of a young and hungry assistant professor, who managed to get the project funded. Soon enthusiastic, powerful and hardworking people defended its potential, and with a few strokes of luck, and a lot of just plain hard work, developed a manufacturing technology that spawned the additive manufacturing industry. (University of Texas, 2012).

By the end of his senior year in 1984, Deckard had come up with the idea of using a directed energy beam (such as a laser or electron beam) to melt particles of powder together to make a part. Realizing he had more than just another of his previous thought experiments and in need of a graduate school project, Deckard approached one of his professors, Dr. Joe Beaman, then a young assistant professor who saw value in the idea. Beaman agreed to work with Deckard on the project and took him in as a master's student later that year. (University of Texas, 2012).

‘Revolutionary’

Machine makes 3-D objects from drawings

By Kathleen Sullivan
American-Statesman Staff

Wedged into the corner of an unused photo lab at the University of Texas is an ungainly machine that can transform a computer drawing into a three-dimensional model at the touch of a button.

Sometime next year, the machine, which was developed by a UT graduate student, will make its way out of the lab and into the commercial arena. It will leave with the blessing of the UT Board of Regents, which Thursday gave an Austin company exclusive licensing rights to the "revolutionary" new technology embodied in the machine.

The licensing pact paves the way for the first transfer of technology from the University of Texas at Austin to a commercial venture.

The company that won the right to market the invention is Nova Automation Corp., whose principal shareholders are an Austin consulting engineer and Nova Graphics International Corp., an Austin-based computer graphics software firm.

The agreement represents a "hard fought" victory for UT's fledgling Center for Technology Development and Transfer, said Meg Wilson, coordinator of the center, which was given life during the last Texas Legislature and got

See Inventor, A11

Staff photo by Ralph Barrera

Associate Professor Joe Beaman shows some three-dimensional plastic models made by the 'selective laser centering' device developed by Carl Deckard, left.

A 1987 news clipping from the Austin American-Statesman newspaper describing Nova Automation and their "revolutionary" new technology. Pictured are Carl Deckard (left) and Joe Beaman (right). (University of Texas, 2012).

DTM was held up as a model by both the university and NSF as how a small investment in a start-up venture could grow into a successful larger business. McClure remains proud of DTM's success as a technology innovator and the financial benefits bestowed on the many people involved with the company, the university and Central Texas. (University of Texas, 2012).

With work beginning in mid-1989, the Mod A was designed and built in a rush to be finished in time for the Autofact annual trade show in Detroit later that year. Although the rush and inadequate testing caused the machine to break down, the machine was completed and shipped in time for Autofact '89 and lasted until the last hour of the three-day trade show. The demonstration was a success, and soon after the first commercial sale was made to Frank Zanner, Principle Scientist at Sandia National Laboratories. Clinton L. Atwood, the project leader at Sandia working with the machine, used it primarily for a process known as investment casting where a wax model is used to create a cast for making metal parts. (University of Texas, 2012).

In the early days of additive manufacturing, the term "manufacturing" actually wasn't accurate at all. Companies interested in SLS and the other additive technologies developing at the time were not interested in using them for manufacturing production parts, but rather as a way to make "look and feel" prototypes or to streamline the process of casting, an intermediate step in certain manufacturing processes (as was Deckard's original goal for SLS). (University of Texas, 2012).

With the SLS process showing improvement, it was time to pair up with a private corporation to continue improving the technology. In October 1986, Dr. Paul F. McClure (LinkedIn profile), then an Assistant Dean of Engineering and occasional adjunct professor, and Harold Blair, an Austin business owner, approached Deckard about commercializing the technology. The UT research team formed the first SLS company named Nova Automation after Blair's existing company, Nova Graphics Intl. Corp. Although Deckard originally estimated that they would only need $75,000 to start their company, Beaman doubled the number to $150,000, and McClure doubled the number again to $300,000. UT agreed with that figure and licensed Nova Automation to commercially develop SLS under the condition that they raise $300,000 by the end of 1988. (University of Texas, 2012).

The company was established in 1989 through the founder's simple ambition to automate the making process of a toy frog. (All3DP, 2019).

Professor Kodama presented his work in national and international meetings. However, he was unsuccessful to get the attention of the scientific community causing him to abandon the project. He started to file a patent but never completed the application. His work therefore remained unrecognized for several years, until 1995, when he was awarded the Rank Prize, a privately funded British award for outstanding inventors. He shared the prize with Charles Hull. (Lengua, 2017).

[…] George O. Smith's imagined 'era of duplication' was a relatively brief affair. Indeed, in Smith's fictional universe, it only takes thirty days for the entire interplanetary manufacturing sector to be rendered obsolete by the emergence of affordable, mass-produced duplication machines. Yet, whilst the technical conversion from production-line manufacturing to industrial duplication was portrayed by Smith as a relatively seamless process, the socio-economic and cultural effects of the so-called 'era of duplication' were imagined to be far more problematical. In particular, Smith worried a great deal about whether the emergence of duplicating technology might serve to disrupt the social fabric of the *Venus Equilateral* universe, 'weeding all ambition out and leaving the race decadent' (Smith (1975b: 134). Likewise, he also hypothesised that the emergence of fully-fledged duplicating technology would erode social and familial relations and might potentially result in the breakdown of civic society (114-115). (Hollow, 2013).

Alain Le Méhauté, Olivier de Witte, and Jean Claude André filed their patents for the stereolithography process three weeks before Chuck Hull but their applications were abandoned by the French General Electric Company (now Alcatel-Alsthom) and CILAS (The Laser Consortium). However, far from seeming bitter, the grand duke of 3D printing is as proud as ever of their innovative work and he passionately advocates for the value of the technology. (Mendoza, 2015).

He describes the commitment that led to the patent application as arising from a theoretical commitment: mathematical order, a passion for transdisciplinary science, and the belief in the explosive commercial potential. At first, the team was flying high–until they learned (through second-hand rumors) that their patent application had been abandoned because their employers could not perceive the size of the commercial potential. As with all good invention stories, the creation of the stereolithography printing process occurred outside of the bounds of the normal performance of their jobs and required efforts to convince the otherwise technically minded engineers and technicians to engage with their creative potential. Also, the laser was leaking and polluting their illegal laboratory. Sounds like the makings of a comic book super hero, doesn't it? (Mendoza, 2015).

What ultimately led to the denial of their place in the patent office wasn't a masked villain, but instead the inability of those in leadership roles in financial institutions and the high-tech industry to see the potential of something as unprecedented as this. It's almost as if they were handed the first laptop before the invention of electricity. (Mendoza, 2015).

B.3.2. Strategy

FDM was invented by a company called Stratasys, which has trademarked the term. (Steenhuis & Pretorius, 2015).

On 16 July 1984, Alain Le Méhauté, Olivier de Witte, and Jean Claude André filed their patent for the stereolithography process.[9] The application of the French inventors was abandoned by the French General Electric Company (now Alcatel-Alsthom) and CILAS (The Laser Consortium).[10] The claimed reason was "for lack of business perspective".[11] https://en.wikipedia.org/wiki/3D_printing (2018-01-24)

As mentioned above, the first modern AM company was Helisys, founded by Feygin in 1985 (26, pp. 6–19). […] The Denken venture in Japan started in 1985, but it did not introduce its first stereolithography machine, the SLP-3000, until 1993 (D. L. Bourell, 2016).

Charles Hull was the inventor of stereolithography for which he received a patent in 1986 which is also the year that he formed 3D Systems Corporation (Barnatt, 2013). (Steenhuis & Pretorius, 2015).

DTM was founded in 1987 and shipped the first commercial laser sintering machine in 1992. From 1990 to 1993, DTM operated as a service bureau for laser sintering. (Bourell, 2016).

Modern AM, or 3D printing, began with the sale of the first modern machine by 3D Systems in 1987 (D. L. Bourell, 2016). (*timing of introduction*)

In 1988, the first industrial level 3D printer, SLA-250, based on the stereo lithography molding technique, was released by 3D Systems. At the same year, Scott Crump invented a new cheaper printing technique, FDM, and established another company, Stratasys. (Hu & Yin, 2014).

Scott Crump was the inventor of fused deposition modelling for which he received a patent in 1988, which is also the year that he formed Stratasys with his wife (Barnatt, 2013). (Steenhuis & Pretorius, 2015).

Soligen was the first company based on binder jetting and operated as a service bureau. It was founded in 1991, with the first parts shipped in 1993. (Bourell, 2016).

Oettmeier and Hofmann (2016) describe that additive manufacturing requires a significant redesign of the external supply chain structure around a company and the internal processes within a company (J. R. Ortt, 2017).

Stratasys has grown in part via acquisitions. For example, it took over Solidscape in 2010 and merged with another important Israeli company, Objet, in 2013. (Steenhuis & Pretorius, 2015). (*also before 1988?*)

3D Systems has followed an aggressive growth through acquisition strategy. For instance, between early 2011 and October 2012 it acquired sixteen companies (Pfeifle, 2012). (Steenhuis & Pretorius, 2015). (*also before 1988?*)

Hideo Kodama of the Nagoya Municipal Industrial Research Institute (Nagoya, Japan) was among the first to invent the single-beam laser curing approach, according to several sources. In May 1980, he applied for a patent in Japan, which later expired without proceeding to the examination stage, a requirement of the Japanese patent application process. Kodama claimed to have difficulty in securing funds for additional research and development. (Wohlers & Gornet, 2014).

In July 1984, Jean-Claude Andre, now with the French National Center for Scientific Research (CNRS) in Nancy, France, and colleagues working for the French Cilas Alcatel Industrial Laser Company, filed a patent titled Apparatus for Fabricating a Model of an Industrial Part, involving a singlebeam laser approach. The French patent was granted in January 1986. Laser 3D, also of Nancy, France, tried to commercialize the technique outlined in the patent on a service basis with no plans to sell systems. (Wohlers & Gornet, 2014).

In 1986, Hull was not the only one with patent activity on his mind. The same year, Takashi Morihara of Fujitsu Ltd. patented two elements of stereolithography. One of them involved passing a blade over the surface of a new layer of resin to speed the leveling of the layer. This technique is especially important when the resin is viscous. For many years, 3D Systems used this leveling technique in its SLA family of stereolithography products. Another approach developed by Morihara involved the dispensing of the resin from a slot moving above the surface of the resin. From early 1990 to early 1992, Quadrax Laser Technologies (Portsmouth, Rhode Island) used this resin deposition technique in its fast resin applicator, a feature contained in its Mark 1000 stereolithography machine. (Wohlers & Gornet, 2014).

In 1984, Yoji Marutani of the Osaka Prefectural Industrial Research Institute (OPIRI), also referred to as the Osaka Institute of Industrial Technology, developed and demonstrated a stereolithography process. It's not clear whether his work was connected with Kodama's early work, although there's a very good chance that Marutani at least studied Kodama's May 1980 patent application and his October 1980 and November 1981 technical papers. It's also possible that Marutani obtained a copy of Herbert's 1982 paper, but it's doubtful that Marutani knew about Hull's and Andre's work in 1984. Marutani's patent document, titled Optical Molding Method, dated May 23, 1984, describes his invention in detail. The document describes many key elements of stereolithography, including the use of photocurable liquid material, focusing rays of light onto the surface of the liquid resin and presenting a fresh layer of material on top of the hardened layer. Marutani continued his research and development of stereolithography, at least until mid-1987. In a paper dated August 7, 1987, Takashi Nakai and Yoji Marutani explained that they had developed a new type of system for constructing 3D models using a UV laser and liquid polymer. Rather than discussing the development of a new type of system, however, the paper discusses refinements to already known processes—refinements that increase speed and dimensional accuracy. At the time of publication, both Nakai and Marutani were working in the Department of Electronics at the OPIRI. Kodama's 1981 paper and Herbert's 1982 paper were included as references. It is believed that Marutani is still involved with AM today. (Wohlers & Gornet, 2014).

OPIRI, operated by the Ministry of International Trade and Industry (MITI), licensed its stereolithography technology to a group of Japanese companies, including Mitsubishi Heavy Industries, NTT Data Communications, Asahi Denka Kogyo, Toyo Denki Seizo, and YAC. Together they formed Computer Modeling and Engineering Technology (CMET) to develop, manufacture, and sell AM systems. The exact licensing date is not known, although Mitsubishi announced in July 1988 that it would sell a stereolithography machine developed jointly with OPIRI. It has been documented that these five companies supported the development and commercialization of the technology in 1989, leading to the introduction of the SOUP system in 1990. A dated SOUP product brochure, published by CMET, states that the "product had been developed on the invention of Osaka Prefectural Industrial Research Institute." Mitsubishi, with a 54% stake, was responsible for planning and development; NTT Data Communications, with 20%, was responsible for software development; Asahi Denka Kogyo, 20%, photosensitive resins; Toyo Denki Seizo, 3%, development of the x-y plotter mechanism and other hardware; YAC, 3%, precision machine manufacturing technology. Mitsubishi Heavy Industries reportedly spent 3 billion yen on further developing the OPIRI technology. At 40–50 million yen per unit, Mitsubishi reportedly sold nine SOUP systems from early 1989 to early 1990. (Wohlers & Gornet, 2014).

In 1989, Design-Model and Engineering Center (D-MEC) was launched as a joint venture between Sony and Japan Synthetic Rubber (JSR). In April/May 1989, D-MEC introduced its Solid Creation System (SCS) for 53 million yen. The system was capable of building urethane acrylate resin parts up to 1000 x 1000 x 750 mm in size from layers at thin as 50 microns (0.002 inch). According to one reliable source, the system was developed behind closed doors and details about its origins have been kept quiet. Clearly, Sony had knowledge of OPIRI and CMET's technology, as well as the technology developed by 3D Systems. (Wohlers & Gornet, 2014).

3D Systems began to establish a presence in Japan in early 1988 when the company formed a joint venture with Japan Steel Works, Ltd. (JSW), a Mitsui company. 3D executives signed the agreement with JSW in March 1988. The new company, JSW-3D Co., Ltd. (Tokyo), served as a sales, marketing, and service organization for 3D Systems in Japan. SLA machines were made available to the Japanese by the third or fourth quarter of 1988. Near the end of 1989, 3D terminated the agreement and formed a wholly owned subsidiary, 3D Systems Japan. (Wohlers & Gornet, 2014).

In 1989, DuPont announced the development of its Somos 1000 Solid Imaging System, a technology similar to 3D Systems' SLA. Because of their similarities, DuPont petitioned the U.S. Patent Office in September 1988 for a reexamination of Hull's 1986 patent. DuPont made the Patent Office aware of Kodama's publications, as well as those of others. Seven months later, the Patent Office told 3D Systems that it had rejected all claims in Hull's patent. This was about the time DuPont chose to go public with its Somos system, which occurred around June 1989. In late 1989, the U.S. Patent Office reversed its decision after 3D Systems produced strong evidence to support the claims in Hull's patent, but required the addition of new language that narrowed its scope. This was a turning point for DuPont. (Wohlers & Gornet, 2014).

In 1989, DuPont filed several patent applications related to stereolithography. Four of them concentrated on photopolymer developments. In the mid 1990s, DuPont supplied resins to Teijin Seiki, Electro Optical Systems (Germany), and users of 3D Systems' SLA 250 and SLA 500 models. (Wohlers & Gornet, 2014).

In June 1986, Itzchak Pomerantz, founder and former president of Cubital (Raanana, Israel), filed for an Israeli patent. At the time, Pomerantz was working for Scitex Corporation, an Israeli company that owned a small percentage of Cubital. Pomerantz' patent, titled Three-Dimensional Mapping and

Modeling System, laid the ground work for the Solider 5600, which Cubital introduced in July 1987. In May 1988, Cubital and 3D Systems cross-licensed certain parts of their technologies to minimize the possibility of subsequent legal conflicts. (Wohlers & Gornet, 2014).

In 1986, Russian immigrant Dr. Efrem Fudim of Light Sculpting (Milwaukee, WI) offered one of the first commercially available partbuilding services using an AM technology he invented. His system projects a flood of light from a UV lamp through a mask onto the surface of photopolymer. This mask approach was similar to Cubital’s photo mask, although Cubital had automated the process. With Fudim’s system, individual masks were produced on a Gerber photoplotter and manually positioned over the build chamber for each new layer. This labor intensive, time-consuming approach did not win the hearts of buyers. Consequently, Fudim did not sell a single system. (Wohlers & Gornet, 2014).

Carl Deckard. The results shows 11 patents that are owned by the University of Texas in Austin and are filed no later than 1988, all of which concern selective sintering. (Espacenet, 2019b)

The SLS patents were the highest revenue generating intellectual property out of UT Austin for many years. (Lorek, 2014).

If a few things had been different—an early math error not caught, a pending patent not defended, another patent not purchased, a corporate partnership not established, it wouldn't have happened. The ME department, the Regents from The University of Texas at Austin, the Austin Technology Incubator, and National Science Foundation backed the idea from the beginning, and the resulting business became the first student/faculty-owned entrepreneurial enterprise spun out from the university. It served as an initial example of the research-to-corporate link that continues to fuel the American economy. (University of Texas, 2012).

October 1986, Deckard filed first patent. (University of Texas, 2012).

End of 1986, Deckard meets Blair and McClure and form Nova Automation. (University of Texas, 2012).

With the SLS process showing improvement, it was time to pair up with a private corporation to continue improving the technology. In October 1986, Dr. Paul F. McClure (LinkedIn profile), then an Assistant Dean of Engineering and occasional adjunct professor, and Harold Blair, an Austin business owner, approached Deckard about commercializing the technology. The UT research team formed the first SLS company named Nova Automation after Blair's existing company, Nova Graphics Intl. Corp. Although Deckard originally estimated that they would only need $75,000 to start their company, Beaman doubled the number to $150,000, and McClure doubled the number again to $300,000. UT agreed with that figure and licensed Nova Automation to commercially develop SLS under the condition that they raise $300,000 by the end of 1988. (University of Texas, 2012).

Another UT ME professor, Dave Bourell, got involved at this time because of his knowledge of laser technology and materials science. Although not an expert in laser technology at the time, he had recently done a project for International Business Machines Corp. (IBM) involving lasers in their packaging effort and was already well versed in materials science. While Bourell worked with the metals and general materials, UT Chemical Engineering professor Joel Barlow was working in polymer synthesis at the time. Although never employed directly at Nova Automation, Bourell or Barlow were both consulted by Nova Automation and their expertise used in further developing SLS. (University of Texas, 2012).

By the end of 1988, Nova Automation had formulated a tentative funding arrangement with chemicals and aerospace manufacturing giant Goodrich Corp. but required more time past the deadline to finalize the deal. Nova Automation obtained a three-month extension from UT, and in early 1989 they had finally gotten an investment. Around the same time, McClure became President of the company and it was renamed DTM Corp. (University of Texas, 2012).

B.3.3. Resources

Based on network platforms, distribution and demand can be integrated in order to rapidly provide various creative designs and solutions to customers. Manufacturing resources are also distributed, allowing customers to be part of the network and participate in the manufacturing process (even finishing the manufacturing in their own homes). In this way, it is possible to fabricate numerous creative products, and to guarantee that the fabrication cycle time and costs of these products are similar to those of products fabricated by highvolume production. This customized fabrication mode will finally be able to integrate public demand with public innovation and ideas (Lu, 2015).

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The computer in AM is crucial not only for driving and controlling the fabricator but also for providing a user-machine interface for virtual part creation, situation, and modification prior to fabrication (D. L. Bourell, 2016).

Hideo Kodama of the Nagoya Municipal Industrial Research Institute (Nagoya, Japan) was among the first to invent the single-beam laser curing approach, according to several sources. In May 1980, he applied for a patent in Japan, which later expired without proceeding to the examination stage, a requirement of the Japanese patent application process. Kodama claimed to have difficulty in securing funds for additional research and development. (Wohlers & Gornet, 2014).

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From 1986-89, academic and commercial progress were going on concurrently. Deckard was involved in both ventures. From 1990-92, Joe Beaman took a leave of absence from the university to head up of Advanced Development for Nova Automation/DTM. (University of Texas, 2012).

This is the story of the birth of an industry that began here in the 1980s. A mechanical engineering undergraduate, with an idea hatched while working a summer job, asked for the help of a young and hungry assistant professor, who managed to get the project funded. Soon enthusiastic, powerful and hardworking people defended its potential, and with a few strokes of luck, and a lot of just plain hard work, developed a manufacturing technology that spawned the additive manufacturing industry. (University of Texas, 2012).

At the time that Deckard was transitioning into graduate school, the UT ME Department was moving to a new building and had a budget to spend on new equipment. The window of time to request money was closing, so Beaman had Deckard spend his first semester of graduate school specifying the equipment he would need to begin working on his project. Deckard specified a 2-watt laser and a fast scanner and came up with a budget of $30,000, but something seemed wrong. He kept looking over his calculations trying to find an error, but all of his calculations were correct. It wasn't until after submitting his $30,000 budget request that Deckard finally realized he had incorrectly copied a physical constant from one page to the next, off by three orders of magnitude, which led him to think he needed a much smaller laser than he actually did. Fortunately, the correct laser was still within his budget, so Deckard ordered the right one: a 100 watt YAG laser. (University of Texas, 2012).

1987, Deckard develops Betsy machine and shows it to potential investors. (University of Texas, 2012).

After completing his master's in 1986, Deckard decided to stay at UT as a Ph.D. student to continue working on the project. He and Dr. Beaman, who was the Principal Investigator (PI), received a $30,000 grant from the National Science Foundation (NSF) to advance the technology, building another academic machine nicknamed "Betsy." They improved the system by enclosing it in an electrical box and adding a counter-rotating roller for more even powder deposition, which Deckard had previously been controlling by hand using a device similar to a saltshaker. By this point, the parts coming out of Deckard's machine were good enough to use as casting patterns for real parts. (University of Texas, 2012).

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B.3.4. Knowledge

The earliest application of additive manufacturing was on the toolroom end of the manufacturing spectrum. For example, rapid prototyping was one of the earliest additive variants, and its mission was to reduce the lead time and cost of developing prototypes of new parts and devices, which was earlier only done with subtractive toolroom methods such as CNC milling, turning, and precision grinding.[57] In the 2010s, additive manufacturing entered production to a much greater extent. https://en.wikipedia.org/wiki/3D_printing (2018-01-31)

FDM was invented by a company called Stratasys. (Steenhuis & Pretorius, 2015).

Three prehistorical threads of AM include photosculpture, topography, and material deposition, which date back to the 1860s. (D. L. Bourell, 2016).

The AM field was born in the automotive industry as a means of rapid prototyping (e.g., Reference 11). In fact, the field was referred to as rapid prototyping until the early 1990s. (D. L. Bourell, 2016).

In 1981, Hideo Kodama of Nagoya Municipal Industrial Research Institute invented two additive methods for fabricating three-dimensional plastic models with photo-hardening thermoset polymer, where the UV exposure area is controlled by a mask pattern or a scanning fiber transmitter.[7][8] https://en.wikipedia.org/wiki/3D_printing (2018-01-24)

Hull's contribution was the STL (Stereolithography) file format and the digital slicing and infill strategies common to many processes today. https://en.wikipedia.org/wiki/3D_printing (2018-01-24)

Several versions of stereolithography had been separately published earlier by Munz (23), Kodama (24), and Herbert (25). The first modern commercial AM machine was the SLA-1, introduced in 1987, with the first machine sold in 1988. (Bourell, 2016).

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Also in 1989, C.R.Dechard, a researcher at University of Texas at Austin, invented a new process, SLS. Multi-materials, such as nylon, ceramics and metal, could be used in this 3D printer. (Hu & Yin, 2014).

The earliest commercialization was the LENS®process developed at Sandia National Laboratories in the late 1990s. (Bourell, 2016). (*developments before 1988?*)

With respect to directed energy deposition, LENS® technology was initiated at Sandia Labs in the early 1990s and was later transferred to Optomec. The first machine shipment was in 1998. (Bourell, 2016).

In China, the study on 3D printing technology turned up in the early 1990s, research institutions mainly included Tsinghua University, Xi'an Jiaotong University, Huazhong University of Science and Technology, Beihang University and Beijing Longyuan etc. Their research areas varied but mainly focused on basic process and material. For examples, Xi'an Jiaotong University focused on SLS equipments and materials, while Beihang University on SLS equipment, South China University of Technology on SLM, Tsinghua University on EBM, Huazhong University of Science and Technology and Nanjing University of Aeronautics and Astronautics on SLS (Hu & Yin, 2014). (*much started after the innovation phase*)

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In October 1980, Kodama published a paper titled Three-Dimensional Data Display by Automatic Preparation of a Three-Dimensional Model that outlined his work in detail. His experiments consisted of projecting UV rays using a Toshiba mercury lamp and a photosensitive resin called Tevistar manufactured by Teijin. The method involved black and white film used to mask and control the region of exposure, corresponding to each cross section. The paper also discusses the use of an x-y plotter device and optical fiber to deliver a spot of UV light. CMET used a version of this technique in its SOUP 530, 600, and 850 machines. Kodama published a second paper in November 1981, titled Automatic Method for Fabricating a Three-Dimensional Plastic Model with Photo Hardening. In Review of Scientific Instruments, Kodama describes three basic techniques he used to create plastic parts by solidifying thin, consecutive layers of photopolymer. In the paper, Kodama claims, “If the solidified layer is immersed into the liquid with the top at a depth equal to the thickness of the layer to be solidified, its top surface is covered with unsolidified liquid polymer,” essentially describing a key element of the stereolithography process. Kodama’s experiments with the three techniques were perhaps the first evidence of working additive manufacturing (AM) techniques in the world. (Wohlers & Gornet, 2014).

In 1986, Hull was not the only one with patent activity on his mind. The same year, Takashi Morihara of Fujitsu Ltd. patented two elements of stereolithography. One of them involved passing a blade over the surface of a new layer of resin to speed the leveling of the layer. This technique is especially important when the resin is viscous. For many years, 3D Systems used this leveling technique in its SLA family of stereolithography products. Another approach developed by Morihara involved the dispensing of the resin from a slot moving above the surface of the resin. From early 1990 to early 1992, Quadrax Laser Technologies (Portsmouth, Rhode Island) used this resin deposition technique in its fast resin applicator, a feature contained in its Mark 1000 stereolithography machine. (Wohlers & Gornet, 2014).

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Deckard developed "Selective Laser Sintering" with Joe Beaman, a professor at UT. Deckard was working on his undergraduate degree and later his masters and Ph.D. in the UT Mechanical Engineering Department. (Lorek, 2014).

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Efforts in 3D printing date back to the 1950s but the machines needed Computer Aided Design software that didn't exist until the 1980s. And the computing power wasn't sufficient back then either. Faster computers, better software and cheaper storage make 3D printing accessible to more people now, said Bourell with UT. (Lorek, 2014).

October 1986, Deckard filed first patent. (University of Texas, 2012).

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B.3.5. Product

"Fused Deposition Modeling (FDM) is a material extrusion 3D printing process that creates objects in layers by depositing a heated thermoplastic from a computer-controlled print head nozzle. (Steenhuis & Pretorius, 2015).

The AM field was born in the automotive industry as a means of rapid prototyping (e.g., Reference 11). In fact, the field was referred to as rapid prototyping until the early 1990s. The main benefit was accelerated generation of form-and-feel objects that reduced the design cycle for new vehicles. The day or two required for rapid prototyping was in contrast with the time interval between submission of a prototype request to a model shop and receiving the part, often 1–2 months if there was a backlog (12). One might then conclude that, presently, AM is extremely fast for prototyping but extremely slow for manufacturing. (D. L. Bourell, 2016).

The first commercial 3D printer was created in 1984 when Chuck Hull, working for the US company 3D Systems Corp, developed the stereolithography (STL) process using lasers to selectively cure liquid photopolymers. At the same time, Hull defined the STL file format that is now the de facto standard for the exchange and printing of 3D models. The development of this first 3D printer established the slicing and filling algorithms present in many devices today. During this period, alternative technologies (i.e., selective laser sintering (SLS) and direct metal laser sintering and extrusion) were also under development. (Wilkinson & Cope, 2015).

Laminated object manufacturing (LOM) was based on a stack-and-cut approach wherein paper was glued to a previous layer followed by laser cutting. (Bourell, 2016).

Several versions of stereolithography had been separately published earlier by Munz (23), Kodama (24), and Herbert (25). The first modern commercial AM machine was the SLA-1, introduced in 1987, with the first machine sold in 1988. (Bourell, 2016).

In 1988, the first industrial level 3D printer, SLA-250, based on the stereo lithography molding technique, was released by 3D Systems. At the same year, Scott Crump invented a new cheaper printing technique, FDM, and established another company, Stratasys. (Hu & Yin, 2014).

Also in 1989, C.R.Dechard, a researcher at University of Texas at Austin, invented a new process, SLS. Multi-materials, such as nylon, ceramics and metal, could be used in this 3D printer. (Hu & Yin, 2014).

Soligen was the first company based on binder jetting and operated as a service bureau. It was founded in 1991, with the first parts shipped in 1993. (Bourell, 2016).

For additive manufacturing, several barriers seem to prevent direct large-scale diffusion. The costs of the emerging technology was initially high, and both the performance and user friendliness of additive manufacturing appliances were low (Ortt, 2016). In some market niches, however, the new additive manufacturing technologies were already cost-effective from the beginning on. In specific market niches, such as the market for hearing aids (Oettmeier and Hofmann, 2016), the market for dedicated parts in remote or austere environments (Meisel et al., 2016), or the market for after sales service logistics in high-tech industries (Knofius et al., 2016), additive manufacturing technologies provided unique benefits that made companies overcome the initial hurdles of low performance, high cost and lack of user friendliness. These market niches can be seen as the precursors of a transitions towards large-scale diffusion (Kemp et al., 1998; Schot and Geels, 2008) (J. R. Ortt, 2017).

There are many product innovations such as improvement in build volume, print accuracy, print speed, dual extruders (allowing more colors), heated platforms to prevent warping, etc. This state of flux does not only characterize development and manufacture of consumer 3D printers but also for example design software companies (dealing with scanning technologies, CAD etc.), 3D-printed designs (providing object designs) and service bureaus (providing access to 3D printers). (Steenhuis & Pretorius, 2015). (*Can this be found in the innovation phase?*)

Due to the combination of the design software and no need for a mold and the ability to produce one unit, it has made manufacturing a possibility for persons who previously needed a manufacturing background and the ability to buy expensive equipment in order to produce something (Steenhuis & Pretorius, 2015).

Performance and reliability, ease-of-use and user-friendliness still need to be improved. (J. R. Ortt, 2017).

Additive manufacturing first emerged in 1987 with stereolithography (SL) from 3D Systems, a process that solidifies thin layers of ultraviolet (UV) light-sensitive liquid polymer using a laser. The SLA-1, the first commercially available AM system in the world, was the precursor of the once popular SLA 250 machine. (SLA stands for StereoLithography Apparatus.) The Viper SLA product from 3D Systems replaced the SLA 250 many years ago. (Wohlers & Gornet, 2014).

In March 1986, Hull and Raymond Freed co-founded 3D Systems Inc. According to Alan Herbert, published illustrations show impressive detailed parts produced by Hull's early system, much more so than those shown by Kodama or himself. (Wohlers & Gornet, 2014).

In 1989, Design-Model and Engineering Center (D-MEC) was launched as a joint venture between Sony and Japan Synthetic Rubber (JSR). In April/May 1989, D-MEC introduced its Solid Creation System (SCS) for 53 million yen. The system was capable of building urethane acrylate resin parts up to 1000 x 1000 x 750 mm in size from layers at thin as 50 microns (0.002 inch). According to one reliable source, the system was developed behind closed doors and details about its origins have been kept quiet. Clearly, Sony had knowledge of OPIRI and CMET's technology, as well as the technology developed by 3D Systems. (Wohlers & Gornet, 2014).

In 1986, Russian immigrant Dr. Efrem Fudim of Light Sculpting (Milwaukee, WI) offered one of the first commercially available partbuilding services using an AM technology he invented. His system projects a flood of light from a UV lamp through a mask onto the surface of photopolymer. This mask approach was similar to Cubital's photo mask, although Cubital had automated the process. With Fudim's system, individual masks were produced on a Gerber photoplotter and manually positioned over the build chamber for each new layer. This labor intensive, time-consuming approach did not win the hearts of buyers. Consequently, Fudim did not sell a single system. (Wohlers & Gornet, 2014).

The first 3D Systems machine using stereolithography, the SLA 250, made a ten inch by ten inch part for a large automotive company that needed rapid prototyping, Hull said. But the technology quickly spread to other industries like medical and aerospace, he said. "It's a down and dirty industry machine that the general public doesn't know about," Hull said. (Lorek, 2014).

Efforts in 3D printing date back to the 1950s but the machines needed Computer Aided Design software that didn't exist until the 1980s. And the computing power wasn't sufficient back then either. Faster computers, better software and cheaper storage make 3D printing accessible to more people now, said Bourell with UT. (Lorek, 2014).

After completing his master's in 1986, Deckard decided to stay at UT as a Ph.D. student to continue working on the project. He and Dr. Beaman, who was the Principal Investigator (PI), received a $30,000 grant from the National Science Foundation (NSF) to advance the technology, building another academic machine nicknamed "Betsy." They improved the system by enclosing it in an electrical box and adding a counter-rotating roller for more even powder deposition, which Deckard had previously been controlling by hand using a device similar to a saltshaker. By this point, the parts coming out of Deckard's machine were good enough to use as casting patterns for real parts. (University of Texas, 2012).

In order to meet the decided temperature and pressure requirements, which in hindsight were too much for its time, Godzilla would have been much too big, heavy and expensive to economically produce — it would have taken $50,000 and over 6 months just to build the pressure vessel alone. Godzilla was never built, and the design team went back to the drawing board. (University of Texas, 2012).

Toward the late 1980s and early 1990s, the term "desktop manufacturing" started being replaced with "rapid prototyping" (RP) because most of the companies involved, primarily in the automotive industry, were interested in using the technology strictly for prototyping. The parts being made weren't yet strong enough to be used in production parts, nor was it an economical option compared to traditional methods, but they still had the enormous advantage of being created from a CAD model that could be stored and altered on a computer. (University of Texas, 2012).

B.3.6. Demand

The AM field was born in the automotive industry as a means of rapid prototyping (e.g., Reference 11). In fact, the field was referred to as rapid prototyping until the early 1990s. The main benefit was accelerated generation of form-and-feel objects that reduced the design cycle for new vehicles. The day or two required for rapid prototyping was in contrast with the time interval between submission of a prototype request to a model shop and receiving the part, often 1–2 months if there was a backlog (12). One might then conclude that, presently, AM is extremely fast for prototyping but extremely slow for manufacturing. (Bourell, 2016).

For additive manufacturing, several barriers seem to prevent direct large-scale diffusion. The costs of the emerging technology was initially high, and both the performance and user friendliness of additive manufacturing appliances were low (Ortt, 2016). In some market niches, however, the new additive manufacturing technologies were already cost-effective from the beginning on. In specific market niches, such as the market for hearing aids (Oettmeier and Hofmann, 2016), the market for dedicated parts in remote or austere environments (Meisel et al., 2016), or the market for after sales service logistics in high-tech industries (Knofius et al., 2016), additive manufacturing technologies provided unique benefits that made companies overcome the initial hurdles of low performance, high cost and lack of user friendliness. These market niches can be seen as the precursors of a transitions towards large-scale diffusion (Kemp et al., 1998; Schot and Geels, 2008) (J. R. Ortt, 2017).

The computer in AM is crucial not only for driving and controlling the fabricator but also for providing a user-machine interface for virtual part creation, situation, and modification prior to fabrication (D. L. Bourell, 2016).

Due to the combination of the design software and no need for a mold and the ability to produce one unit, it has made manufacturing a possibility for persons who previously needed a manufacturing background and the ability to buy expensive equipment in order to produce something (Steenhuis & Pretorius, 2015).

3D printing and associated software technologies that can be used by the general public still need to be developed, and a cloud platform for design and manufacturing needs to be established (Lu, 2015). (*that is now, so it was worse during the innovation phase*)

In late 1987, 3D shipped its first beta units to customer sites in the U.S., followed by production systems in April 1988. These were the first commercial additive-manufacturing system installations in the world. (Wohlers & Gornet, 2014).

In 1986, Russian immigrant Dr. Efrem Fudim of Light Sculpting (Milwaukee, WI) offered one of the first commercially available partbuilding services using an AM technology he invented. His system projects a flood of light from a UV lamp through a mask onto the surface of photopolymer. This mask approach was similar to Cubital's photo mask, although Cubital had automated the process. With Fudim's system, individual masks were produced on a Gerber photoplotter and manually positioned over the build chamber for each new layer. This labor intensive, time-consuming approach did not win the hearts of buyers. Consequently, Fudim did not sell a single system. (Wohlers & Gornet, 2014).

Stratasys’ first customer, Biomed, made custom hips and knees. (Lorek, 2014).

1987, Deckard develops Betsy machine and shows it to potential investors. (University of Texas, 2012).

With work beginning in mid-1989, the Mod A was designed and built in a rush to be finished in time for the Autofact annual trade show in Detroit later that year. Although the rush and inadequate testing caused the machine to break down, the machine was completed and shipped in time for Autofact '89 and lasted until the last hour of the three-day trade show. The demonstration was a success, and soon after the first commercial sale was made to Frank Zanner, Principle Scientist at Sandia National Laboratories. Clinton L. Atwood, the project leader at Sandia working with the machine, used it primarily for a process known as investment casting where a wax model is used to create a cast for making metal parts. (University of Texas, 2012).

Toward the late 1980s and early 1990s, the term "desktop manufacturing" started being replaced with "rapid prototyping" (RP) because most of the companies involved, primarily in the automotive industry, were interested in using the technology strictly for prototyping. The parts being made weren't yet strong enough to be used in production parts, nor was it an economical option compared to traditional methods, but they still had the enormous advantage of being created from a CAD model that could be stored and altered on a computer. (University of Texas, 2012).

B.3.7. Other companies

“Fused Deposition Modeling (FDM) […] Other companies subsequently refer to this type of technology as plastic jet printing (PJP), fused filament modelling (FFM), fused filament fabrication (FFF), the fused deposition method, or simply thermoplastic extrusion.” (Barnatt, 2013: 225). (Steenhuis & Pretorius, 2015).

Precursor AM technologies are defined to be those techniques invented in the 1950s to 1980s, none of which were commercialized and all of which predated the widespread availability of distributed computers with intuitive graphical interfaces. (D. L. Bourell, 2016).

On 16 July 1984, Alain Le Méhauté, Olivier de Witte, and Jean Claude André filed their patent for the stereolithography process.[9] The application of the French inventors was abandoned by the French General Electric Company (now Alcatel-Alsthom) and CILAS (The Laser Consortium).[10] The claimed reason was "for lack of business perspective".[11] https://en.wikipedia.org/wiki/3D_printing (2018-01-24)

Hull defined the STL file format that is now the de facto standard for the exchange and printing of 3D models. The development of this first 3D printer established the slicing and filling algorithms present in many devices today. During this period, alternative technologies (i.e., selective laser sintering (SLS) and direct metal laser sintering and extrusion) were also under development. (Wilkinson & Cope, 2015). (*computers enabled the creation and use of an STL-file*)

Several versions of stereolithography had been separately published earlier by Munz (23), Kodama (24), and Herbert (25). The first modern commercial AM machine was the SLA-1, introduced in 1987, with the first machine sold in 1988. (Bourell, 2016).

With respect to directed energy deposition, LENS® technology was initiated at Sandia Labs in the early 1990s and was later transferred to Optomec. The first machine shipment was in 1998. (Bourell, 2016).

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The computer in AM is crucial not only for driving and controlling the fabricator but also for providing a user-machine interface for virtual part creation, situation, and modification prior to fabrication (D. L. Bourell, 2016).

Topology optimization is a part design methodology based on computational analysis of the service requirements. In a typical application, one might use topology optimization to create a part that carries a prescribed traction while minimizing the part mass or volume. In this case, a computational approach might be to start with a large, virtual, volume-filling slab of material. The tractions are applied, and a finite element analysis identifies volume elements in the slab that carry little or no stress. These elements are computationally removed from the slab, and the process is repeated, generally multiple times. The final result is a part that safely withstands the tractions with minimum mass or volume and that generally has all volume elements contributing significantly in terms of the resultant stresses. Figure 10 shows a virtual stress representation of a topology-optimized piston head and the final topology-optimized part. As seen here, topology optimized parts are typically geometrically complex, which makes them suitable for fabrication using AM technologies. In this instance, AM is an enabling technology for topology optimization. There is therefore a strong synergism between topology optimization and AM, and this synergism is predicted to develop and grow in the coming years (D. L. Bourell, 2016). (*Can this be found in the innovation phase?*)

The key date of transition from precursor to modern AM processes was 1984, the year Apple released the Macintosh (Mac), the first PC with an intuitive graphical user interface. Over an astonishingly short period of time—a few years—personal computing became ubiquitous in developed societies worldwide. Prior to this, PCs had already existed. In fact, IBM had $4 billion in sales in the PC market in 1984. The Mac, though, was intuitive and operated graphically without the need to learn a programming language. IBM followed suit in 1985 with the introduction of its Windows operating system. (Bourell, 2016).

Due to the combination of the design software and no need for a mold and the ability to produce one unit, it has made manufacturing a possibility for persons who previously needed a manufacturing background and the ability to buy expensive equipment in order to produce something (Steenhuis & Pretorius, 2015).

The complementary products and services, including education of engineers and even kids on primary schools, 3D-design software and so on, are all widely available. Business models to apply additive manufacturing technologies on a larger scale are known and the price of additive manufacturing technologies is rapidly dropping. As a result, the first companies decided to adopt additive manufacturing for large-scale production of specific parts. (J. R. Ortt, 2017). (*was this known during the innovation phase?*)

Oettmeier and Hofmann (2016) describe that additive manufacturing requires a significant redesign of the external supply chain structure around a company and the internal processes within a company (J. R. Ortt, 2017).

In 1988, 3D Systems and Ciba-Geigy partnered in SL materials development and commercialized the first-generation acrylate resins. DuPont's Somos stereolithography machine and materials were developed the same year. Loctite also entered the SL resin business in the late 1980s, but remained in the industry only until 1993. (Wohlers & Gornet, 2014).

After 3D Systems commercialized SL in the U.S., Japan’s NTT Data CMET and Sony/D-MEC commercialized versions of stereolithography in 1988 and 1989, respectively. NTT Data CMET (now a part of Teijin Seiki, a subsidiary of Nabtesco) called its system Solid Object Ultraviolet Plotter (SOUP), while Sony/D-MEC (now D-MEC) called its product Solid Creation System (SCS). Sony stopped manufacturing SL systems for D-MEC in 2007. In 1988, Asahi Denka Kogyo introduced the first epoxy resin for the CMET SL machine. The following year, Japan Synthetic Rubber (now JSR Corp.) and DSM Desotech began to offer resins for the Sony/D-MEC machines. (Wohlers & Gornet, 2014).

In 1990, Electro Optical Systems (EOS) of Germany sold its first Stereos stereolithography system. The same year, Quadrax introduced the Mark 1000 SL system, which used visible light resin. The following year, Imperial Chemical Industries introduced a visible light resin product for use with the Mark 1000. ICI stopped selling its resin about one year later when Quadrax dissolved due to a legal conflict with 3D Systems. (Wohlers & Gornet, 2014).

Hideo Kodama of the Nagoya Municipal Industrial Research Institute (Nagoya, Japan) was among the first to invent the single-beam laser curing approach, according to several sources. In May 1980, he applied for a patent in Japan, which later expired without proceeding to the examination stage, a requirement of the Japanese patent application process. Kodama claimed to have difficulty in securing funds for additional research and development. (Wohlers & Gornet, 2014).

In October 1980, Kodama published a paper titled Three-Dimensional Data Display by Automatic Preparation of a Three-Dimensional Model that outlined his work in detail. His experiments consisted of projecting UV rays using a Toshiba mercury lamp and a photosensitive resin called Tevistar manufactured by Teijin. The method involved black and white film used to mask and control the region of exposure, corresponding to each cross section. The paper also discusses the use of an x-y plotter device and optical fiber to deliver a spot of UV light. CMET used a version of this technique in its SOUP 530, 600, and 850 machines. (Wohlers & Gornet, 2014).

In July 1984, Jean-Claude Andre, now with the French National Center for Scientific Research (CNRS) in Nancy, France, and colleagues working for the French Cilas Alcatel Industrial Laser Company, filed a patent titled Apparatus for Fabricating a Model of an Industrial Part, involving a singlebeam laser approach. The French patent was granted in January 1986. Laser 3D, also of Nancy, France, tried to commercialize the technique outlined in the patent on a service basis with no plans to sell systems. (Wohlers & Gornet, 2014).

In August 1984, Charles Hull, co-founder and chief technical officer of 3D Systems (at that time, in Valencia, California), applied for a U.S. patent titled Apparatus for Production of Three-Dimensional Objects by Stereolithography, which was granted in March 1986. At the time of the patent application, Hull was working for UVP, Inc. (San Gabriel, California) as vice president of engineering. (Wohlers & Gornet, 2014).

Hull’s 1986 patent describes a process of photo-hardening a series of cross sections using a computer-controlled beam of light. Also in 1986, Yehoram Uziel, then of Operatech (Israel) had invented a basic machine resembling stereolithography. Uziel had read about Hull’s work, so he traveled to the U.S. to visit him and Ray Freed. In January 1989, he joined 3D Systems as vice president of engineering. (Wohlers & Gornet, 2014).

OPIRI, operated by the Ministry of International Trade and Industry (MITI), licensed its stereolithography technology to a group of Japanese companies, including Mitsubishi Heavy Industries, NTT Data Communications, Asahi Denka Kogyo, Toyo Denki Seizo, and YAC. Together they formed Computer Modeling and Engineering Technology (CMET) to develop, manufacture, and sell AM systems. The exact licensing date is not known, although Mitsubishi announced in July 1988 that it would sell a stereolithography machine developed jointly with OPIRI. It has been documented that these five companies supported the development and commercialization of the technology in 1989, leading to the introduction of the SOUP system in 1990. A dated SOUP product brochure, published by CMET, states that the "product had been developed on the invention of Osaka Prefectural Industrial Research Institute." (Wohlers & Gornet, 2014).

3D Systems began to establish a presence in Japan in early 1988 when the company formed a joint venture with Japan Steel Works, Ltd. (JSW), a Mitsui company. 3D executives signed the agreement with JSW in March 1988. The new company, JSW-3D Co., Ltd. (Tokyo), served as a sales, marketing, and service organization for 3D Systems in Japan. SLA machines were made available to the Japanese by the third or fourth quarter of 1988. Near the end of 1989, 3D terminated the agreement and formed a wholly owned subsidiary, 3D Systems Japan. (Wohlers & Gornet, 2014).

In 1989, DuPont announced the development of its Somos 1000 Solid Imaging System, a technology similar to 3D Systems' SLA. Because of their similarities, DuPont petitioned the U.S. Patent Office in September 1988 for a reexamination of Hull's 1986 patent. DuPont made the Patent Office aware of Kodama's publications, as well as those of others. Seven months later, the Patent Office told 3D Systems that it had rejected all claims in Hull's patent. This was about the time DuPont chose to go public with its Somos system, which occurred around June 1989. In late 1989, the U.S. Patent Office reversed its decision after 3D Systems produced strong evidence to support the claims in Hull's patent, but required the addition of new language that narrowed its scope. This was a turning point for DuPont. (Wohlers & Gornet, 2014).

In 1989, DuPont filed several patent applications related to stereolithography. Four of them concentrated on photopolymer developments. In the mid 1990s, DuPont supplied resins to Teijin Seiki, Electro Optical Systems (Germany), and users of 3D Systems' SLA 250 and SLA 500 models. (Wohlers & Gornet, 2014).

In early 1989, Hans J. Langer, formally of General Scanning (German branch), and a few associates started Electro Optical Systems (EOS). By mid-1990, BMW ordered its first system from EOS, and later a second for about DM 1 million. European Technology Holding, a venture capital company in Amsterdam, provided the basic financial support for Langer to go into business. Langer also secured DM 1 million from the German Federal Government's program for young technology entrepreneurs. Between mid-1991 and July 1993, EOS had shipped 15 STEREOS stereolithography systems to sites in Europe and Japan. Another customer, Hitachi Zosen Information Systems, had begun to market the EOS system in Japan. (Wohlers & Gornet, 2014).

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1987, Deckard develops Betsy machine and shows it to potential investors. (University of Texas, 2012).

With the SLS process showing improvement, it was time to pair up with a private corporation to continue improving the technology. In October 1986, Dr. Paul F. McClure (LinkedIn profile), then an Assistant Dean of Engineering and occasional adjunct professor, and Harold Blair, an Austin business owner, approached Deckard about commercializing the technology. The UT research team formed the first SLS company named Nova Automation after Blair's existing company, Nova Graphics Intl. Corp. Although Deckard originally estimated that they would only need $75,000 to start their company, Beaman doubled the number to $150,000, and McClure doubled the number again to $300,000. UT agreed with that figure and licensed Nova Automation to commercially develop SLS under the condition that they raise $300,000 by the end of 1988. (University of Texas, 2012).

B.3.8. Institutions

FDM was invented by a company called Stratasys, which has trademarked the term. (Steenhuis & Pretorius, 2015).

Charles Hull was the inventor of stereolithography for which he received a patent in 1986 which is also the year that he formed 3D Systems Corporation (Barnatt, 2013). (Steenhuis & Pretorius, 2015).

Scott Crump was the inventor of fused deposition modelling for which he received a patent in 1988, which is also the year that he formed Stratasys with his wife (Barnatt, 2013). (Steenhuis & Pretorius, 2015).

In 1990, Electro Optical Systems (EOS) of Germany sold its first Stereos stereolithography system. The same year, Quadrax introduced the Mark 1000 SL system, which used visible light resin. The following year, Imperial Chemical Industries introduced a visible light resin product for use with the Mark 1000. ICI stopped selling its resin about one year later when Quadrax dissolved due to a legal conflict with 3D Systems. (Wohlers & Gornet, 2014).

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If a few things had been different—an early math error not caught, a pending patent not defended, another patent not purchased, a corporate partnership not established, it wouldn't have happened. The ME department, the Regents from The University of Texas at Austin, the Austin Technology Incubator, and National Science Foundation backed the idea from the beginning, and the resulting business became the first student/faculty-owned entrepreneurial enterprise spun out from the university. It served as an initial example of the research-to-corporate link that continues to fuel the American economy. (University of Texas, 2012).

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B.3.9. Broad environment

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The AM precursors are processes that included most, if not all, of the features of AM processes but that, being invented before widespread societal acceptance of distributed computing (circa 1984), were never commercialized. (D. L. Bourell, 2016).

The key date of transition from precursor to modern AM processes was 1984, the year Apple released the Macintosh (Mac), the first PC with an intuitive graphical user interface. Over an astonishingly short period of time—a few years—personal computing became ubiquitous in developed societies worldwide. Prior to this, PCs had already existed. In fact, IBM had $4 billion in sales in the PC market in 1984. The Mac, though, was intuitive and operated graphically without the need to learn a programming language. IBM followed suit in 1985 with the introduction of its Windows operating system. (D. L. Bourell, 2016).

3D Printing is igniting that inventive spirit, especially in young people and creating excitement about engineering and manufacturing this country hasn’t seen since the space race in the 1960s, Wohlers said. Other factors bringing manufacturing back to the U.S. include the availability of cheap natural gas, Deckard said. “In a lot of areas, the cost of the product isn’t as much driven by labor as it has been in the past,” he said. “When the labor content goes down there’s less reason to go off shore.” (Lorek, 2014). (*This is long after 1988*).

If a few things had been different—an early math error not caught, a pending patent not defended, another patent not purchased, a corporate partnership not established, it wouldn't have happened. The ME department, the Regents from The University of Texas at Austin, the Austin Technology

Incubator, and National Science Foundation backed the idea from the beginning, and the resulting business became the first student/faculty-owned entrepreneurial enterprise spun out from the university. It served as an initial example of the research-to-corporate link that continues to fuel the American economy. (University of Texas, 2012).

At the time that Deckard was transitioning into graduate school, the UT ME Department was moving to a new building and had a budget to spend on new equipment. The window of time to request money was closing, so Beaman had Deckard spend his first semester of graduate school specifying the equipment he would need to begin working on his project. Deckard specified a 2-watt laser and a fast scanner and came up with a budget of $30,000, but something seemed wrong. He kept looking over his calculations trying to find an error, but all of his calculations were correct. It wasn't until after submitting his $30,000 budget request that Deckard finally realized he had incorrectly copied a physical constant from one page to the next, off by three orders of magnitude, which led him to think he needed a much smaller laser than he actually did. Fortunately, the correct laser was still within his budget, so Deckard ordered the right one: a 100 watt YAG laser. (University of Texas, 2012).

In order to meet the decided temperature and pressure requirements, which in hindsight were too much for its time, Godzilla would have been much too big, heavy and expensive to economically produce — it would have taken $50,000 and over 6 months just to build the pressure vessel alone. Godzilla was never built, and the design team went back to the drawing board. (University of Texas, 2012).

DTM was held up as a model by both the university and NSF as how a small investment in a start-up venture could grow into a successful larger business. McClure remains proud of DTM's success as a technology innovator and the financial benefits bestowed on the many people involved with the company, the university and Central Texas. (University of Texas, 2012).

B.3.10. Other factors

Innovators

The technology was first developed and marketed by Stratasys, founded by Scott and Lisa Crump in the late 1980s. (Bourell, 2016).

In 1981, Hideo Kodama of Nagoya Municipal Industrial Research Institute invented two additive methods for fabricating three-dimensional plastic models. https://en.wikipedia.org/wiki/3D_printing (2018-01-24)

On 16 July 1984, Alain Le Méhauté, Olivier de Witte, and Jean Claude André filed their patent for the stereolithography process. Three weeks later in 1984, Chuck Hull of 3D Systems Corporation[12] filed his own patent for a stereolithography fabrication system. https://en.wikipedia.org/wiki/3D_printing (2018-01-24)

DTM was founded in 1987 and shipped the first commercial laser sintering machine in 1992. From 1990 to 1993, DTM operated as a service bureau for laser sintering. (Bourell, 2016).

Several versions of stereolithography had been separately published earlier by Munz (23), Kodama (24), and Herbert (25). The first modern commercial AM machine was the SLA-1, introduced in 1987, with the first machine sold in 1988. (Bourell, 2016).

Hull and Freed formed 3D Systems in 1986, and the first modern AM machine, the SLA-1, was introduced in 1987, with the first sale occurring in 1988. (Bourell, 2016).

In March 1986, Hull and Raymond Freed co-founded 3D Systems Inc. According to Alan Herbert, published illustrations show impressive detailed parts produced by Hull's early system, much more so than those shown by Kodama or himself. (Wohlers & Gornet, 2014).

Hull's 1986 patent describes a process of photo-hardening a series of cross sections using a computer-controlled beam of light. Also in 1986, Yehoram Uziel, then of Operatech (Israel) had invented a basic machine resembling stereolithography. Uziel had read about Hull's work, so he traveled to the U.S. to visit him and Ray Freed. In January 1989, he joined 3D Systems as vice president of engineering. In late 1987, 3D shipped its first beta units to customer sites in the U.S., followed by production systems in April 1988. These were the first commercial additive-manufacturing system installations in the world. (Wohlers & Gornet, 2014).

Also in 1989, C.R.Dechard, a researcher at University of Texas at Austin, invented a new process, SLS. Multi-materials, such as nylon, ceramics and metal, could be used in this 3D printer. (Hu & Yin, 2014).

Soligen was the first company based on binder jetting and operated as a service bureau. It was founded in 1991, with the first parts shipped in 1993. (Bourell, 2016).

With respect to directed energy deposition, LENS® technology was initiated at Sandia Labs in the early 1990s and was later transferred to Optomec. The first machine shipment was in 1998. (Bourell, 2016).

In 1988, 3D Systems and Ciba-Geigy partnered in SL materials development and commercialized the first-generation acrylate resins. DuPont's Somos stereolithography machine and materials were developed the same year. Loctite also entered the SL resin business in the late 1980s, but remained in the industry only until 1993. (Wohlers & Gornet, 2014).

After 3D Systems commercialized SL in the U.S., Japan's NTT Data CMET and Sony/D-MEC commercialized versions of stereolithography in 1988 and 1989, respectively. NTT Data CMET (now a part of Teijin Seiki, a subsidiary of Nabtesco) called its system Solid Object Ultraviolet Plotter (SOUP), while Sony/D-MEC (now D-MEC) called its product Solid Creation System (SCS). Sony stopped manufacturing SL systems for D-MEC in 2007. In 1988, Asahi Denka Kogyo introduced the first epoxy resin for the CMET SL machine. The following year, Japan Synthetic Rubber (now JSR Corp.) and DSM Desotech began to offer resins for the Sony/D-MEC machines. (Wohlers & Gornet, 2014).

In 1990, Electro Optical Systems (EOS) of Germany sold its first Stereos stereolithography system. The same year, Quadrax introduced the Mark 1000 SL system, which used visible light resin. The following year, Imperial Chemical Industries introduced a visible light resin product for use with the Mark 1000. ICI stopped selling its resin about one year later when Quadrax dissolved due to a legal conflict with 3D Systems. (Wohlers & Gornet, 2014).

Hideo Kodama of the Nagoya Municipal Industrial Research Institute (Nagoya, Japan) was among the first to invent the single-beam laser curing approach, according to several sources. In May 1980, he applied for a patent in Japan, which later expired without proceeding to the examination stage, a requirement of the Japanese patent application process. Kodama claimed to have difficulty in securing funds for additional research and development. (Wohlers & Gornet, 2014).

In July 1984, Jean-Claude Andre, now with the French National Center for Scientific Research (CNRS) in Nancy, France, and colleagues working for the French Cilas Alcatel Industrial Laser Company, filed a patent titled Apparatus for Fabricating a Model of an Industrial Part, involving a singlebeam laser approach. The French patent was granted in January 1986. Laser 3D, also of Nancy, France, tried to commercialize the technique outlined in the patent on a service basis with no plans to sell systems. (Wohlers & Gornet, 2014).

OPIRI, operated by the Ministry of International Trade and Industry (MITI), licensed its stereolithography technology to a group of Japanese companies, including Mitsubishi Heavy Industries, NTT Data Communications, Asahi Denka Kogyo, Toyo Denki Seizo, and YAC. Together they formed Computer Modeling and Engineering Technology (CMET) to develop, manufacture, and sell AM systems. The exact licensing date is not known, although Mitsubishi announced in July 1988 that it would sell a stereolithography machine developed jointly with OPIRI. It has been documented that these five companies supported the development and commercialization of the technology in 1989, leading to the introduction of the SOUP system in 1990. A dated SOUP product brochure, published by CMET, states that the "product had been developed on the invention of Osaka Prefectural Industrial Research Institute." (Wohlers & Gornet, 2014).

In 1989, Design-Model and Engineering Center (D-MEC) was launched as a joint venture between Sony and Japan Synthetic Rubber (JSR). In April/May 1989, D-MEC introduced its Solid Creation System (SCS) for 53 million yen. The system was capable of building urethane acrylate resin parts up to 1000 x 1000 x 750 mm in size from layers at thin as 50 microns (0.002 inch). According to one reliable source, the system was developed behind closed doors and details about its origins have been kept quiet. Clearly, Sony had knowledge of OPIRI and CMET's technology, as well as the technology developed by 3D Systems. (Wohlers & Gornet, 2014).

3D Systems began to establish a presence in Japan in early 1988 when the company formed a joint venture with Japan Steel Works, Ltd. (JSW), a Mitsui company. 3D executives signed the agreement with JSW in March 1988. The new company, JSW-3D Co., Ltd. (Tokyo), served as a sales, marketing, and service organization for 3D Systems in Japan. SLA machines were made available to the Japanese by the third or fourth quarter of 1988. Near the end of 1989, 3D terminated the agreement and formed a wholly owned subsidiary, 3D Systems Japan. (Wohlers & Gornet, 2014).

In 1989, DuPont announced the development of its Somos 1000 Solid Imaging System, a technology similar to 3D Systems' SLA. Because of their similarities, DuPont petitioned the U.S. Patent Office in September 1988 for a reexamination of Hull's 1986 patent. DuPont made the Patent Office aware of Kodama's publications, as well as those of others. Seven months later, the Patent Office told 3D Systems that it had rejected all claims in Hull's patent. This was about the time DuPont chose to go public with its Somos system, which occurred around June 1989. In late 1989, the U.S. Patent Office reversed its decision after 3D Systems produced strong evidence to support the claims in Hull's patent, but required the addition of new language that narrowed its scope. This was a turning point for DuPont. (Wohlers & Gornet, 2014).

In early 1989, Hans J. Langer, formally of General Scanning (German branch), and a few associates started Electro Optical Systems (EOS). By mid-1990, BMW ordered its first system from EOS, and later a second for about DM 1 million. European Technology Holding, a venture capital company in Amsterdam, provided the basic financial support for Langer to go into business. Langer also secured DM 1 million from the German Federal Government's program for young technology entrepreneurs. Between mid-1991 and July 1993, EOS had shipped 15 STEREOS stereolithography systems to sites in Europe and Japan. Another customer, Hitachi Zosen Information Systems, had begun to market the EOS system in Japan. (Wohlers & Gornet, 2014).

In June 1986, Itzchak Pomerantz, founder and former president of Cubital (Raanana, Israel), filed for an Israeli patent. At the time, Pomerantz was working for Scitex Corporation, an Israeli company that owned a small percentage of Cubital. Pomerantz' patent, titled Three-Dimensional Mapping and Modeling System, laid the ground work for the Solider 5600, which Cubital introduced in July 1987. In

May 1988, Cubital and 3D Systems cross-licensed certain parts of their technologies to minimize the possibility of subsequent legal conflicts. (Wohlers & Gornet, 2014).

In 1986, Russian immigrant Dr. Efrem Fudim of Light Sculpting (Milwaukee, WI) offered one of the first commercially available partbuilding services using an AM technology he invented. His system projects a flood of light from a UV lamp through a mask onto the surface of photopolymer. This mask approach was similar to Cubital's photo mask, although Cubital had automated the process. With Fudim's system, individual masks were produced on a Gerber photoplotter and manually positioned over the build chamber for each new layer. This labor intensive, time-consuming approach did not win the hearts of buyers. Consequently, Fudim did not sell a single system. (Wohlers & Gornet, 2014).

Deckard developed "Selective Laser Sintering" with Joe Beaman, a professor at UT. Deckard was working on his undergraduate degree and later his masters and Ph.D. in the UT Mechanical Engineering Department. (Lorek, 2014).

End of 1986, Deckard meets Blair and McClure and form Nova Automation. (University of Texas, 2012).

Meanwhile on campus, Deckard and Paul Forderhase, another graduate student of Joe Beaman, were designing a second machine which later earned the nickname "Godzilla" for its design. (University of Texas, 2012).

Appendix C. Work-report – Case study on Augmented Reality

C.1. Search

Primary sources are Alhamisi & Monowar (2013), Arth et al. (2015), Bensch (2015), and Van Krevelen & Poelman (2010). Below are the keywords from each of those sources that are important for the innovation phase.

Alkhamisi & Monowar (2013)

Myron Krueger, Videoplace.

Arth et al. (2015)

Ivan Sutherland.

Caudell and Mizell: first use of the term augmented reality.

Fitzmaurice: Chameleon.

Paul Milgram and Fumio Kishino: "Taxonomy of Mixed Reality Visual Displays".

Jun Rekimoto and Katashi Nagao: NaviCam.

Bensch (2015)

Tom Caudell, an engineer working in Boeing’s Computer Service’s Adaptive Neural Systems Research and Development Project.

Van Krevelen & Poelman (2010)

Ivan Sutherland.

Group of researchers at U.S. Air Force‟s Armstrong Laboratory, the NASA Ames Research Center, the Massachusetts Institute of Technology, and the University of North Carolina at Chapel Hill

Caudell and Mizell: first use of the term augmented reality.

C.1.1. Results

The keywords from the sources above are used for the further search. Results are only *included* when something new is added or when it is a reliable source that confirms something in the work-report. Other search results are *excluded* from the work-report, like confirmation of known information which is not any more reliable and has already been shown in at least two sources. However, the most important reason for exclusion is when the information is relevant only after 1994 and when it also does not imply any development before 1994. The market introduction of a new augmented reality application in 1995 would, as a counterexample, imply developments in 1994. In that case the source is not excluded.

A Google search on “Ivan Sutherland” gives many articles and webpages that give the information that was already known: he built the a head-mounted display, making the first Augmented Reality machine. *Results excluded*. A search on Google Scholar gives two promising hits, two publications from Sutherland. *Included*. (Sutherland, 1965, 1968).

The same problem for “Myron Krueger Videoplace”, a Google search gives results of unreliable sources. The seemingly most interesting result on the first page of results turns out to be based on a Wikipedia page, which in turn is based on three sources to which Krueger has no contributed. Google

Scholar immediately gives interesting results, the first of which is a 1985 paper that explains developments, starting in 1969. *Included*. (Krueger, Gionfriddo, & Hinrichsen, 1985).

The second result for “Fitzmaurice Chameleon” shows an article from 1994 named “The Chameleon: spatially aware palmtop computers”. A search on this title via https://tudelft.on.worldcat.org leads to a 1993 article named “Situated information spaces and spatially aware palmtop computers”. *Included*. (Fitzmaurice, 1993).

Paul Milgram and Fumio Kishino: "Taxonomy of Mixed Reality Visual Displays". *Included*. (Milgram & Kishino, 1994).

Searching “Caudell Boeing” gives a paper as second result: Augmented reality: An application of heads-up display technology to manual manufacturing processes (1992). *Included*. (Caudell & Mizell, 1992). An online article tells us that the system did not catch on. **Perhaps this was not the start of the market adaptation phase?** The article is *included*. (Metz, 2014).

Searching for all the names of: U.S. Air Force‟s Armstrong Laboratory, the NASA Ames Research Center, the Massachusetts Institute of Technology, and the University of North Carolina at Chapel Hill gives a book as number one result on Google. Augmented Reality: Where We Will All Live. *Chapter on the history of AR is included, chapter* . (Peddie, 2017).

An additional search for “history augmented reality” gives several comparable articles on the first page of results. A number of them are excluded for being too short or having no focus on the time period of the innovation phase. Three remain and are *included*. (Augment, 2016; Flanagan, 2018; Isberto, 2018).

Wikipedia

“Virtual fixtures Armstrong laboratory Rosenberg” leads to Rosenberg’s publication of his Virtual Fixtures system. *Included*. (Rosenberg, 1992).

Virtual Light by William Gibson is a novel that is supposed AR “as it is known today”. A search brings some results which show a relation between the book and mixed reality, but all stay vague about Gibson’s exact vision on this point. *Excluded*.

“Researchers at the Aviation Research Laboratory of the University of Illinois at Urbana-Champaign used augmented reality in the form of a flight path in the sky to teach flight students how to land a flight simulator.” Source article is from 1978 and is *included*. (Lintern & Roscoe, 1978).

“Rockwell International created video map overlays of satellite and orbital debris tracks to aid in space observations” Paper could not be found, *excluded*.

“Mike Abernathy pioneered one of the first successful augmented video overlays (also called hybrid synthetic vision) using map data for space debris in 1993,[178] while at Rockwell International. He co-founded Rapid Imaging Software, Inc. and was the primary author of the LandForm system in 1995, and the SmartCam3D system.[182][183] LandForm augmented reality was successfully flight tested in 1999 aboard a helicopter and SmartCam3D was used to fly the NASA X-38 from 1999–2002.” Confirmation of this story was found on the company’s website, *included*. (Rapid Imaging Technologies, 2019).

“S. Ravela, B. Draper, J. Lim and A. Hanson developed a marker/fixture-less augmented reality system with computer vision in 1994.” Their paper is *included*. (Ravela, Draper, Lim, & Weiss, 1995).

“Dan Reitan geospatially maps multiple weather radar images [..].] for television weather broadcasts.” This is confirmed by AR Unleashed. *Included*. (AR Unleashed, 2019).

“1987: Douglas George and Robert Morris create a working prototype of an astronomical telescope-based "heads-up display" system (a precursor concept to augmented reality) which superimposed in the telescope eyepiece, over the actual sky images, multi-intensity star, and celestial body images, and other relevant information.[267][268]” Article *included*. (George & Morris, 1989).

“1992: Steven Feiner, Blair MacIntyre and Doree Seligmann present an early paper on an AR system prototype, KARMA, at the Graphics Interface conference.” Published version of this paper is *included.* (Feiner, Macintyre, & Seligmann, 1993).

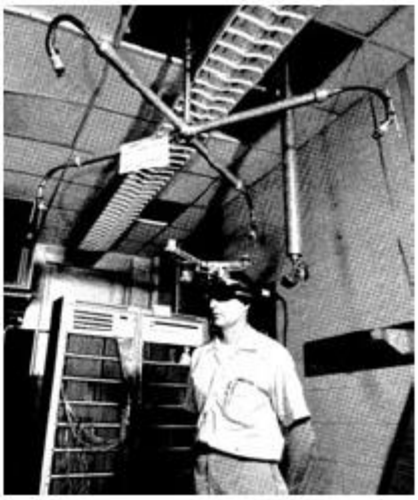
“1993: Loral WDL, with sponsorship from STRICOM, performed the first demonstration combining live AR-equipped vehicles and manned simulators. Unpublished paper, J. Barrilleaux, "Experiences and Observations in Applying Augmented Reality to Live Training", 1999.[272]” *Included*. (Barrilleaux, 1999).

“1994: Julie Martin creates first 'Augmented Reality Theater production', Dancing In Cyberspace.” A search on “martin Augmented Reality Theater production” leads to an online article from the European Theatre Lab about augmented reality in theaters. *Included*. (European Theatre Lab, 2017).

C.2. Timeline

Year	Hallmarks	Remarks
1862 – 1950s		1862: Pepper’s ghost is an illusion technique used in theatre, amusement parks, museums, television, and concerts. It is named after John Henry Pepper (1821–1900), a scientist who popularized the effect in a famed demonstration in 1862. (Peddie, 2017). The first mention of an augmented reality-like device is believed to have been in L. Frank Baum’s (1856–1919) (author of The Wonderful Wizard of Oz) 1901 novel, The Master Key: An Electrical Fairy Tale, [1] where he described a set of electronic glasses called a “character marker” that could reveal a person’s hidden personality traits and give insight into a person’s character. (Peddie, 2017). L. Frank Baum, in 1901 wrote a short story called “The Master Key” in it appear a set of spectacles, electrical in nature, that can show the wearer the nature of one’s character, by showing a letter on peoples foreheads to the user. “These things are quite improbable, to be sure; but are they impossible?”L. Frank Baum (The Master Key, 1901). (Flanagan, 2018). 1901: An adaptation of Pepper’s ghost was put forth in 1901 by Sir Howard Grubb (1844–1931) an optical designer from Dublin, who patented “A New Collimating-Telescope Gun Sight for Large and Small Ordnance (Fig. 5.3).” (Peddie, 2017). Some would argue its inspiration can be traced back to 1901, and the publication of a novel called "The Master Key: An Electrical Fairy Tale", by L. Frank Baum - yes the same Frank Baum who wrote The Wonderful Wizard of Oz! (AR Unleashed, 2019) 1942: The history of augmented, or mitigated reality in the form of a head-up display (HUD), can be traced back to the early 1940s during World War II, in England. In October 1942, the Telecommunications Research Establishment (TRE), in charge of UK radar development successfully combined the image from the Airborne Interception Mk. II radar (AI Mk. II) radar tube with a projection from their standard GGS Mk. II gyro gunsight on a flat area of the windscreen of a de Havilland Mosquito night fighter. (Peddie, 2017). The teleprompter, developed by Hubert Schiafly in 1950, consisted of a transparent panel placed in front of a speaker like a podium, and a projector projected the speaker’s text or script on it. The text was only visible to the speaker. That allowed the speaker to look straight ahead and not look down to consult written notes, he appears to have memorized the speech or to be speaking spontaneously, looking directly into the camera lens (Fig. 5.4). (Peddie, 2017). The term augmented reality appears for the first time in 1950s when Morton Heilig, a motion-picture cameraman, believed that cinema as an art should be capable of drawing the watcher into the on screen activity. (Alkhamisi & Monowar, 2013).

		A precursor technology to augmented reality, heads-up displays were first developed for pilots in the 1950s, projecting simple flight data into their line of sight, thereby enabling them to keep their "heads up" and not look down at the instruments. https://en.wikipedia.org/wiki/Augmented_reality (04-06-2019). 1953: The first synthetic-vision aircraft system was the Army-Navy Instrumentation Program (ANIP) [8]. Conceived in 1953 for the purpose of providing a new concept of flight data instrumentation which would make possible the optimum use of performance capability and true all-weather operation of aircraft (Fig. 5.5). (Peddie, 2017). 1961: Philco is credited with having developed the first augmented reality-like head-mounted system, they called Headsight. It features a helmet with a cathode-ray tube and had magnetic head-position tracking (Fig. 5.6). (Peddie, 2017). 1962: Hughes Aircraft also had a head-mounted device in the same time period, called the Electrocular (Fig. 5.7) [10]. (Peddie, 2017). 1963: Bell Helicopter Company in Fort Worth, Texas was experimenting with a servo-controlled camera and remote viewing device on a headset. The display provided the pilot with an augmented view of the ground, captured by an infrared camera under the helicopter. (Peddie, 2017).
1962	Heilig, Sensorama	In 1962, Heilig developed a model of his idea, that he termed in 1955 as “The Cinema of the Future”, known as Sensorama, which exist before digital computing [5]. (Alkhamisi and Monowar, 2013, p.25). In 1962 Morton Helig, a filmmaker, filed a patent for what was known as the Sensorama Simulator, an “apparatus to stimulate the senses of an individual to simulate an actual experience realistically”. Although its original application was for entertainment. Providing the user a simulated experience of driving through the streets of Brooklyn on a motorbike. According to his patent, he envisioned its eventual use to be for teaching and training in jobs and environments that might otherwise cause the trainees harm, such as military training. Unfortunately, The device never succeeded past the prototype stage. (Flanagan, 2018). In 1957, Morton Heilig invented the world's first virtual reality device, the Sensorama Machine. His Sensorama Machine was capable of providing the illusion of reality by using 3-D motion pictures, stereo sound, a vibrating seat, wind in the hair, and even smells! He patented the Sensorama Machine in 1962, and has been known as the Father of Virtual Reality ever since. (AR Unleashed, 2019).
1965		Ivan Sutherland, famous for his SketchPad project at MIT in 1962 took a position as an associate professor at Harvard University. He envisioned augmented reality in his 1965 essay entitled The Ultimate Display [11]. (Peddie, 2017). Numerous mentions in the paper published by Caudell and Mizell reference earlier designs but none stand out more than Ivan Sutherland. Who, in the Proceedings of IFIP 1965, wrote ‘The Ultimate Display’. Something more akin to Star Treks holodeck, where a computer could control the existence of matter within that room. (Flanagan, 2018).
1967	Experiments	I did some preliminary three-dimensional display experiments during late 1966 and early 1967 at the MIT Lincoln Laboratory. (Sutherland, 1968).

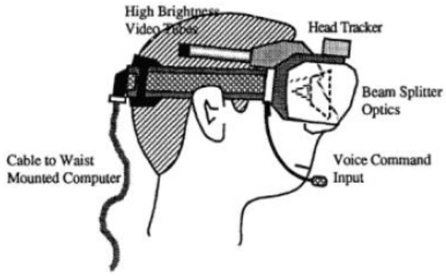
1967		Tom Furness (April 19, 1943–) was working in the Air Force on pilot head-mounted displays for weapon aiming. Approximately 22 years later, he started the Human Interface Technology lab (HIT Lab) at the University of Washington (Fig. 5.8). (Peddie, 2017).
1968	Invention of AR	Then, Ivan Sutherland devised the head mounted in 1966 [2,5]. While in 1968, he developed a working prototype of the first AR system [2]. (Alkhamisi & Monowar, 2013). Ivan Sutherland [67] creates the first augmented reality system, which is also the first virtual reality system (see Fig.2(a) left). It uses an optical see-through head-mounted display that is tracked by one of two different 6DOF trackers: a mechanical tracker and an ultrasonic tracker. Due to the limited processing power of computers at that time, only very simple wireframe drawings could be displayed in real time. (Arth et al., 2015).  In 1968, Sutherland, with his student Bob Sproull (1945–), Quintin Foster, and Chuck Seitz, a grad student at MIT, built the headset with head-tracking and a special purpose computer to generate a single cube with some lettering on the sides (Fig. 5.9). They used the same display Bell Helicopter used, with two CRTs (one for each eye) and developed a head-mounted display suspended from the ceiling, which became named, “The Sword of Damocles.” (Peddie, 2017).

	Founding of Evans & Sutherland Computer Corporation	Later that year, Sutherland moved to Utah, where he joined the Computer Science Department at the University of Utah founded by Dave Evans (1924–), Sutherland had known Evans from his ARPA days at MIT. Together they founded Evans & Sutherland Computer Corporation in 1968, the first computer graphics company in the world, and a pioneer in CG. (Peddie, 2017). The first AR prototypes (Fig. 2), created by computer graphics pioneer Ivan Sutherland and his students at Harvard University and the University of Utah, appeared in the 1960s and used a see-through HMD to present 3D graphics. (Van Krevelen & Poelman, 2007). Ivan Sutherland developed the first head-mounted display system. The system used computer-generated graphics to show users simple wireframe drawings. (Augment, 2016). From 1966 on, at MIT's Lincoln Lab Sutherland and his colleagues worked on projects relating to head mounted displays. Then, again in Proceedings of IFIP 1968, Sutherland wrote 'A head mounted three dimensional display' which has been commonly referred to as the sword of Damocles. A head mounted display so heavy it had to be suspended from the ceiling. (Flanagan, 2018). In 1968, a Harvard professor and computer scientist by the name of Ivan Sutherland invented what he called The Sword of Damocles. He invented this first sort of augmented reality device with his student, Bob Sproull. (Isberto, 2018). The year 1968 saw Harvard Associate Professor of Electrical Engineering, Ivan Sutherland, and his student Bob Sproull, create the first virtual reality and augmented reality head mounted display. Suspended by a giant claw mounted to the ceiling of their lab, its imposing appearance inspired them to name it the Sword of Damocles. (AR Unleashed, 2019).
1969	Myron Krueger	In 1969 Myron Krueger (1942–) while earning a Ph.D. in Computer Science at the University of Wisconsin–Madison, developed a series of interactive computer artworks which he termed "artificial reality" in which he developed computer-generated environments that responded to the people in it. This technology enabled people to communicate with each other in a responsive computer generated environment despite being miles apart, the forerunner of telepresence. The projects named Glowflow, Metaplay, and Psychic Space were progressions in his research and in 1975 led to the development of Videoplace technology (funded by the National Endowment for the arts). It surrounded the users, and responded to their movements and actions, without the use of goggles or gloves. The work done in the lab contributed to his well received and often cited 1983 book, Artificial Reality [13]. (Peddie, 2017).
1970s 1980s	Research	A small group of researchers at U.S. Air Force‟s Armstrong Laboratory, the NASA Ames Research Center, the Massachusetts Institute of Technology, and the University of North Carolina at Chapel Hill continued research during the 1970s and 1980s. (Van Krevelen and Poelman, 2010, p.1). During the 1970s and 1980s, augmented reality was a research topic at some institutions, including the U.S. Air Force's Armstrong Laboratory, the NASA Ames Research Center, the Massachusetts Institute of Technology, and the University of North Carolina at Chapel Hill. (Peddie, 2017).

1971	SAAF	1971: South Africa emerged as one of the pioneers and leaders in helmet-mounted gun-sight technology. The SAAF was also the first air force to fly the helmet gun-sight operationally. (Peddie, 2017).
1972 - 1992	Complementary products Mobile devices	The first conceptual tablet computer was proposed in 1972 by Alan Kay, named the Dynabook [32]. The Dynabook was proposed as personal computer for children, having the format factor of a tablet with a mechanical keyboard (really similar design from the One Laptop per Child project started in 2005). The Dynabook is probably recognized as being the precursor of the tablet computers decades before the iPad (see Fig. 2(b)). (Arth et al., 2015). The first handheld mobile phone was presented by Motorola and demonstrated in April 1973 by Dr Martin Cooper [1]. The mobile named DynaTAC for Dynamic Adaptive Total Area Coverage was supporting only 35 minutes of call (see Fig. 2(c)). (Arth et al., 2015). The first laptop, the Grid Compass2 1100 is released, which was also the first computer to use a clamshell design. The Grid Compass 1100 had an Intel 8086 CPU, 350 Kbytes of memory and a display with a resolution of 320x240 pixels, which was extremely powerful for that time and justified the enormous costs of 10.000 USD. However, its weight of 5kg made it hardly portable. (Arth et al., 2015). At COMDEX 1992, IBM and Bellsouth introduce the first smart-phone, the IBM Simon Personal Communicator3, which was released in 1993 (see Fig.2(e)). The phone has 1 Megabyte of memory and a B/W touch screen with a resolution of 160 x 293 pixels. The IBM Simon works as phone, pager, calculator, address book, fax machine, and e-mail device. It weights 500 grams and cost 900 USD. (Arth et al., 2015). During this time (*1970s/1980s, red.*) mobile devices like the Sony Walkman (1979), digital watches and personal digital organisers were introduced. This paved the way for wearable computing (Mann, 1997; Starner et al., 1997) in the 1990s as personal computers became small enough to be worn at all times. Early palmtop computers include the Psion I (1984), the Apple Newton MessagePad (1993), and the Palm Pilot (1996). Today, many mobile platforms exist that may support AR, such as personal digital assistants (PDAs), tablet PCs, and mobile phones. (Van Krevelen and Poelman, 2010, p.1-2).
1974	VTAS	The US Navy were the first to field an operational helmet-mounted sight system in a fighter aircraft, the Visual Target Acquisition System, also known as VTAS. (Peddie, 2017).
1974	Steve Mann	Also in 1974: Steve Mann creates the concept of wearable augmented reality, using wearable computers to overlay phenomenological signals onto visual reality. (Peddie, 2017).

1975	Founding of Videoplace	After that Myron Krueger in 1975 established an artificial reality laboratory called video place. It is an area which enables users to easily deal with the virtual elements for the first time [5,6]. (Alkhamisi and Monowar, 2013, p.25). The VIDEOPLACE System combines a participant's live video image with a computer graphic world. It also coordinates the behavior of graphic objects and creatures so that they appear to react to the movements of the participant's image in real-time. A prototype system has been implemented and a number of experiments with aesthetic and practical implications have been conducted. (Krueger et al., 1985). 1974: Myron Krueger built an 'artificial reality' laboratory called the Videoplace. The Videoplace combined projectors with video cameras that emitted onscreen silhouettes, surrounding users in an interactive environment. (Augment, 2016). One of the next big developments in augmented reality was in 1974 by Myron Krueger. The project was called, Videoplace, which combined a projection system and video cameras that produced shadows on the screen. This setup made the user feel as though they were in an interactive environment. (Isberto, 2018). In 1974, Videoplace, an artificial reality laboratory, was established by American computer artist Myron Krueger. By utilizing video cameras, projectors, special hardware, and silhouettes projected onto a screen, he was able to immerse users in an interactive artificial environment. (AR Unleashed, 2019).
1978	Landing an aircraft	A simple and relatively inexpensive computer -generated visual display was used to teach flight -naive subjects to land an aircraft simulator. One aim of this experiment was to test augmented feedback techniques for simulator landing instruction. Another aim was to examine the value of a visual landing display, in conjunction with a ground -based trainer, for teaching airplane landing skills. (Lintern & Roscoe, 1978).
1980	Eyetap	1980: Steve Mann's WearComp 1, cobbled together many devices to create visual experience. It included an antenna to communicate wirelessly and share video. Mann later re-named the next version, "Eyetap." (Peddie, 2017). A couple of years later in 1978, University of Toronto professor Steven Mann invented EyeTap, a wearable computer imaging system that delivered computer mediated reality to the wearer. (AR Unleashed, 2019).
1981	Dan Reitan	1981: The idea of overlaying computer and RADAR augmented reality data over a TV image was developed by Dan Reitan (1960–) for television weather broadcasts which brought augmented reality to TV. Reitan is credited with inventing the original augmented reality-based weather visualizations at KSDK St. Louis, Mo. The inventions went live on-air at KSDK, WGN and many other stations; not just overlay, but mixed real-time images from multiple radar imaging systems and satellites in real-time. Reitain went on to develop an application called ReinCloud, and obtained serval patents [14]. (Peddie, 2017). The augmented reality concept remained in relative obscurity until the early 1980's. That's when the world at large got it's first real taste of AR. Dan Reitan's interactive AR system for weather broadcasters debuted for the first time on television in 1982. It combined multiple image sources in real time (including RADAR, space-based and studio cameras) with 3-D graphics in an interactive on-air system. (AR Unleashed, 2019).

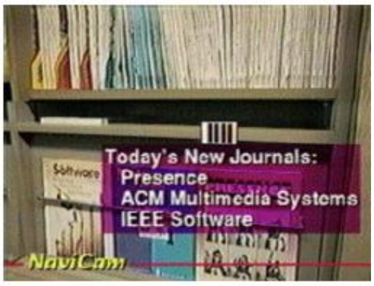
1985		1985: While working at the Armstrong Laboratory at Wright-Patterson Air Force Base, Thomas Furness conceived the idea of a virtual retinal display as a means of providing a higher luminance helmet-mounted display for pilots. About the same time in 1986, Kazuo Yoshinaka (1916–2001) while working at Nippon Electric Co also developed the idea. (In November 1991, Furness and his colleague Joel S. Kollin completed the development of the VRD at the Human Interface Technology Laboratory at the University of Washington and filed a patent in 1992.) (Peddie, 2017).
1989	Reflection Technology	Reflection Technology introduced The Private Eye head-mounted display. It had a monochrome array of LEDs in a 1.25-inch display that was scanned vertically using a vibrating mirror. Images appeared to be like a 15-inch display at 18-inches distance (Fig. 5.14). (Peddie, 2017).
1989	Telescope guidance	A unique and novel device is proposed which can display computer generated, multi-intensity star images and other graphics in the eyepiece of an astronomical telescope. These graphics are superimposed upon and synchronized with the actual sky image. (George & Morris, 1989).
1990s	Research	At the beginning of 1990s, AR became a field of study. (Alkhamisi & Monowar, 2013).
1990	"AR" coined	1990: The term "Augmented Reality" is attributed to Thomas P. Caudell, and David Mizell [16] former Boeing researchers [17]. (Peddie, 2017). 1990: Boeing researcher, Tom Caudell, coins the term "Augmented Reality". (Augment, 2016). In 1990, a Boeing researcher named Tom Caudell coined the term "Augmented Reality". (Isberto, 2018). It all started in 1990 when Boeing researcher, Tom Caudell, would coin the term Augmented Reality to describe a wearable device that could overlay digital versions of expensive wiring diagrams used by aircraft electricians onto a physical object. (AR Unleashed, 2019).
1991	CyberEdge	1991: Ben Delaney launched CyberEdge Journal. From January 1991 until January 1997, CyberEdge Journal was the voice of the virtual reality industry [18]. (Peddie, 2017).

1992	Experimental application Term AR	It took until the early 1990s before the term „augmented reality‟ was coined by Caudell and Mizell (1992), scientists at Boeing Corporation who were developing an experimental AR system to help workers put together wiring harnesses. (Van Krevelen and Poelman, 2010, p.2). Tom Caudell and David Mizell coin the term "augmented reality" to refer to overlaying computer-presented material on top of the real world [8] (see Fig.2(d)). Caudell and Mizell discuss the advantages of AR versus VR such as requiring less processing power since less pixels have to be rendered. They also acknowledge the increased registration requirements in order to align real and virtual. (Arth et al., 2015, p.3)  Our research and development project at Boeing is aimed at advancing the components of this technology to the point at which the use of AR in manufacturing applications is practical. (Caudell & Mizell, 1992). Four applications have been developed for this demonstration system. […] The first of these is the wiring formboard. […] The second application is connector assembly. […] The third application is composite cloth layup. […] The final application in this demonstration system is maintenance or assembly. (Caudell & Mizell, 1992). Caudell and Mizell built such a system that the workers could wear on their heads. But, as with other early attempts to overlay the real world with bits of the virtual, it didn’t catch on. Caudell says that was largely because the head-tracking required to make the system work while people moved around wasn’t responsive enough, and wearable computers were nowhere near as powerful as they are today. However, he did come up with a term for this new kind of digital vision: augmented reality. (Metz, 1994). Caudell and Mizell worked at Boeing on simplifying the process of conveying wiring instructions for aircraft assembly to construction workers, and they referred to their proposed solution of overlaying computer represented material on top of the real world as augmented reality. In 1992 it was published in a paper in the Proceedings of the Twenty-Fifth Hawaii International Conference on System Sciences. Krueger pre-dates that with his 1983 book, Artificial Reality [13], and his work at the University of Wisconsin in 1969. (Peddie, 2017).

		Although it is hard to determine the absolute first implementation of an AR system, one of the first industry applications of computer-based AR explicitly referred to as an “augmented reality” device was designed and implemented for industrial applications in 1994 by Tom Caudell, an engineer working in Boeing’s Computer Service’s Adaptive Neural Systems Research and Development Project [11]. While at first computer-generated models were displayed on computer screens and available to the workers as “guides”, Caudell’s revolutionary approach, based on the work of Ivan Sutherland in 1968 [12], resorted to the use of a see-through display mounted on a head-set device work by the workers that enabled the superposition of computer models on to the real view of the physical parts hence facilitating the workers task by truly augmenting the users view with computer-simulated cues. This would be the first industrial application of Sutherland’s concept of a Head-mounted Display (HMD) [12], a tool that is only just recently being explored for commercial use by companies like Oculus VR and Valve Software. (Bensch, 2015). Boeing researchers, Thomas Caudell and David Mizell are widely regarded as the men who coined the phrase ‘Augmented Reality’ in 1992. When the first industrial use of AR was designed at Boeing for the assembly of aircraft parts. (Flanagan, 2018).
1992	Feiner, KARMA	1992: Although several working prototypes of augmented reality had been demonstrated, Steven Feiner (1952–), Blair MacIntyre, and Doree Seligmann are credited with presenting the first major paper on an augmented reality system prototype, KARMA (Knowledge-based Augmented Reality for Maintenance Assistance) [20, 21], at the Graphics Interface conference (Fig. 5.15). (Peddie, 2017). 1993- Steven K. Feiner introduced KARMA (Knowledge Based Augmented Reality); a system of maintenance and repair instruction using a head mounted display. (AR Unleashed, 2019). We discuss KARMA—Knowledge based Augmented Reality for Maintenance Assistance--a testbed system for exploring the automated design of augmented realities that explain maintenance and repair tasks. […]KARMA represents our first steps in designing a testbed for the knowledge-based generation of maintenance and repair instructions using a head-mounted, see-through display. (Feiner et al., 1993).
1992	Snow Crash	1992: Neal Stephenson publishes Snow Crash introducing the concept of the Metaverse. Stephenson joined the Magic Leap company in 2015. (Peddie, 2017).

1992 1993	Experimental system for the military Founding of Immersion corporation	Louis Rosenberg developed one of the first known AR systems, called Virtual Fixtures, while working at the U.S. Air Force Armstrong Labs in 1991, and published the first study of how an AR system can enhance human performance.[248] Rosenberg's subsequent work at Stanford University in the early 90's, was the first proof that virtual overlays when registered and presented over a user's direct view of the real physical world, could significantly enhance human performance.[249][250][251]. https://en.wikipedia.org/wiki/Augmented_reality (2019-06-03). 1992: Louis Rosenberg (1969–) developed Virtual Fixtures, one of the first functioning augmented reality systems, for the Air Force Research Laboratories. This allowed the military to work in remote areas [19]. In 1993, Rosenberg founded the virtual reality company, Immersion Corporation. Then in 2000, Rosenberg then founded Outland Research, a company specializing in advanced methods of human-computer interaction and in 2001 Google purchased Outland Research, along with its patents. (Peddie, 2017). 1992: Louis Rosenberg develops Virtual Fixtures – one of the earliest functioning AR systems, built for the Air Force. The full upper-body exoskeleton allowed the military to control virtually guided machinery to perform tasks from a remote operating space. (Augment, 2016). In 1992, Louis Rosenburg from the USAF Armstrong's Research Lab created the first real operational augmented reality system, Virtual Fixtures. A robotic system places information on top the workers work environment to help with efficiency. This system could be thought of as an early version of what most AR systems currently do today. (Isberto, 2018). In 1992, while working with the U.S. Air Force, Louis Rosenberg created the first ever augmented reality system Virtual Fixtures. Through his related studies at Stanford University, he also provided the first proof that the augmented reality concept of overlaying digital information directly over a person's field of view could significantly improve their performance at given tasks. (AR Unleashed, 2019).
1992 1993	Military simulation	Between 1992 and 1993 a series of three high visibility Augmented Reality / Seamless Simulation demonstrations were conducted. Augmented Reality allowed vehicle crews to see virtual vehicles and weapon effects. Two-way Seamless Simulation allowed live and virtual vehicles to interact in real-time on the same battlefield. The work was primarily sponsored by STRICOM, the Army's command for simulation and training. The author of this paper served as the chief architect and technical manager. (Barrilleaux, 1999).
1993	Navigation system (speech only?)	Loomis et al. develop a prototype of an outdoor navigation system for visually impaired [39]. They combine a notebook with a differential GPS receiver and a head-worn electronic compass. The application uses data from a GIS (Geographic Information System) database and provides navigational assistance using an "acoustic virtual display": labels are spoken using a speech synthesizer and played back at correct locations within the auditory space of the user. (Arth et al., 2015, p.4). True mobile AR was still out of reach, but a few years later Loomis et al. (1993) developed a GPS-based outdoor system that presents navigational assistance to the visually impaired with spatial audio overlays. Soon computing and tracking devices became sufficiently powerful and small enough to support graphical overlay in mobile settings. (Van Krevelen and Poelman, 2010, p.2).

1993	AR with hand-held device	Fitzmaurice creates Chameleon (see Fig.3(a)), a key example of displaying spatially situated information with a tracked and hand-held device. In his setup the output device consists of a 4" screen connected to a video camera via a cable [16]. The video camera records the content of a Silicon Graphics workstation's large display in order to display it on the small screen. Fitzmaurice uses a tethered magnetic tracker (Ascension bird) for registration in a small working environment. Several gestures plus a single button allow the user to interact with the mobile device. Chameleon's mobility was strongly limited due to the cabling. It did also not augment in terms of overlaying objects on a video feed of the real world. (Arth et al., 2015, p.4). 
1993	Technology component GPS for augmented reality	In December 1993 the Global Positioning System (GPS, official name "NAVSTAR-GPS") achieves initial operational capability (see Fig.3(b)). Although GPS4 was originally launched as a military service, nowadays millions of people use it for navigation and other tasks such as geo-caching or Augmented Reality. A GPS receiver calculates its position by carefully timing the signals sent by the constellation of GPS satellites. The accuracy of civilian GPS receivers is typically in the range of 15 meter. More accuracy can be gained by using Differential GPS (DGPS) that uses correction signals from fixed, ground-based reference stations. (Arth et al., 2015, p.4).
1993	Thad Starner	1993: Lizzy—Thad Starner (1969–) starts constantly wearing his computer based on Doug Platt's design [MIT]. (Peddie, 2017).
1993	Loral WDL	1993: Loral WDL, with sponsorship from STRICOM, performed the first demonstration combining live augmented reality-equipped vehicles and manned simulators. (Peddie, 2017).
1994	Steve Mann	Steve Mann starts wearing a webcam for almost 2 years. From 1994-1996 Mann wore a mobile camera plus display for almost every waking minute. Both devices were connected to his website allowing online visitors to see what Steve was seeing and to send him messages that would show up on his mobile display. (Arth et al., 2015).
1994	First AR application Theatre	1994: Augmented reality was first used for entertainment purposes when Julie Martin created what is believed to be the first Augmented Reality Theater production, "Dancing in Cyberspace." Funded by the Australia Council for the Arts, featuring acrobats and dancers manipulating body–sized virtual objects in real time, projected into the same physical space and performance plane. (Peddie, 2017). 1994: Julie Martin creates the first augmented reality Theater production, "Dancing in Cyberspace", featuring acrobats who danced within and around virtual objects on their physical stage. (Augment, 2016). In 1994, the first theater production to use augmented reality was created. "Dancing in Cyberspace" presented acrobats dancing in and around virtual objects on stage as a piece of art was produced by Julie Martin. (Isberto, 2018). During the 90s, augmented reality was also used in the arts. One such example is Julie Martin, an Australian woman who created a show called Dancing in Cyberspace, which was funded by the Australia Council for the Arts. Said show features acrobats who play with virtual objects. (European Theatre Lab, 2017).

1994	SixthSense	1994: SixthSense is a gesture-based wearable computer system developed at MIT Media Lab by Steve Mann in 1994 [25] and 1997 (head worn gestural interface), and 1998 (neckworn version), and further developed by Pranav Mistry (also at MIT Media Lab). (Peddie, 2017).
1994/ 1997 ?	Definition of AR	Paul Milgram and Fumio Kishino write their seminal paper "Taxonomy of Mixed Reality Visual Displays" in which they define the Reality-Virtuality Continuum [41] (see Fig.4(a)). Milgram and Kishino describe a continuum that spans from the real environment to the virtual environment. In between there are Augmented Reality, closer to the real environment and Augmented Virtuality, which is closer to the virtual environment. Today Milgram's Continuum and Azuma's definition (1997) are commonly accepted as defining Augmented Reality. (Arth et al., 2015, p.6).
1995	Removing markers and beacons	Temporal registration can be achieved using two basic approaches. One relatively expensive yet proven technology is to instrument the real world with location beacons and position sensors. The other is to visually track modelled object features and use pose estimation to update the object-camera transform. This approach is cheaper, can be used in unmodified environments and permits annotation of independently moving objects1. (Ravela et al., 1995).
1995	NaviCam	Jun Rekimoto and Katashi Nagao create the NaviCam, a tethered setup, similar to Fitzmaurice's Chameleon [58] (see Fig.4(b)). The NaviCam also uses a nearby powerful workstation, but has a camera mounted on the mobile screen that is used for optical tracking. The computer detects color-coded markers in the live camera image and displays context sensitive information directly on top of the video feed in a see-through manner. (Arth et al., 2015, p.6).  Rekimoto (1997) presented NaviCam for indoor use that augmented a video stream from a hand held camera using fiducial markers for position tracking. (Van Krevelen and Poelman, 2010).
1995	Audio AR	Benjamin Bederson introduced the term Audio Augmented Reality by presenting a system that demonstrated an augmentation of the audition modality [5]. The developed prototype uses a MDplayer which plays audio information based on the tracked position of the user as part of a museum guide. (Arth et al., 2015, p.6).
1996	2D matrix markers	Jun Rekimoto presents 2D matrix markers7 (square-shaped barcodes), one of the first marker systems to allow camera tracking with six degrees of freedom [57] (see Fig.4(c)). (Arth et al., 2015, p.6). 1996- Professor Jun Rekimoto, of the University of Tokyo, invents 2d matrix markers. (AR Unleashed, 2019).
1996	Sony Glasstron	1996: Sony released the Glasstron, a head-mounted display which included two LCD screens and two earphones for video and audio respectively. It also had a mechanical shutter to allow the display to become see-through. (Peddie, 2017).

1997	First survey on AR	In 1997, Ronald Azuma conducted the first survey in AR whereas he introduced a broadly accepted definition of AR. He defined it as assembling real and virtual environment together while both of them is being recorded in 3D and interactive in real time. (Alkhamisi & Monowar, 2013). Ronald Azuma presents the first survey on Augmented Reality. In his publication, Azuma provides a widely acknowledged definition for AR [4], as identified by three characteristics: it combines real and virtual, it is interactive in real time, it is registered in 3D. (Arth et al., 2015, p.6). 1997: Ronald T. Azuma's, A Survey of Augmented Reality, examined the varied uses of augmented reality such as medical, manufacturing, research, mechanical operation and entertainment. (Peddie, 2017).
Late 1990s	Computing and tracking devices	Soon computing and tracking devices became sufficiently powerful and small enough to support graphical overlay in mobile settings. (Van Krevelen and Poelman, 2010, p.2).
1997	Community with AR	Thad Starner et al. explore possible applications of mobile augmented reality, creating a small community of users equipped with wearable computers interconnected over a network [66]. The explored applications include an information system for offices, people recognition and coarse localization with infrared beacons. (Arth et al., 2015, p.7). Starner et al. (1997) consider applications and limitations of AR for wearable computers, including problems of finger tracking and facial recognition. (Van Krevelen and Poelman, 2010).
1997	First mobile AR system	Steve Feiner et al. present the Touring Machine, the first mobile augmented reality system (MARS) [15] (see Fig.4(d) and Fig. 4(e)). It uses a see-through head-worn display with integral orientation tracker; a backpack holding a computer, differential GPS, and digital radio for wireless web access; and a hand-held computer with stylus and touchpad interface8. (Arth et al., 2015, p.6). Feiner et al. (1997) created an early prototype of a mobile AR system (MARS) that registers 3D graphical tour guide information with buildings and artefacts the visitor sees. (Van Krevelen and Poelman, 2010, p.2). 1996: Steven Feinberg, professor of computer science at Columbia University, created the first outdoor mobile augmented reality system using a see-through display. 1997: Mobile Backpack augmented reality, The Touring Machine, developed at Columbia starting in 1996, was the first mobile augmented reality system (MARS) that did graphical augmented reality. It combined a head-mounted display, handheld tablet display, and a backpack with computer, GPS, and Internet connection (Peddie, 2017). 1997- Steven K. Feiner prototypes a 3-D mobile augmented reality system for exploring urban environments. (AR Unleashed, 2019).
1997	Invention camera phone	Philippe Kahn invents the camera phone9, a mobile phone which is able to capture still photographs (see Fig.5(a)). Back in 1997, Kahn used his invention to share a picture of his newborn daughter with more than 2000 relatives and friends, spread around the world. Today more than half of all mobile phones in use are camera phones. (Arth et al., 2015).

Late 1990s	More research Software toolkits	By the late 1990s, as AR became a distinct field of research, several conferences on AR began, including the International Workshop and Symposium on Augmented Reality, the International Symposium on Mixed Reality, and the Designing Augmented Reality Environments workshop. Organisations were formed such as the Mixed Reality Systems Laboratory (MRLab) in Nottingham and the Arvika consortium in Germany. Also, it became possible to rapidly build AR applications thanks to freely available software toolkits like the ARToolKit. In the meantime, several surveys appeared that give an overview on AR advances, describe its problems, classify and summarise developments (Azuma, 1997; Azuma et al., 2001). (Van Krevelen and Poelman, 2010, p.2). Late 1990s: Augmented reality became a distinct field of research, and conferences on augmented reality were started, including the International Workshop and Symposium on Augmented Reality [27], the International Symposium on Mixed Reality, and the Designing Augmented Reality Environments workshop. Organizations were formed such as the Mixed Reality Systems Laboratory (MRLab) in Nottingham and the Arvika consortium3 in Germany [28]. (Peddie, 2017).
1997	Sony: intro Glasstron	Sony releases the Glasstron, a series of optical HMD (optionally see-through) for the general public. Adoption was rather small, but the affordable price of the HMD made it really popular in AR research labs and for the development of wearable AR prototype (see Fig. 5(b)). (Arth et al., 2015, p.7).
1997	Sports	One example is the FoxTrax system (Cavallaro, 1997), used to highlight the location of a hard-to-see hockey puck as it moves rapidly across the ice, but AR is also applied to annotate racing cars (Fig. 27a), snooker ball trajectories, life swimmer performances, etc. (Van Krevelen and Poelman, 2010).
1997	MicroOptical	1997: MicroOptical, under a Defense Advanced Research Projects Agency funded project (DARPA), demonstrated the eyewear display in which the viewing optics were incorporated in the eyeglass lens. (Peddie, 2017).
1997	Three main elements of AR	1997: Ronald Azuma is credited with establishing the three main elements that define augmented reality [29] (Peddie, 2017).: • it connects real and virtual worlds • it’s interactive in real time • it allows movement in 3D
1998	Intro Map-in-the-hat	Bruce Thomas et al. present "Map-in-the-hat", a backpackbased wearable computer that includes GPS, electronic compassband a head-mounted display [71] (see Fig.5(c)). At this stage the system was utilized for navigation guidance, but it later evolved into Tinmith, an AR platform used for several other AR projects10. (Arth et al., 2015, p.7).
1998	Surgery	An early optical see-through augmentation is presented by Fuchs et al. (1998) for laparoscopic surgery where the overlayed view of the laparoscopes inserted through small incisions is simulated (Fig. 25). (Van Krevelen and Poelman, 2010).
1998	Virtual Retinal Display	A virtual retinal display (VRD) is a personal display device under development at the University of Washington's Human Interface Technology Laboratory under Dr. Thomas A. Furness III.[51] With this technology, a display is scanned directly onto the retina of a viewer's eye. This results in bright images with high resolution and high contrast. The viewer sees what appears to be a conventional display floating in space.[52] https://en.wikipedia.org/wiki/Augmented_reality (04-06-2019).

1998	Spatial AR	1998: Spatial Augmented Reality introduced at University of North Carolina at Chapel Hill by Ramesh Raskar, Welch, Henry Fuchs.[59] https://en.wikipedia.org/wiki/Augmented_reality (06-06-2019). 1998: Concept of spatial augmented reality (SAR) introduced at the University of North Carolina, where virtual objects are rendered directly within or on the user's physical space without a headset [30]. (Peddie, 2017).
1998	Wearable PC	1998: IBM Japan demonstrated a wearable PC. (Peddie, 2017).
1998	Sportvision	1998: augmented reality in sports broadcasting—Sportvision, The use of augmented reality was introduced in a wide variety of graphics overlays used in sports broadcasting. The most well-known one was the (yellow) scrimmage line in U.S. football. (Peddie, 2017). 1998: The 1st & Ten line computer system is broadcast by Sportvision, casting the first virtual yellow first down marker during a live NFL game. (Augment, 2016). In 1998, Sportsvision uses the 1st and Ten line computer system. This system showed the original virtual yellow first down marker during a live NFL game. A variation of this virtual first down marker is now a norm in all televised football games today and is a big part of the augmented reality history. (Isberto, 2018).
1999	ARToolKit	Hirokazu Kato and Mark Billinghurst present ARToolKit, a pose tracking library with six degrees of freedom, using square ducials and a template-based approach for recognition [31]. ARToolKit is available as open source under the GPL license and is still very popular in the AR community (see Fig. 5(d)). (Arth et al., 2015, p.7). 1999: The ARToolkit developed by Mark Billinghurst and Hirokazu Kato by the Human Interface Technology Laboratory at the University of Washington. The technology was first demonstrated publicly at SIGGRAPH in 1999. It was released open source in 2001 by the HIT and commercialized by ARToolworks under a dual licensing model (Fig. 5.19). (Peddie, 2017).
1999	Mobile AR with news	Tobias Höllerer et al. develop a mobile AR system that allows the user to explore hypermedia news stories that are located at the places to which they refer and to receive a guided campus tour that overlays models of earlier buildings [26] (see Fig. 6(a)). This was the first mobile AR system to use RTK GPS and an inertial-magnetic orientation tracker. (Arth et al., 2015). Höllerer et al. (1999) use AR to create situated documentaries about historic events. (Van Krevelen and Poelman, 2010). 1999- Tobias Höllerer, Steven Feiner, Drexel Hallaway, Gus Rashid, Tachio Terauchi, introduce the Mobile Augmented Reality System (MARS). (AR Unleashed, 2019).
1999	Interaction indoor vs outdoor	Tobias Höllerer et al. present a mobile augmented reality system that includes indoor user interfaces (desktop, AR tabletop, and head-worn VR) to interact with the outdoor user [27] (see Fig. 6(b)). While outdoor users experience a first-person spatialized multimedia presentation via a head-mounted display, indoor users can get an overview of the outdoor scene. (Arth et al., 2015, p.7).
1999	Worldboard	Jim Spohrer publishes the Worldboard concept, a scalable infrastructure to support mobile applications that span from low-end location-based services, up to high-end mobile AR [65]. In his paper, Spohrer also envisions possible application cases for mobile AR, and social implications. (Arth et al., 2015, p.7).

1999	Localization -Based Services	The first consumer LBS device was the Palm VII, only supporting zip code based location services (see Fig.5(d)). 2 years later, different mobile operators provided different location based services using private network technology11. (Arth et al., 2015, p.9).
1999	First GPS in mobile phone	Benefon Esc! NT200212, the first GSM phone with a built-in GPS receiver is released in late 1999 (see Fig. 6(c)). It had a black and white screen with a resolution of 100x160 pixels. Due to limited storage, the phone downloaded maps on demand. The phone also included a friend finder that exchanged GPS positions with other Esc! devices via SMS. (Arth et al,. 2015).
1999	Construction	An example by Feiner et al. (1999) generates overview renderings of the entire construction scene while workers use their HMD to see which strut is to be placed where in a space-frame structure. (Van Krevelen and Poelman, 2010).
1999	Military	Extra benefits specific for military users may be training in large-scale combat scenarios and simulating real-time enemy action, as in the Battlefield Augmented Reality System (BARS) by Julier et al. (1999) and research by Piekarski et al. (1999). (Van Krevelen and Poelman, 2010). 1999: The US Naval Research Laboratory engages on a decade-long research program called the Battlefield Augmented Reality System (BARS) to prototype some of the early wearable systems for dismounted soldier operating in urban environment for situation awareness and training.[273] https://en.wikipedia.org/wiki/Augmented_reality (06-06-2019). 1999: Naval researchers begin Work on Battle-field Augmented Reality System (BARS), the original model of early Wearable systems for soldiers. (Peddie, 2017).
1999	X-ray and photos	Navab et al. (1999) take advantage of the physical constraints of a C-arm x-ray machine to automatically calibrate the cameras with the machine and register the xray imagery with the real objects. (Van Krevelen and Poelman, 2010).
1999	Lens	The first contact lens display was reported in 1999,[38] https://en.wikipedia.org/wiki/Augmented_reality (04-06-2019).

1999	Use of LandForm	1999: NASA X-38 flown using LandForm software video map overlays at Dryden Flight Research Center.[274] https://en.wikipedia.org/wiki/Augmented_reality (06-06-2019). 1999: NASA turns to augmented reality with the X-38 program, which would allow researchers to better understand what technologies would be needed to build inexpensive and reliable spacecraft. (Peddie, 2017). 1999: The NASA X-38 spacecraft is flown using a Hybrid Synthetic Vision system that used to overlay map data to provide enhanced visual navigation during flight tests. (Augment, 2016). In 1999, NASA uses a hybrid synthetic vision system that integrated augmented reality in their X-38 spacecraft. The augmented reality technology was used to help improve navigation during their test flights. (Isberto, 2018). Rapid Imaging created Landform®, a synthetic vision software designed for use in the NASA X-38 Remote Cockpit program, in 1995. This early application of augmented reality proved remote pilots experienced enhanced situational awareness when utilizing geographic overlays on live video. These overlays provided visual cues highlighting geographic points of interest, giving astronauts enhanced awareness in times of poor video transmission. (Rapid Imaging Technologies, 2019).
1999	Steve Mann Meta	1999: Steve Mann is one of the earliest pioneers in digital eyewear and what he calls “mediated” reality. His breakthrough development was the enabling of mobile augmented reality. He is a professor in the department of electrical and computer engineering at the University of Toronto and an IEEE senior member, and also serves as chief scientist for the augmented reality startup, Meta (Fig. 5.20). (Peddie, 2017).

C.3. Factors

C.3.1. Expectations

The term augmented reality appears for the first time in 1950s when Morton Heilig, a motion-picture cameraman, believed that cinema as an art should be capable of drawing the watcher into the on screen activity. (Alkhamisi and Monowar, 2013, p.25).

Steve Mann starts wearing a webcam for almost 2 years. From 1994-1996 Mann wore a mobile camera plus display for almost every waking minute. Both devices were connected to his website allowing online visitors to see what Steve was seeing and to send him messages that would show up on his mobile display. (Arth et al., 2015).

It took until the early 1990s before the term „augmented reality‟ was coined by Caudell and Mizell [42], scientists at Boeing Corporation who were developing an experimental AR system to help workers put together wiring harnesses. (Van Krevelen and Poelman, 2010, p.2).

The goal of the AR is to make the life of the user easier through providing the virtual information to his adjacent environment as well as to any indirect view of the real-world environment like the live-video stream. Another goal of AR is to develop the user’s insight into and communications with the real world. (Alkhamisi & Monowar, 2013). *Was this already the expectation during the innovation phase?*

A display connected to a digital computer gives us a chance to gain familiarity with concepts not realizable in the physical world. It is a looking glass into a mathematical wonderland. (Sutherland, 1965).

If the task of the display is to serve as a looking-glass into the mathematical wonderland constructed in computer memory, it should serve as many senses as possible. So far as I know, no one seriously proposes computer displays of smell, or taste. Excellent audio displays exist, but unfortunately we have little ability to have the computer produce meaningful sounds. I want to describe for you a kinesthetic display. (Sutherland, 1965).

By working with such displays of mathematical phenomena we can learn to know them as well as we know our own natural world. Such knowledge is the major promise of computer displays. (Sutherland, 1965).

The ultimate display would, of course, be a room within which the computer can control the existence of matter. A chair displayed in such a room would be good enough to sit in. Handcuffs displayed in such a room would be confining, and a bullet displayed in such a room would be fatal. With appropriate programming such a display could literally be the Wonderland into which Alice walked. (Sutherland, 1965).

The fundamental idea behind the three-dimensional display is to present the user with a perspective image which changes as he moves. The retinal image of the real objects which we see is, after all, only two-dimensional. Thus if we can place suitable two-dimensional images on the observer's retinas, we can create the illusion that he is seeing a three-dimensional object. Although stereo presentation is important to the three-dimensional illusion, it is less important than the change that takes place in the image when the observer moves his head. (Sutherland, 1968).

When I started work on the head-mounted display I had no idea how much effort would be involved. The project would have died many times but for the spirit of the many people who have become involved. […] And finally, Stewart Ogden, so called "project engineer," actually chief administrator, who defended us all from the pressures of paperwork so that something could be accomplished. (Sutherland, 1968).

This paper describes a number of experiments in alternate modes of human-machine interaction. The premise is that interaction is a central, not peripheral, issue in computer science. We must explore this domain for insight as well as immediate application. It is as important to suggest new applications as it is to solve the problems associated with existing ones. Research should anticipate future practicality and not be bound by the constraints of the present. (Krueger et al., 1985).

As a greater percentage of the population becomes involved in the use of computers, it is natural to expect the manner of controlling computers to move away from the programming model and closer to the perceptual process we use to accomplish our goals in the physical world. (Krueger et al., 1985).

When people see their image displayed with a graphic object, they feel a universal and irresistible desire to reach out and touch it. (Fig. 2) Furthermore, they expect the act of touching to affect the graphic world. By placing each participant against a neutral background, it is possible to digitize the image of his silhouette and to recognize the moment when it touches a graphic object. The system can then cause the object to move, apparently in response to the participant's touch. (Krueger et al., 1985).

The long term objective is to develop an online real-time intelligence that understands the participant's behavior and the interaction in human terms. (Krueger et al., 1985).

VIDEOPLACE could be used to create a physically active form of Computer Aided Instruction in which the computer is used not to teach traditional material, but to alter what, as well as how, we teach. (Krueger et al., 1985).

VIDEOPLACE was originally conceived and implemented as a telecommunication environment allowing people in different places to share a common video experience. (Krueger et al., 1985).

The VIDEOPLACE techniques described in this paper can be used to duplicate any touch screen capability. A video camera pointed down at a desk surface can be used to create a VIDEODESK environment that will have several advantages over a touch screen. (Krueger et al., 1985).

This means that your personal electronic phone book, a log of your incoming and outgoing calls, and fax messages could be accessible by browsing a situated 3D electronic information space surrounding the fax machine. (Fitzmaurice, 1993).

We need highly portable displays and protocols for visualizing and filtering the electronic spheres of information. (Fitzmaurice, 1993).

As an example of a more widespread electronic information space, a computer-augmented library could offer significant improvements over a traditional library. (Fitzmaurice, 1993).

Not only can users remotely browse the contents of the office, but additional functionality can be offered such as voice and graphical annotations. (Fitzmaurice, 1993).

Electronic information will be available everywhere. In order to avoid being flooded and overwhelmed with the quantity of information, we need to adopt the notion of situated information spaces. The electronic information associated with physical objects should be collected, associated, and collocated with those objects. (Fitzmaurice, 1993).

The next generation telecommunication environment is envisaged to be one which will provide an "ideal virtual space with [sufficient] reality essential for communication"º . (Milgram & Kishino, 1994). *This is the other way around: not AR envisioned for communication, but communication in a virtual way.*

Medical imaging is an important instance of an environment in which many of these factors are relevant. Many medical imaging systems are highly specialised and have as their objective the creation of a completely modelled world. (Milgram & Kishino, 1994).

Successful development of the HUDset technology will enable cost reductions and efficiency improvements in many of the human-involved operations in aircraft manufacturing, by eliminating templates, formboard diagrams, and other masking devices. (Caudell & Mizell, 1992).

UNC group is now designing another see-through head-mounted display with custom optics. They foresee the eventual use of this technology in a variety of applications, including some similar to the manufacturing operations on which our work is focused. (Caudell & Mizell, 1992).

In 1962 Morton Helig, a filmmaker, filed a patent for what was known as the Sensorama Simulator, an "apparatus to stimulate the senses of an individual to simulate an actual experience realistically". Although its original application was for entertainment. Providing the user a simulated experience of driving through the streets of Brooklyn on a motorbike. According to his patent, he envisioned its eventual use to be for teaching and training in jobs and environments that might otherwise cause the trainees harm, such as military training. Unfortunately, The device never succeeded past the prototype stage. (Flanagan, 2018).

Like the ruler guiding the pencil, virtual fixtures overlaid on top of a remote workspace could act to reduce mental processing required to perform the task, reduce the workload of certain sensory modalities, and most of all allow precision and performance to exceed natural human abilities. (Rosenberg, 1992).

We discuss KARMA—Knowledge based Augmented Reality for Maintenance Assistance--a testbed system for exploring the automated design of augmented realities that explain maintenance and repair tasks. (Feiner et al., 1993).

Looking beyond military applications, commercial applications for AUGSIM (AUGmented SIMulation) might include: Training for civil services and disaster teams. Visualization for business, architecture and science. Maintenance and manufacturing tools for industry. Medium for education and collaboration. Games for entertainment and therapy. (Barrilleaux, 1999).

Between 1992 and 1993 a series of three high visibility Augmented Reality / Seamless Simulation demonstrations were conducted. Augmented Reality allowed vehicle crews to see virtual vehicles and weapon effects. Two-way Seamless Simulation allowed live and virtual vehicles to interact in real-time on the same battlefield. The work was primarily sponsored by STRICOM, the Army's command for simulation and training. The author of this paper served as the chief architect and technical manager. […] The motivation for the first demonstration was borne out of the simple need to do "something different" at an important trade show. (Barrilleaux, 1999).

C.3.2. Strategy

A small group of researchers at U.S. Air Force‟s Armstrong Laboratory, the NASA Ames Research Center, the Massachusetts Institute of Technology, and the University of North Carolina at Chapel Hill continued research during the 1970s and 1980s. (Van Krevelen and Poelman, 2010, p.1).

When I started work on the head-mounted display I had no idea how much effort would be involved. The project would have died many times but for the spirit of the many people who have become involved. […] And finally, Stewart Ogden, so called "project engineer," actually chief administrator, who defended us all from the pressures of paperwork so that something could be accomplished. (Sutherland, 1968).

The interface described is a deliberately informal one. The resemblance to video games might seem frivolous to the hard-nosed computer scientist used to catering to the needs of government agencies and three letter companies. However, games are a multi-billion dollar industry and by that measure practical. More importantly, games provide an extremely compelling interface whose advantages should be considered for more standard applications. Therefore, before adapting the techniques described to fit a more familiar practical context, we will examine their potential in the current VIDEOPLACE environment. (Krueger et al., 1985).

As a proof of concept, we have built a simple system that demonstrates the application of augmented reality to manufacturing. (Caudell & Mizell, 1992).

Later that year, Sutherland moved to Utah, where he joined the Computer Science Department at the University of Utah founded by Dave Evans (1924–), Sutherland had known Evans from his ARPA days at MIT. Together they founded Evans & Sutherland Computer Corporation in 1968, the first computer graphics company in the world, and a pioneer in CG. (Peddie, 2017).

1985: While working at the Armstrong Laboratory at Wright-Patterson Air Force Base, Thomas Furness conceived the idea of a virtual retinal display as a means of providing a higher luminance helmet-mounted display for pilots. About the same time in 1986, Kazuo Yoshinaka (1916–2001) while working at Nippon Electric Co also developed the idea. (In November 1991, Furness and his colleague Joel S. Kollin completed the development of the VRD at the Human Interface Technology Laboratory at the University of Washington and filed a patent in 1992.) (Peddie, 2017).

1992: Louis Rosenberg (1969–) developed Virtual Fixtures, one of the first functioning augmented reality systems, for the Air Force Research Laboratories. This allowed the military to work in remote areas [19]. In 1993, Rosenberg founded the virtual reality company, Immersion Corporation. Then in 2000, Rosenberg then founded Outland Research, a company specializing in advanced methods of human-computer interaction and in 2001 Google purchased Outland Research, along with its patents. (Peddie, 2017).

1993: Lizzy—Thad Starner (1969–) starts constantly wearing his computer based on Doug Platt’s design [MIT]. (Peddie, 2017).

1993: Loral WDL, with sponsorship from STRICOM, performed the first demonstration combining live augmented reality-equipped vehicles and manned simulators. (Peddie, 2017).

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C.3.3. Resources

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To date, only very simple graphics have been used because of the very modest resources available and the fact that until recently commercial equipment did not emphasize high speed manipulation of raster data. To a great extent, we have worked with graphic hardware of our own construction which provides a number of features important to our interactions. In addition, we have recently acquired three Silicon Graphics workstations, which will greatly enhance our ability to create and manipulate realistic three-dimensional scenes. (Krueger et al., 1985).

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This research was supported, in part, by NSERC Grant A7781. (George & Morris, 1989).

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During the 90s, augmented reality was also used in the arts. One such example is Julie Martin, an Australian woman who created a show called Dancing in Cyberspace, which was funded by the Australia Council for the Arts. Said show features acrobats who play with virtual objects. (European Theatre Lab, 2017).

C.3.4. Knowledge

A small group of researchers at U.S. Air Force‟s Armstrong Laboratory, the NASA Ames Research Center, the Massachusetts Institute of Technology, and the University of North Carolina at Chapel Hill continued research during the 1970s and 1980s. (Van Krevelen and Poelman, 2010, p.1).

Louis Rosenberg developed one of the first known AR systems, called Virtual Fixtures, while working at the U.S. Air Force Armstrong Labs in 1991, and published the first study of how an AR system can enhance human performance.[248] Rosenberg's subsequent work at Stanford University in the early 90's, was the first proof that virtual overlays when registered and presented over a user's direct view of the real physical world, could significantly enhance human performance.[249][250][251]. https://en.wikipedia.org/wiki/Augmented_reality (2019-06-03).

Paul Milgram and Fumio Kishino write their seminal paper "Taxonomy of Mixed Reality Visual Displays" in which they define the Reality-Virtuality Continuum [41] (see Fig.4(a)). Milgram and Kishino describe a continuum that spans from the real environment to the virtual environment. In between there are Augmented Reality, closer to the real environment and Augmented Virtuality, which is closer to the virtual environment. Today Milgram's Continuum and Azuma's definition (1997) are commonly accepted as defining Augmented Reality. (Arth et al., 2015, p.6).

In 1997, Ronald Azuma conducted the first survey in AR whereas he introduced a broadly accepted definition of AR. He defined it as assembling real and virtual environment together while both of them is being recorded in 3D and interactive in real time. (Alkhamisi & Monowar, 2013).

Finally, my work in Responsive Environments, beginning in 1969 and continuing to the present, has allowed a participant's movements around a room to be translated into actions in a projected graphic scene generated by the computer. [KRUE77, 83] (Krueger et al., 1985).

The interface described is a deliberately informal one. The resemblance to video games might seem frivolous to the hard-nosed computer scientist used to catering to the needs of government agencies and three letter companies. However, games are a multi-billion dollar industry and by that measure practical. More importantly, games provide an extremely compelling interface whose advantages should be considered for more standard applications. Therefore, before adapting the techniques described to fit a more familiar practical context, we will examine their potential in the current VIDEOPLACE environment. (Krueger et al., 1985).

Heads-up display technology has been with us for more than 20 years (Furness), the traditional application being fighter pilot situation displays. (Caudell & Mizell, 1992).

During the 1970s and 1980s, augmented reality was a research topic at some institutions, including the U.S. Air Force’s Armstrong Laboratory, the NASA Ames Research Center, the Massachusetts Institute of Technology, and the University of North Carolina at Chapel Hill. (Peddie, 2017).

1990: The term “Augmented Reality” is attributed to Thomas P. Caudell, and David Mizell [16] former Boeing researchers [17]. Caudell and Mizell worked at Boeing on simplifying the process of conveying wiring instructions for aircraft assembly to construction workers, and they referred to their proposed solution of overlaying computer represented material on top of the real world as augmented reality. In 1992 it was published in a paper in the Proceedings of the Twenty-Fifth Hawaii International Conference on System Sciences. Krueger pre-dates that with his 1983 book, Artificial Reality [13], and his work at the University of Wisconsin in 1969. (Peddie, 2017).

1991: Ben Delaney launched CyberEdge Journal. From January 1991 until January 1997, CyberEdge Journal was the voice of the virtual reality industry [18]. (Peddie, 2017).

The results of this study confirm that overlaying abstract sensory information in the form of virtual fixtures on top of the sensory feedback from a remote environment can greatly enhance performance in telemanipulation tasks. (Rosenberg, 1992).

A simple and relatively inexpensive computer -generated visual display was used to teach flight - naive subjects to land an aircraft simulator. One aim of this experiment was to test augmented feedback techniques for simulator landing instruction. Another aim was to examine the value of a visual landing display, in conjunction with a ground -based trainer, for teaching airplane landing skills. (Lintern & Roscoe, 1978).

C.3.5. Product

The four tasks carried out by the AR system are: scene capture; scene identification for choosing the accurate information for boosting it; scene processing and visualization of the augmented scene [8,9]. (Alkhamisi & Monowar, 2013).

Optical see-through. The most difficult aspect of using this type of HMD is obtaining an accurate registration between the real and virtual image data both spatially and temporally. The head has the capability of move very rapidly relative to the surrounding environment, thus placing a heavy constraint on processing time. Additionally, the intensity of light presents a significant obstacle to overcome, as ambient light (or a lack thereof) can result in the user having difficulty visualizing the virtual data. (Bensch, 2015, p.26).

Video see-through. There are a multitude of difficulties that come with this form of display. Without a camera with optical properties customized and selected based upon the displays used, the disparity between the field of view of each camera and the field of view of the display can cause image distortion. The positioning of the cameras also is problematic, as it is physically impossible to center the camera origin at the same place where the user's view originates. Thus cameras must be offset from the eyes, causing a sense of displacement when the user views the world from this new position. (Bensch, 2015, p.26).

The first AR prototypes (Fig. 3), created by computer graphics pioneer Ivan Sutherland and his students at Harvard University and the University of Utah, appeared in the 1960s and used a see-through to present 3D graphics [151]. (Van Krevelen and Poelman, 2010, p.1).

Ivan Sutherland [67] creates the first augmented reality system, which is also the first virtual reality system (see Fig.2(a) left). It uses an optical see-through head-mounted display that is tracked by one of two different 6DOF trackers: a mechanical tracker and an ultrasonic tracker. Due to the limited processing power of computers at that time, only very simple wireframe drawings could be displayed in real time. (Arth et al., 2015, p.2).

Loomis et al. develop a prototype of an outdoor navigation system for visually impaired [39]. They combine a notebook with a differential GPS receiver and a head-worn electronic compass. The application uses data from a GIS (Geographic Information System) database and provides navigational assistance using an "acoustic virtual display": labels are spoken using a speech synthesizer and played back at correct locations within the auditory space of the user. (Arth et al., 2015, p.4).

True mobile AR was still out of reach, but a few years later [102] developed a GPS-based outdoor system that presents navigational assistance to the visually impaired with spatial audio overlays. Soon computing and tracking devices became sufficiently powerful and small enough to support graphical overlay in mobile settings. (Van Krevelen and Poelman, 2010, p.2).

Fitzmaurice creates Chameleon (see Fig.3(a)), a key example of displaying spatially situated information with a tracked and hand-held device. In his setup the output device consists of a 4" screen connected to a video camera via a cable [16]. The video camera records the content of a Silicon Graphics workstation's large display in order to display it on the small screen. Fitzmaurice uses a tethered magnetic tracker (Ascension bird) for registration in a small working environment. Several gestures plus a single button allow the user to interact with the mobile device. Chameleon's mobility was strongly limited due to the cabling. It did also not augment in terms of overlaying objects on a video feed of the real world. (Arth et al., 2015, p.4).

Although it is hard to determine the absolute first implementation of an AR system, one of the first industry applications of computer-based AR explicitly referred to as an “augmented reality” device was designed and implemented for industrial applications in 1994 by Tom Caudell, an engineer working in Boeing’s Computer Service’s Adaptive Neural Systems Research and Development Project [11]. While at first computer-generated models were displayed on computer screens and available to the workers as “guides”, Caudell’s revolutionary approach, based on the work of Ivan Sutherland in 1968 [12], resorted to the use of a see-through display mounted on a head-set device work by the workers that enabled the superposition of computer models on to the real view of the physical parts hence facilitating the workers task by truly augmenting the users view with computer-simulated cues. This would be the first industrial application of Sutherland’s concept of a Head-mounted Display (HMD) [12], a tool that is only just recently being explored for commercial use by companies like Oculus VR and Valve Software. (Bensch, 2015, p. 5-6).

Jun Rekimoto and Katashi Nagao create the NaviCam, a tethered setup, similar to Fitzmaurice's Chameleon [58] (see Fig.4(b)). The NaviCam also uses a nearby powerful workstation, but has a camera mounted on the mobile screen that is used for optical tracking. The computer detects color-coded markers in the live camera image and displays context sensitive information directly on top of the video feed in a see-through manner. (Arth et al., 2015, p.6).

Benjamin Bederson introduced the term Audio Augmented Reality by presenting a system that demonstrated an augmentation of the audition modality [5]. The developed prototype uses a MDplayer which plays audio information based on the tracked position of the user as part of a museum guide. (Arth et al., 2015, p.6).

We have concluded that showing "opaque" objects with hidden lines removed is beyond our present capability. The three-dimensional objects shown by our equipment are transparent "wire frame" line drawings. (Sutherland, 1968).

Our equipment can provide for display of 3000 lines at 30 frames per second, which amounts to a little over 10 microseconds per line. (Sutherland, 1968).

To date, only very simple graphics have been used because of the very modest resources available and the fact that until recently commercial equipment did not emphasize high speed manipulation of raster data. To a great extent, we have worked with graphic hardware of our own construction which provides a number of features important to our interactions. In addition, we have recently acquired three Silicon Graphics workstations, which will greatly enhance our ability to create and manipulate realistic three-dimensional scenes. (Krueger et al., 1985).

In the prototype configuration (Figure 2), a small 4-inch color, LCDbased hand-held monitor acts as a palmtop computer with the capabilities of a Silicon Graphics 4D/310 Iris workstation. […] Translation (x and y axes) and zoom (z axis) controls are available on the prototype to navigate through a 3D workspace roughly equivalent to a 3-foot cube. (Fitzmaurice, 1993).

Successful development of the HUDset technology will enable cost reductions and efficiency improvements in many of the human-involved operations in aircraft manufacturing, by eliminating templates, formboard diagrams, and other masking devices. (Caudell & Mizell, 1992).

Caudell and Mizell built such a system that the workers could wear on their heads. But, as with other early attempts to overlay the real world with bits of the virtual, it didn’t catch on. Caudell says that was largely because the head-tracking required to make the system work while people moved around wasn’t responsive enough, and wearable computers were nowhere near as powerful as they are today. However, he did come up with a term for this new kind of digital vision: augmented reality. (Metz, 1994).

The user is wearing an experimental see-through head-mounted display that we built using a Reflection Technology Private Eye [21]. The Private Eye is a small display that generates a 720-x280 resolution, red, bilevel virtual image that can be focused to appear to be at a distance from 10" to infinity. (Feiner et al., 1993).

C.3.6. Demand

The technological demands for AR are much higher than for virtual environments or VR, which is why the field of AR took longer to mature than that of VR. However, the key components needed to build an AR system have remained the same since Ivan Sutherland‟s pioneering work of the 1960s. (Van Krevelen and Poelman, 2010, p.2).

After that Myron Krueger in 1975 established an artificial reality laboratory called video place. It is an area which enables users to easily deal with the virtual elements for the first time [5,6]. (Alkhamisi and Monowar, 2013, p.25).

It took until the early 1990s before the term „augmented reality‟ was coined by Caudell and Mizell [42], scientists at Boeing Corporation who were developing an experimental AR system to help workers put together wiring harnesses. (Van Krevelen and Poelman, 2010, p.2).

Loomis et al. develop a prototype of an outdoor navigation system for visually impaired [39]. They combine a notebook with a differential GPS receiver and a head-worn electronic compass. The application uses data from a GIS (Geographic Information System) database and provides navigational assistance using an "acoustic virtual display": labels are spoken using a speech synthesizer and played back at correct locations within the auditory space of the user. (Arth et al., 2015, p.4).

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AUGSIM offers the ability to introduce more realistic and more complex battlefield environments into live exercises, with much of the flexibility, safety and cost effectiveness of simulator exercises. (Barrilleaux, 1999).

During the 90s, augmented reality was also used in the arts. One such example is Julie Martin, an Australian woman who created a show called Dancing in Cyberspace, which was funded by the Australia Council for the Arts. Said show features acrobats who play with virtual objects. (European Theatre Lab, 2017).

C.3.7. Other companies

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Tom Caudell and David Mizell coin the term "augmented reality" to refer to overlaying computer-presented material on top of the real world [8] (see Fig.2(d)). Caudell and Mizell discuss the advantages of AR versus VR such as requiring less processing power since less pixels have to be rendered. They also acknowledge the increased registration requirements in order to align real and virtual. (Arth et al., 2015, p.3).

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During this time mobile devices like the Sony Walkman (1979), digital watches and personal digital organisers were introduced. This paved the way for wearable computing [103, 147] in the 1990s as personal computers became small enough to be worn at all times. Early palmtop computers include the Psion I (1984), the Apple Newton MessagePad (1993), and the Palm Pilot (1996). Today, many mobile platforms exist that may support AR, such as personal digital assistants (PDAs), tablet PCs, and mobile phones. (Van Krevelen and Poelman, 2010, p.1-2).

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In December 1993 the Global Positioning System (GPS, official name "NAVSTAR-GPS") achieves initial operational capability (see Fig.3(b)). Although GPS4 was originally launched as a military service, nowadays millions of people use it for navigation and other tasks such as geo-caching or Augmented Reality. A GPS receiver calculates its position by carefully timing the signals sent by the constellation of GPS satellites. The accuracy of civilian GPS receivers is typically in the range of 15 meter. (Arth et al., 2015, p.4).

The first conceptual tablet computer was proposed in 1972 by Alan Kay, named the Dynabook [32]. The Dynabook was proposed as personal computer for children, having the format factor of a tablet with a mechanical keyboard (really similar design from the One Laptop per Child project started in 2005). The Dynabook is probably recognized as being the precursor of the tablet computers decades before the iPad (see Fig. 2(b)). (Arth et al., 2015).

The first handheld mobile phone was presented by Motorola and demonstrated in April 1973 by Dr Martin Cooper [1]. The mobile named DynaTAC for Dynamic Adaptive Total Area Coverage was supporting only 35 minutes of call (see Fig. 2(c)). (Arth et al., 2015).

The first laptop, the Grid Compass2 1100 is released, which was also the first computer to use a clamshell design. The Grid Compass 1100 had an Intel 8086 CPU, 350 Kbytes of memory and a display with a resolution of 320x240 pixels, which was extremely powerful for that time and justified the enormous costs of 10.000 USD. However, its weight of 5kg made it hardly portable. (Arth et al., 2015).

At COMDEX 1992, IBM and Bellsouth introduce the first smart- phone, the IBM Simon Personal Communicator3, which was released in 1993 (see Fig.2(e)). The phone has 1 Megabyte of memory and a B/W touch screen with a resolution of 160 x 293 pixels. The IBM Simon works as phone, pager, calculator, address book, fax machine, and e-mail device. It weights 500 grams and cost 900 USD. (Arth et al., 2015).

Computer displays today cover a variety of capabilities. Some have only the fundamental ability to plot dots. Displays being sold now generally have built in line-drawing capability. An ability to draw simple curves would be useful. Some available displays are able to plot very short line segments in arbitrary directions, to form characters or more complex curves. Each of these abilities has a history and a known utility. (Sutherland, 1965).

It is likely that new display equipment will have area-filling capability. (Sutherland, 1965).

C.3.8. Institutions

In December 1993 the Global Positioning System (GPS, official name "NAVSTAR-GPS") achieves initial operational capability (see Fig.3(b)). Although GPS4 was originally launched as a military service, nowadays millions of people use it for navigation and other tasks such as geo-caching or Augmented Reality. A GPS receiver calculates its position by carefully timing the signals sent by the constellation of GPS satellites. The accuracy of civilian GPS receivers is typically in the range of 15 meter. (Arth et al., 2015, p.4).

When I started work on the head-mounted display I had no idea how much effort would be involved. The project would have died many times but for the spirit of the many people who have become involved. […] And finally, Stewart Ogden, so called "project engineer," actually chief administrator, who defended us all from the pressures of paperwork so that something could be accomplished. (Sutherland, 1968).

During the 1970s and 1980s, augmented reality was a research topic at some institutions, including the U.S. Air Force’s Armstrong Laboratory, the NASA Ames Research Center, the Massachusetts Institute of Technology, and the University of North Carolina at Chapel Hill. (Peddie, 2017).

1985: While working at the Armstrong Laboratory at Wright-Patterson Air Force Base, Thomas Furness conceived the idea of a virtual retinal display as a means of providing a higher luminance helmet-mounted display for pilots. About the same time in 1986, Kazuo Yoshinaka (1916–2001) while working at Nippon Electric Co also developed the idea. (In November 1991, Furness and his colleague Joel S. Kollin completed the development of the VRD at the Human Interface Technology Laboratory at the University of Washington and filed a patent in 1992.) (Peddie, 2017).

C.3.9. Broad environment

The technological demands for AR are much higher than for virtual environments or VR, which is why the field of AR took longer to mature than that of VR. However, the key components needed to build an AR system have remained the same since Ivan Sutherland‟s pioneering work of the 1960s. (Van Krevelen and Poelman, 2010, p.2).

Tom Caudell and David Mizell coin the term "augmented reality" to refer to overlaying computer-presented material on top of the real world [8] (see Fig.2(d)). Caudell and Mizell discuss the advantages of AR versus VR such as requiring less processing power since less pixels have to be rendered. They also acknowledge the increased registration requirements in order to align real and virtual. (Arth et al., 2015, p.3).

During this time mobile devices like the Sony Walkman (1979), digital watches and personal digital organisers were introduced. This paved the way for wearable computing [103, 147] in the 1990s as personal computers became small enough to be worn at all times. Early palmtop computers include the Psion I (1984), the Apple Newton MessagePad (1993), and the Palm Pilot (1996). Today, many mobile platforms exist that may support AR, such as personal digital assistants (PDAs), tablet PCs, and mobile phones. (Van Krevelen and Poelman, 2010, p.1-2).

True mobile AR was still out of reach, but a few years later [102] developed a GPS-based outdoor system that presents navigational assistance to the visually impaired with spatial audio overlays.

Soon computing and tracking devices became sufficiently powerful and small enough to support graphical overlay in mobile settings. (Van Krevelen and Poelman, 2010, p.2).

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Computer displays today cover a variety of capabilities. Some have only the fundamental ability to plot dots. Displays being sold now generally have built in line-drawing capability. An ability to draw simple curves would be useful. Some available displays are able to plot very short line segments in arbitrary directions, to form characters or more complex curves. Each of these abilities has a history and a known utility. (Sutherland, 1965).

It is likely that new display equipment will have area-filling capability. (Sutherland, 1965).

VIDEOPLACE was originally conceived and implemented as a telecommunication environment allowing people in different places to share a common video experience. While the possibility of such graphic interaction may seem unnecessary to communication, we should remember two points. First, a hundred years ago the telephone seemed to have no advantage over the telegraph which could transmit the content of messages equally well. Second, since communication between friends or business associates is not limited to words, it is clearly desirable to provide a place in which individuals who are geographically separated can share a common visual environment. (Krueger et al., 1985).

A number of technologies are competing for space on the modern professional's desk. Telephones, answering devices, modems and computer terminals with touch screens are all candidates for the desk top. From the user's point of view, an empty desk is preferable. Two technology trends augur the removal of the computer terminal from the desk's surface. First, the keyboard will ultimately succumb to voice input. Second, flat screen displays of adequate resolution already exist. They are likely to be placed on a wall behind the desk, not on it, making touch screen input awkward. (Krueger et al., 1985).

When first interacting with the palmtop unit, approximately 25 percent of the users felt that the controls were completely backwards. That is, they had an object view instead of an egocentric view for the input controls. (Fitzmaurice, 1993).

Electronic information will be available everywhere. In order to avoid being flooded and overwhelmed with the quantity of information, we need to adopt the notion of situated information spaces. The electronic information associated with physical objects should be collected, associated, and collocated with those objects. (Fitzmaurice, 1993).

The enabling technology for this access interface is a heads-up (see-thru) display head set (we call it the "HUDset"), combined with head position sensing and workplace registration systems. (Caudell & Mizell, 1992).

Caudell and his colleague David Mizell had an idea: what if they could give the assembly workers a see-through display that could guide them by superimposing lines for where the wires should go on top of the board? Trying such a thing with the 777 made particular sense, since it was the first jetliner to be fully digitally modelled before it was physically assembled, so there were already computerized images of its components. (Metz, 2014).

Later that year, Sutherland moved to Utah, where he joined the Computer Science Department at the University of Utah founded by Dave Evans (1924–), Sutherland had known Evans from his ARPA days at MIT. Together they founded Evans & Sutherland Computer Corporation in 1968, the first computer graphics company in the world, and a pioneer in CG. (Peddie, 2017).

C.3.10. Other factors

Competing technology

The technological demands for AR are much higher than for virtual environments or VR, which is why the field of AR took longer to mature than that of VR. However, the key components needed to build an AR system have remained the same since Ivan Sutherland‟s pioneering work of the 1960s. (Van Krevelen and Poelman, 2010, p.2).

Tom Caudell and David Mizell coin the term "augmented reality" to refer to overlaying computer-presented material on top of the real world [8] (see Fig.2(d)). Caudell and Mizell discuss the advantages of AR versus VR such as requiring less processing power since less pixels have to be rendered. They also acknowledge the increased registration requirements in order to align real and virtual. (Arth et al., 2015, p.3).

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Innovators

In 1962, Heilig developed a model of his idea, that he termed in 1955 as "The Cinema of the Future", known as Sensorama, which exist before digital computing [5]. (Alkhamisi and Monowar, 2013, p.25).

The first AR prototypes (Fig. 3), created by computer graphics pioneer Ivan Sutherland and his students at Harvard University and the University of Utah, appeared in the 1960s and used a see-through to present 3D graphics [151]. (Van Krevelen and Poelman, 2010, p.1).

A small group of researchers at U.S. Air Force‟s Armstrong Laboratory, the NASA Ames Research Center, the Massachusetts Institute of Technology, and the University of North Carolina at Chapel Hill continued research during the 1970s and 1980s. (Van Krevelen and Poelman, 2010, p.1).

After that Myron Krueger in 1975 established an artificial reality laboratory called video place. It is an area which enables users to easily deal with the virtual elements for the first time [5,6]. (Alkhamisi and Monowar, 2013, p.25).

It took until the early 1990s before the term „augmented reality‟ was coined by Caudell and Mizell [42], scientists at Boeing Corporation who were developing an experimental AR system to help workers put together wiring harnesses. (Van Krevelen and Poelman, 2010, p.2).

Louis Rosenberg developed one of the first known AR systems, called Virtual Fixtures, while working at the U.S. Air Force Armstrong Labs in 1991, and published the first study of how an AR system can enhance human performance.[248] Rosenberg's subsequent work at Stanford University in the early 90's, was the first proof that virtual overlays when registered and presented over a user's direct view of the real physical world, could significantly enhance human performance.[249][250][251]. https://en.wikipedia.org/wiki/Augmented_reality (2019-06-03).

Loomis et al. develop a prototype of an outdoor navigation system for visually impaired [39]. They combine a notebook with a differential GPS receiver and a head-worn electronic compass. The application uses data from a GIS (Geographic Information System) database and provides navigational assistance using an "acoustic virtual display": labels are spoken using a speech synthesizer and played back at correct locations within the auditory space of the user. (Arth et al., 2015, p.4).

Fitzmaurice creates Chameleon (see Fig.3(a)), a key example of displaying spatially situated information with a tracked and hand-held device. In his setup the output device consists of a 4" screen connected to a video camera via a cable [16]. The video camera records the content of a Silicon Graphics workstation's large display in order to display it on the small screen. Fitzmaurice uses a tethered magnetic tracker (Ascension bird) for registration in a small working environment. Several gestures plus a single button allow the user to interact with the mobile device. Chameleon's mobility was strongly limited due to the cabling. It did also not augment in terms of overlaying objects on a video feed of the real world. (Arth et al., 2015, p.4).

Although it is hard to determine the absolute first implementation of an AR system, one of the first industry applications of computer-based AR explicitly referred to as an “augmented reality” device was designed and implemented for industrial applications in 1994 by Tom Caudell, an engineer working in Boeing’s Computer Service’s Adaptive Neural Systems Research and Development Project [11]. While at first computer-generated models were displayed on computer screens and available to the workers as “guides”, Caudell’s revolutionary approach, based on the work of Ivan Sutherland in 1968 [12], resorted to the use of a see-through display mounted on a head-set device work by the workers that enabled the superposition of computer models on to the real view of the physical parts hence facilitating the workers task by truly augmenting the users view with computer-simulated cues. This would be the first industrial application of Sutherland’s concept of a Head-mounted Display (HMD) [12], a tool that is only just recently being explored for commercial use by companies like Oculus VR and Valve Software. (Bensch, 2015, p. 5-6).

Paul Milgram and Fumio Kishino write their seminal paper "Taxonomy of Mixed Reality Visual Displays" in which they define the Reality-Virtuality Continuum [41] (see Fig.4(a)). Milgram and Kishino describe a continuum that spans from the real environment to the virtual environment. In between there are Augmented Reality, closer to the real environment and Augmented Virtuality, which is closer to the virtual environment. Today Milgram's Continuum and Azuma's definition (1997) are commonly accepted as defining Augmented Reality. (Arth et al., 2015, p.6).

Jun Rekimoto and Katashi Nagao create the NaviCam, a tethered setup, similar to Fitzmaurice's Chameleon [58] (see Fig.4(b)). The NaviCam also uses a nearby powerful workstation, but has a camera mounted on the mobile screen that is used for optical tracking. The computer detects color-coded markers in the live camera image and displays context sensitive information directly on top of the video feed in a see-through manner. (Arth et al., 2015, p.6).

Benjamin Bederson introduced the term Audio Augmented Reality by presenting a system that demonstrated an augmentation of the audition modality [5]. The developed prototype uses a MDplayer which plays audio information based on the tracked position of the user as part of a museum guide. (Arth et al., 2015, p.6).

Steve Mann starts wearing a webcam for almost 2 years. From 1994-1996 Mann wore a mobile camera plus display for almost every waking minute. Both devices were connected to his website allowing online visitors to see what Steve was seeing and to send him messages that would show up on his mobile display. (Arth et al., 2015).

1985: While working at the Armstrong Laboratory at Wright-Patterson Air Force Base, Thomas Furness conceived the idea of a virtual retinal display as a means of providing a higher luminance helmet-mounted display for pilots. About the same time in 1986, Kazuo Yoshinaka (1916–2001) while working at Nippon Electric Co also developed the idea. (In November 1991, Furness and his colleague Joel S. Kollin completed the development of the VRD at the Human Interface Technology Laboratory at the University of Washington and filed a patent in 1992.) (Peddie, 2017).

Reflection Technology introduced The Private Eye head-mounted display. It had a monochrome array of LEDs in a 1.25-inch display that was scanned vertically using a vibrating mirror. Images appeared to be like a 15-inch display at 18-inches distance (Fig. 5.14). (Peddie, 2017).

1993: Lizzy—Thad Starner (1969–) starts constantly wearing his computer based on Doug Platt’s design [MIT]. (Peddie, 2017).

1993: Loral WDL, with sponsorship from STRICOM, performed the first demonstration combining live augmented reality-equipped vehicles and manned simulators. (Peddie, 2017).

Appendix D. Dynamics of conditions for large-scale diffusion

D.1. Dynamics by Bruinsma

Connection	**Explanation**
Knowledge of technology -> New high tech product	Probably mainly the performance. “Entrepreneurial activity is needed to turn the knowledge of the technology and application into a new high-tech product, a production system that can be used to produce this product, and complementary products and services that are required to make efficient use of the product.” “internal knowledge diffusion in a company is required to translate new knowledge of technology that is developed within the R&D department into tangible Applications.” “Summarizing, when considering Ortt’s framework, knowledge diffusion among actors internal and external (e.g. networks of suppliers) to the organization enables efficient use of the generated knowledge and efficient development of the three core technological factors.” • “The newly developed melt-spinning production process enabled the production of the high-tech product Nylon (1936) • The new knowledge obtained from the pilot plant enabled DuPont to improve the quality of the product (1938) • After DuPont began identifying industrial applications for Teflon (Fu1) a test sample was used to produce a gasket (1942) • DuPont started making Teflon (Fu1) for nose cones (1943) ”
Knowledge of technology -> Production system	“Entrepreneurial activity is needed to turn the knowledge of the technology and application into a new high-tech product, a production system that can be used to produce this product, and complementary products and services that are required to make efficient use of the product.” “Summarizing, when considering Ortt’s framework, knowledge diffusion among actors internal and external (e.g. networks of suppliers) to the organization enables efficient use of the generated knowledge and efficient development of the three core technological factors.” • “R&D efforts led to new knowledge on the production of Nylon and the development of the melt-spinning production process (1936) • Testing the production process in the pilot plant enabled DuPont to obtain new knowledge on the process, which could be used to improve the production process. • During the cooperative research program with the government, DuPont identified applications and built a production system (Arlington semiworks) to produce Teflon for these applications (1943) ”

Knowledge of technology -> Complementary products and services	“Entrepreneurial activity is needed to turn the knowledge of the technology and application into a new high-tech product, a production system that can be used to produce this product, and complementary products and services that are required to make efficient use of the product.” “DuPont used new knowledge to develop an extrusion apparatus, which can be used to manufacture Teflon into products (patent 1944) ”
Knowledge of application -> New high tech product	Probably mainly the performance. “Entrepreneurial activity is needed to turn the knowledge of the technology and application into a new high-tech product, a production system that can be used to produce this product, and complementary products and services that are required to make efficient use of the product.” “internal knowledge diffusion in a company is required to translate new knowledge of technology that is developed within the R&D department into tangible Applications.” • “The newly developed melt-spinning production process enabled the production of the high-tech product Nylon (1936) • The new knowledge obtained from the pilot plant enabled DuPont to improve the quality of the product (1938) • After DuPont began identifying industrial applications for Teflon (Fu1) a test sample was used to produce a gasket (1942) • DuPont started making Teflon (Fu1) for nose cones (1943) ”
Knowledge of application -> Production system	“Entrepreneurial activity is needed to turn the knowledge of the technology and application into a new high-tech product, a production system that can be used to produce this product, and complementary products and services that are required to make efficient use of the product.” • “R&D efforts led to new knowledge on the production of Nylon and the development of the melt-spinning production process (1936) • Testing the production process in the pilot plant enabled DuPont to obtain new knowledge on the process, which could be used to improve the production process. • During the cooperative research program with the government, DuPont identified applications and built a production system (Arlington semiworks) to produce Teflon for these applications (1943) ”
Knowledge of application -> Complementary products and services	“Entrepreneurial activity is needed to turn the knowledge of the technology and application into a new high-tech product, a production system that can be used to produce this product, and complementary products and services that are required to make efficient use of the product.”

	“Summarizing, when considering Ortt’s framework, knowledge diffusion among actors internal and external (e.g. networks of suppliers) to the organization enables efficient use of the generated knowledge and efficient development of the three core technological factors.”
Knowledge of application -> customers	“With the announcement of Nylon (knowledge diffusion), potential customers were informed on the existence of the Nylon application (Fa8). This stimulated a rise of the (potential) customer base (Fa5) for Nylon (1938) .” “When DuPont identified different post-war applications for Teflon in 1948. These new applications stimulated market formation, once customers became aware of the new applications via knowledge diffusion.”
Natural and human resources -> production system	“When DuPont authorized the pilot plant in 1938 (Fu6), funds became available for this purpose, which contributed to the development of the factor labour, natural resources and inputs (Fa9). The funds were used by DuPont (Fu1) to translate knowledge (Fa7, Fa8) into a production system (pilot plant) (Fa2).”
New high-tech product -> knowledge of technology	“Using the pilot plant, DuPont was able to learn directly (Fu2) from the states of the factors high-tech product and production system (1938).” Assume ‘new high-tech’ product to be both performance and price until proven otherwise.
New high-tech product -> knowledge of application	“Using the pilot plant, DuPont was able to learn directly (Fu2) from the states of the factors high-tech product and production system (1938).” Assume ‘new high-tech’ product to be both performance and price until proven otherwise.
New high-tech product -> natural and human resources	Assume ‘new high-tech’ product to be both performance and price until proven otherwise.
Production system -> knowledge of technology	“Using the pilot plant, DuPont was able to learn directly (Fu2) from the states of the factors high-tech product and production system (1938).”
Production system -> knowledge of application	“Using the pilot plant, DuPont was able to learn directly (Fu2) from the states of the factors high-tech product and production system (1938).”
Production system -> natural and human resources	
Suppliers -> new high-tech product	Assume ‘new high-tech’ product to be both performance and price until proven otherwise. Assume ‘suppliers’ to be part of ‘actors and network formation’. “Sharing knowledge through networks of organisations, such as the network of suppliers (Fa4), may also stimulate the development of complementary products.”

	"To realize the translation of knowledge of technology into the high-tech product Nylon (Fa1) and a production system (Fa2), DuPont worked closely (Fu1) with Nylon fabricators (Fa4) (1935)"
Suppliers -> production system	Assume 'suppliers' to be part of 'actors and network formation'. "Sharing knowledge through networks of organisations, such as the network of suppliers (Fa4), may also stimulate the development of complementary products."
Suppliers -> complementary product and services	Assume 'suppliers' to be part of 'actors and network formation'. "Sharing knowledge through networks of organisations, such as the network of suppliers (Fa4), may also stimulate the development of complementary products."
Institutional aspects -> customers	"First of all, as was noted in previous literature, the company aiming to introduce the new high-tech product can apply niche strategies that aim at stimulating market formation ." "Finally, the formulation of legislation by the government can influence the formation of markets." • "After the supreme court ruling against price fixing in licensing agreements, DuPont opened the Nylon knitting business to all companies interested, which meant that more Nylon hosiery could be produced and more customers could be reached (1940) • In WWII governmental interest in Teflon led to the polymer becoming the standard material for the military, which led to its increased use (1943) "
Institutional aspects -> suppliers	"After the supreme court ruling against price fixing in licensing agreements, DuPont decided to open the Nylon knitting business to all companies interested (1940) ." Assume 'suppliers' to be part of 'actors and network formation'.
Financial resources -> Knowledge of technology	"Resources are required to develop the influencing factors knowledge of technology (Fa7) and knowledge of application (Fa8)."
Financial resources -> Knowledge of application	"Resources are required to develop the influencing factors knowledge of technology (Fa7) and knowledge of application (Fa8)."
Natural and human resources -> Knowledge of technology	"Resources are required to develop the influencing factors knowledge of technology (Fa7) and knowledge of application (Fa8)." • "Before the invention of Nylon, Stine received generous funds (Fu6) for fundamental research purposes (Fu2) (1927) • When DuPont authorized the pilot plant in 1938 (Fu6), funds became available for this purpose, which contributed to the development of the factor labour, natural resources and inputs (Fa9) • Government authorizes cooperative research program, which leads to the opening of the Arlington semiworks (1943)

	• DuPont authorized a 1@milion pound per year plant to commercially produce Teflon (1949) ”
Natural and human resources -> Knowledge of application	“Resources are required to develop the influencing factors knowledge of technology (Fa7) and knowledge of application (Fa8).” • “Before the invention of Nylon, Stine received generous funds (Fu6) for fundamental research purposes (Fu2) (1927) • When DuPont authorized the pilot plant in 1938 (Fu6), funds became available for this purpose, which contributed to the development of the factor labour, natural resources and inputs (Fa9) • Government authorizes cooperative research program, which leads to the opening of the Arlington semiworks (1943) • DuPont authorized a 1@milion pound per year plant to commercially produce Teflon (1949) ”

D.2. Dynamics by Moschos

Connection	**Explanation**
Institutional aspects -> financial resources	“They concern mostly interactions that are positive for innovation (i.e. explain why does a function of an IS take place): facilitators that reinforce other facilitators (e.g. government policy increases the availability of financial resources) or facilitators that diminish the effect of barriers (e.g. government policy diminishes the adverse effect of competition).”
Institutional aspects -> macro-economic aspects	“They concern mostly interactions that are positive for innovation (i.e. explain why does a function of an IS take place): facilitators that reinforce other facilitators (e.g. government policy increases the availability of financial resources) or facilitators that diminish the effect of barriers (e.g. government policy diminishes the adverse effect of competition).”
Institutional aspects -> natural and human resources	“For example, a macro-level actor (e.g. the *government*) might be responsible for making funds available for a meso-level actor (e.g. a *company developer*). In turn, an interaction between actors (e.g. “*actors leverage on resources of other actors*”) can explain a function of an IS (e.g. in this case: resources mobilization).” “A lack of clear policy plans by the government, will likely result in a lack of resources for further R&D since an organization will not risk producing a part of a technological system for which there is no expectation also expressed by public policy makers. However, this might inhibit the project planning process, and an organization might also consider to stop promoting a particular radical technology. In turn, this will hamper the creation of network(s) of actors at the market environment level.”
Financial resources -> natural and human resources	“Acquiring funding from venture capital can fill the lack of resources after discovery and before commercialization, thus bringing an invention closer to the market. “

Sociocultural aspects -> high-tech product performance	“Environmental uncertainty about the quality of raw material causes a lack of clear team vision, thus reducing the chance of NPD success.”
Natural and human resources -> high-tech product performance	“A lack of resources after discovery will hinder the creation of a clear team vision since there will be not a formal communication system, thus reducing the chances of a successful NPD process.”
Natural and human resources -> knowledge of technology and application	“A lack of clear policy plans by the government, will likely result in a lack of resources for further R&D since an organization will not risk producing a part of a technological system for which there is no expectation also expressed by public policy makers. However, this might inhibit the project planning process, and an organization might also consider to stop promoting a particular radical technology. In turn, this will hamper the creation of network(s) of actors at the market environment level.”
Complementary products and services -> high-tech product performance	“Vigilance may result in the adoption of complementary technologies that were not apparent initially, and thus also reduce the uncertainty with regards to the performance of a new product (i.e. a technological factor). As a result, the market potential of a newly invented technology might become more visible (i.e. a new market opportunity). “ “The *Technological* progress in laser technology increased the operational capabilities of the *Technology.”*
Actors and network formation -> knowledge of application	“A product champion is expected to promote his vision of a new promising project to different stakeholders within a company, but at the same time cross-functional cooperation is required in order to develop a clear team vision that will result in developing the right product. “
Knowledge of technology and application -> Actors and network formation	“A lack of clear policy plans by the government, will likely result in a lack of resources for further R&D since an organization will not risk producing a part of a technological system for which there is no expectation also expressed by public policy makers. However, this might inhibit the project planning process, and an organization might also consider to stop promoting a particular radical technology. In turn, this will hamper the creation of network(s) of actors at the market environment level.”
Macro-economic aspects -> financial resources	“When the *Organizational Culture & Values* of a company entailed shortsightedness and risk-aversion, the result was a lack of investment by means of *Financial Resources*.”
Complementary products and services -> High-tech product price	“The *Technological* progress in laser technology also meant that they were more affordable *Economically*.”

D.3. Dynamics by Vintilă

Connection	**Explanation**
Knowledge of technology -> production system	“This implies that there was no readily available production system, with the most likely cause for this being the lacking knowledge of the technology.”

	“These developments spilled-over to the automotive industry and by deliberate efforts to apply the knowledge advancements –i.e. internal R&D by Volkswagen and BorgWarner– in the control module of the DCT, the core factors ‘production system’ and ‘new high-tech product’ were removed.”
Knowledge of technology -> high-tech product performance Knowledge of technology -> high-tech product performance and product price	“The lacking knowledge of the technology affecting the availability of the product with sufficient quality” (Racing application, so probably low performance, price not the main issue) “These developments spilled-over to the automotive industry and by deliberate efforts to apply the knowledge advancements –i.e. internal R&D by Volkswagen and BorgWarner– in the control module of the DCT, the core factors ‘production system’ and ‘new high-tech product’ were removed.” “This meant that the lacking knowledge of the physical principles –represented by the contextual factor ‘knowledge of the technology’– influenced the core factor ‘new high-tech product’” “Volkswagen together with its coordinated network of suppliers – VAG – had worked on developing the DCT technology to ready it for the introduction in series production vehicles, i.e. to advance the lacking knowledge of the technology and improve the product’s reliability and/or costs.” “In all of the circumstances above, it becomes apparent that the knowledge of the technology impacted the quality/price ratio with which the new high-tech product could be provided.” “In 1983, the Government of Canada “decided to have a Canadian firm [Ballard] improve the cost and performance of PEMFC technology” (Behling 2013b, p.427). This would entail that, at that time, the price/performance ratio was not satisfactory, which was caused by –at least– the following contextual factors. Firstly, the knowledge of the technology was still lacking, which would explain why the Government of Canada had commissioned Ballard to perform an evaluation of the potential of the PEMFC technology in the first place. Secondly, one of the main reasons for the high costs is that this type of fuel cell requires platinum –an expensive natural resource– which functions as a catalyst at the anode and cathode side (Carlson et al. 2005).”
Knowledge of technology -> customers	“To reach the mass market Volkswagen still needed to educate the customers with respect to the technology’s benefits: fuel efficiency, fast and seamless gear shifts. Following the ‘educate and experiment’ niche strategy in sport cars, Volkswagen could show consumers that the new transmission was anything but slow or sluggish.” “The benefits of the technology were becoming apparent to the mass market; and so yet another barrier hampering large-scale diffusion had disappeared.”

	"The lacking knowledge of the technology impacting the core factor 'customers' relates to the knowledge required to use the product." "However, in their marketing efforts, "the manufacturer and its dealers probably failed to adequately market the technology and explain its benefits to customers" (Koscs 2013)." "Veloso and Fixson (2001, p.248) mention that the initial solutions of the early 1970s "proved to have poor reliability and a prohibitively high price."" "The barrier continued well within the late 1970s, when customers proved to be not fully aware of the product's benefits." "The early niche strategies used to introduce ABS systems in aircrafts resulted in a better understanding of the technological principle. As a result, the technology could migrate to experimental fitting on motorcycles and cars. However, this did not prove enough to remove the barrier hampering large-scale diffusion."
Knowledge of technology -> institutional aspects Above is Vintilă's conclusion, but shouldn't it be knowledge of application?	"As late as 2009 there were no internationally-harmonized standards, codes and regulations with respect to the deployment of fuel cell technology on public roads. For the same year, "surveys generally show[ed] that there is a great acceptance, but a low knowledge level for hydrogen technologies. Males and people with a higher education level seem to have a greater acceptance."
Knowledge of technology -> natural resources and labour	"Autonomous developments –i.e. external R&D– once again influenced the contextual factor 'knowledge of technology', which in turn helped reduce the impact of the 'natural resources and labour' requirements."
Accidents / events -> institutional aspects	Accidents led to the FIA banning the application of the DCT in racing. This dynamic is similar to low performance leading to regulations that stop the application of a technology (high-tech product performance -> institutional aspects).
Accidents / events -> customers	"These critics would have likely had an impact on the public view over the ABS technology, in the case of the Jensen FF at least. This is most proximate to the contextual factor 'accidents or events', which can be seen to have impacted the customers willingness-to-pay for adoption."
Macro-econ. aspects -> customers	"US experienced an economic recession in the late 1980s following the stock-market crash of 1987 and a "precipitous decline of the US dollar. […R]egrettably [Porsche's] customers, 'the doctors, dentists, lawyers, and NASA engineers' in the US were also heavily invested in the stock market" (Ludvigsen 2005, p.112)."
Suppliers -> knowledge of technology	"There was also a coordinated network of suppliers: Continental manufacturing the control unit, BorgWarner supplying the knowledge to produce the technology."

	“Volkswagen together with its coordinated network of suppliers – VAG from […] – had worked on developing the DCT technology to ready it for the introduction in series production vehicles, i.e. to advance the lacking knowledge of the technology and improve the product’s reliability and/or costs.”
Socio-cultural aspects -> customers	“Volkswagen opted to target the technology in Europe, a market characterised at that time by an entrenched socio-cultural preference for manual transmissions on the basis of their greater fuel economy; but also by an emerging preference for automatic transmission due to the increasingly congested roads and cities (see Visnic 2000). The DCT transmission was perfectly positioned to offer the best of both worlds to European drivers.” “The development of hydrogen buses –in particular those operating on the basis of the PEMFC technology– is connected to the level of demand shown by city authorities (Ball et al. 2009). “They favoured the buses for their low pollution [i.e. zero emissions] as well as for social reasons, such as raising public hydrogen awareness and promotion of further research” (Ball et al. 2009, p.257).” “As late as the early 2010s, the cost of PEMFC buses was fivefold than that of a diesel bus. Combined with the costs of the dedicated hydrogen infrastructure it meant that “they [were] only used where a city deem[ed] the environmental benefit to be worth the extra investment” (Fuel Cell Today 2012b).”
Complem. products and services -> high-tech product performance and product price	“One such factor was external R&D. Firstly, the computers had to become compact enough in terms of size in order to be fitted in cars. Secondly, the quality of the electronic controls increased, whereas the price decreased (Beecham 2005). These advancements were arguably driven by the general progression of electronics.” “With the switch to electronic devices in 1969, the product became more affordable (see Starks 1968); the performance was also improved, but not yet enough..” ““[T]he introduction of the semiconductor technology, available from the early 1960’s, […] created the preconditions for the necessary rapid triggering of the [ABS] system” (Robert Bosch GmbH 2003b, p.31). Primarily, the availability of integrated circuits gradually permitted the increase in the speed of response of the sensors.”
Complementary products and services -> knowledge of technology	“Autonomous developments –i.e. external R&D– once again influenced the contextual factor ‘knowledge of technology’, which in turn helped reduce the impact of the ‘natural resources and labour’ requirements.”
Financial resources -> suppliers	“While it became apparent that electronically controlled ABS units were feasible, “their development involved such immense financial investment that their use was virtually limited to aircraft and express trains” (p.31). Therefore, the core factor of ‘suppliers’

	would have likely hampered diffusion due to the high capital cost during this period.”
Financial resources -> macro-economic aspects	“Except for industrial use of hydrogen, there was no infrastructure available which would cater to a mass market for PEMFCVs (see FuelCells.org 2015; section “Worldwide Hydrogen Fueling Stations”). Building up such an infrastructure would require significant amounts of financial resources.”
Institutional aspects -> knowledge of technology	“Government policies were instrumental in furthering the knowledge of the technology, either by proposing clear targets to be met –e.g. Japan’s Hydrogen and Fuel Cell Demonstration Project– or by subsidizing research projects and consumer adoption.”
Institutional aspects -> customers	“The regulatory environment did not hamper large-scale diffusion. In fact, there were several instances when institutional aspects could be best described as having accelerated the diffusion of ABS by influencing the customer willingness-to-pay for the adoption.”
Institutional aspects -> institutional aspects	“The government policy can be seen to have influenced to some extent also the institutional barriers. If public buses running on hydrogen were desired by the Canadian officials, then it would imply that they were willing to grant road certification to such experimental vehicles and therefore create precedent for other similar PEMFCV introductions.” “Given that these vehicles were granted public road certification, it created a precedent for the lessening of the institutional barriers for the introduction of PEMFCV on public roads.”
Institutional aspects -> complementary products and services	“These policies were instrumental in stimulating the development of the hydrogen infrastructure and installed base.”
Institutional aspects -> installed base Isn’t ‘installed base’ part of ‘customers’?	“These policies were instrumental in stimulating the development of the hydrogen infrastructure and installed base.”
Product price -> suppliers	“The ‘suppliers’ barrier was an isolated and short-lived appearance in the early 1960s, triggered by the initial high investments costs required for the integration of electronic controls in the new high-tech product.”
Actors, network formation -> institutional aspects	“Lobbying by OEMs was another external factor observed. ABS developers made “antiskid presentation […] for the U.S. General Services Administration and the National Highway Safety Bureau” (Cutter 1968, p.206). In the customer segment of trucks the factor was successful and “ABS was first required as a mandatory fitment in the USA in the 1970s” (Day 2014, p.386). However, due to the low reliability of the systems this regulation was subsequently withdrawn.”
High-tech product performance -> institutional aspects	“Lobbying by OEMs was another external factor observed. ABS developers made “antiskid presentation […] for the U.S. General Services Administration and the National Highway Safety Bureau” (Cutter 1968, p.206). In the customer segment of trucks the factor was successful and “ABS was first required as a mandatory fitment

	in the USA in the 1970s" (Day 2014, p.386). However, due to the low reliability of the systems this regulation was subsequently withdrawn." This dynamic is similar to accidents leading to regulations that stop the application of a technology (accidents/events -> institutional aspects).
Natural and human resources -> high-tech product price Assume that only the price was influenced in this case.	"In 1983, the Government of Canada "decided to have a Canadian firm [Ballard] improve the cost and performance of PEMFC technology" (Behling 2013b, p.427). This would entail that, at that time, the price/performance ratio was not satisfactory, which was caused by –at least– the following contextual factors. Firstly, the knowledge of the technology was still lacking, which would explain why the Government of Canada had commissioned Ballard to perform an evaluation of the potential of the PEMFC technology in the first place. Secondly, one of the main reasons for the high costs is that this type of fuel cell requires platinum –an expensive natural resource– which functions as a catalyst at the anode and cathode side (Carlson et al. 2005)."
Installed base -> complementary products and services Isn't 'installed base' part of 'customers'?	"The manufacturers increased the installed base, as shown. Via this action, the VMs would indirectly (positively) influence the future availability of a hydrogen infrastructure."

D.4. Synthesis of the dynamics

Causing factor	**Influenced factor**	**Source**
Knowledge technology	Product performance	Vintilă, Bruinsma
	Product price	Vintilă
	Production system	Vintilă, Bruinsma
	Customers	Vintilă
	Natural resources and labour	Vintilă
	Actors and network formation	Moschos
	Complementary products and services	Bruinsma
Knowledge application	Institutional aspects	Vintilă
	Actors and network formation	Moschos
	Product performance	Bruinsma
	Production system	Bruinsma
	Complementary products and services	Bruinsma
	Customers	Bruinsma
Natural and human resources	Product performance	Moschos
	Product price	Vintilă
	Production system	Bruinsma
	Knowledge technology	Moschos, Bruinsma
	Knowledge application	Moschos, Bruinsma
Financial resources	Actors and network formation	Vintilă
	Macro-economic aspects	Vintilă
	Natural and human resources	Moschos
	Knowledge technology	Bruinsma

	Knowledge application	Bruinsma
Macro-economic aspects	Customers	Vintilă
	Financial resources	Moschos
Sociocultural aspects	Customers	Vintilă
	Product performance	Moschos
Accidents and events	Institutional aspects	Vintilă
	Customers	Vintilă
Product performance	Institutional aspects	Vintilă
	Knowledge technology	Bruinsma
	Knowledge application	Bruinsma
	Natural and human resources	Bruinsma
Product price	Actors and network formation	Vintilă
	Knowledge technology	Bruinsma
	Knowledge application	Bruinsma
	Natural and human resources	Bruinsma
Production system	Knowledge technology	Bruinsma
	Knowledge application	Bruinsma
	Natural and human resources	Bruinsma
Complementary products and services	Knowledge technology	Vintilă
	Product performance	Vintilă, Moschos
	Product price	Vintilă, Moschos
Actors and network formation	Institutional aspects	Vintilă
	Knowledge technology	Vintilă
	Knowledge application	Moschos
	Product performance	Bruinsma
	Product price	Bruinsma
	Production system	Bruinsma
	Complementary products and services	Bruinsma
Customers	Complementary products and services	Vintilă
Institutional aspects	Knowledge of technology	Vintilă
	Customers	Vintilă, Bruinsma
	Institutional aspects	Vintilă
	Complementary products and services	Vintilă
	Financial resources	Moschos
	Macro-economic aspects	Moschos
	Natural and human resources	Moschos
	Actors and network formation	Bruinsma

The synthesis contains a total of 59 unique pairs of conditions for large-scale diffusion.