THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Processes and Platforms Aligned with Technology Development

- The Perspective of a Supplier in the Aerospace Industry

Ulf Högman

Department of Product and Production Development
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2011

Processes and Platforms Aligned with Technology Development:
The Perspective of a Supplier in the Aerospace Industry
ULF HÖGMAN
ISBN 978-91-7385-542-6

Doktorsavhandlingar vid Chalmers tekniska högskola
Ny serie nr 3223
ISSN 0346-718X

Department of Product and Production Development
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone + 46 (0)31-772 1000

Chalmers Reproservice
Göteborg, Sweden, 2011

to Pia. I miss you.

Processes and Platforms Aligned with Technology Development:
The Perspective of a Supplier in the Aerospace Industry

ULF HÖGMAN
Department of Product and Production Development
Chalmers University of Technology
Göteborg, Sweden

Abstract

Technology development often has an unclear goal of building knowledge or demonstrating feasibility, is characterized by a high degree of initial uncertainty, and is in need of extensive experimentation. The purpose of this research has been to build knowledge concerning means which support companies in the pursuit of innovation and technology development.

Two different approaches to managing the inherent uncertainty in technology development have been explored: applying a platform formulation and applying a normative stage-gate model for managing the development process. A qualitative research approach has been used. The research has been conducted in eight different studies involving six different companies in total, but where most of the research has been conducted at Volvo Aero Corporation, a Swedish aero engine company. Given the context of the case companies, the following main conclusions have been drawn:

- A platform formulation including product, process, and technology platforms has been proposed that appears both feasible and useful based on the empirical evidence.
- Normative process models based on the stage-gate model can benefit technology development, given that they are adapted to the explorative nature of such uncertain development and used with a higher degree of flexibility. Strategies to achieve flexibility that have been found include, for example, soft gates, loop-backs, stopping projects and redefining the focus, using the model recursively, and defining technology development as a relay race of different projects where each individual project follows a stage-gate process.

The possibility to generalize regarding these conclusions is limited, given that most of the research has been conducted in one company. However, external validity is strengthened by similar results found in literature and through comparison between the different companies included in this research. Finally, the transferability of the results is supported by a thorough description of the studied company and its industrial context.

Keywords: technology development, platform, and process.

Acknowledgements

This research has been carried out at the Department of Product and Production Development, Division of Product Development, at Chalmers University of Technology in Göteborg, Sweden. From the very beginning, this research project has been a part of the industrial PhD program at Volvo Aero Corporation (VAC).

I am indebted to many people for contributing to this research.

First, I would like to thank my supervisor Hans Johannesson for his wise guidance, enthusiasm and optimistic support. Furthermore, I have been fortunate to have three co-supervisors, Fredrik Berglund, Lars Trygg and Lars Almefelt, who have contributed additional insight into how to conduct research and have offered thoughtful critique. In addition, without the support and encouragement of Bengt-Olof Elfström, this research would never have happened. I am very grateful to him and to VAC for this opportunity.

I would also like to thank my colleagues at Chalmers and Volvo for all the support and interest I have encountered. In particular, I am grateful for the very enjoyable collaboration I have had with my co-authors on the different articles included in this thesis, Fredrik, Dag, Kiran, Marcus, Henric, Daniel, Stefan, Lars, and Hans. Furthermore, during the course of this research, I have had the great pleasure of co-operating with a number of very gifted young Masters students, which in some cases has resulted in common publications. Thank you, Rickard, Martin, Alla Maria, Eret, Joel, Johannes, Marcus, Henric, Catarina, Josefine, Daniel B, Stefan, and Daniel C S.

In my work, I have relied on the openness and willingness to share experience and learning from the operational worlds within the Volvo group and four other companies which remain anonymous. I thank all of you who have contributed your time and knowledge to this work.

Furthermore, I would like to gratefully acknowledge the financial support from VINNOVA (Swedish Agency for Innovation Systems) through the National Aviation Engineering Research Programme (NFFP 4/5) and Volvo Aero Corporation.

Finally, I would like to express my thanks to my family and friends, for their support and encouragement. In particular, my gratitude goes to Lovisa, for bringing happiness and laughter, and Pia, who always sought development and remains an inspiration to me.

Trollhättan, Sweden, April, 2011

Ulf Högman

Publications

The following papers are included in the thesis and can be found in the appendices:

Paper A: Högman, U., Berglund, F., (2007) *Technology Management Challenges for a Sub-supplier in the Aerospace Industry*, Proceedings of the 16th International Conference on Management of Technology, IAMOT 2007, Miami Beach, FL, USA, May 13-17, 2007, pp. 672-688

Paper B: Berglund, F., Bergsjö, D., Högman, U., Khadke, K. (2008) *Platform strategies for a supplier in the aircraft engine industry*, Proceedings of ASME 2008 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, IDETC/CIE 2008, Brooklyn, New York, USA, August 3-6, 2008, Paper Number: DETC2008-49526.

Paper C: Högman, U., Bergsjö, D., Anemo, M., Persson, H., (2009) *Exploring the Potential of Applying a Platform Formulation at Supplier Level - The Case of Volvo Aero Corporation,* Proceedings of International Conference on Engineering Design, ICED'09, Stanford University, August 24-27, 2009, pp.227-238 (Design Society, Stanford University, Stanford, CA).

Paper D: Högman, U., Johannesson, H.L., (2011) *The Technology Development Process and its Result - The Case of Volvo Aero Corporation*, submitted to Technovation, 2011.

Paper E: Högman, U., Johannesson, H.L., (2011) *Applying Stage-Gate Processes to Technology Development - Experience from Six Hardware-oriented Companies*, submitted to the Journal of Engineering and Technology Management, 2011.

Paper F: Högman, U., Johannesson, H.L., (2010) *Technology development and normative process models*, Proceedings of 11th International Design Conference - Design 2010, Dubrovnik - Cavtat, Croatia, May 17-20, 2010, pp.265-274. (Design Society)

Paper G: Högman, U., Bengtsson, D., Stetz, S., Trygg, L., Johannesson, H.L., (2010) *Requirements on New Technology and the Technology Implementation Process,* Proceedings of NordDesign 2010, Gothenburg, Sweden, August 25-27, 2010, pp.289-300. (Chalmers University of Technology, Gothenburg)

Paper H: Högman, U., Johannesson, H.L., (2011) *Technology development practices in industry*, accepted for presentation at the 18th International Conference on Engineering Design – ICED 2011 (Design Society, Copenhagen - Denmark, 2011).

Distribution of Work:

Paper A: Ulf Högman and Fredrik Berglund planned and carried out the study in joint collaboration.

Paper B: The study was carried out in joint collaboration between all authors. The planning and definition of the theoretical framework was a joint effort. Empirical data collection was conducted by Dag Bergsjö. The analysis and writing of the paper was primarily a joint effort involving Fredrik Berglund, Dag Bergsjö and Ulf Högman, with the support of Kiran Khadke.

Paper C: The paper is based on an M.Sc. thesis conducted in 2008 by Marcus Anemo and Henric Persson (2008), where Ulf Högman was the industry supervisor. For the paper, the empirical material from the M.Sc. thesis was re-analysed by Ulf Högman. The paper was written by Ulf Högman, with the support of the three co-authors.

Paper D: The paper is partly based on an M.Sc. thesis conducted in 2007 by Adalheidur Maria Vigfusdottir and Eret Rääk (2008), where Ulf Högman was the industry supervisor. Data was collected by Adalheidur Maria Vigfusdottir, Eret Rääk and Ulf Högman. For the paper, the original empirical material from the M.Sc. thesis was re-analysed by Ulf Högman. The paper was written by Ulf Högman, with the support of Hans Johannesson.

Paper E: The study was carried out by Ulf Högman, who also wrote the paper, with the support of Hans Johannesson.

Paper F: The study was carried out by Ulf Högman, who also wrote the paper, with the support of Hans Johannesson.

Paper G: The paper is partly based on an M.Sc. thesis conducted in 2009 by Daniel Bengtsson and Stefan Stetz (2009), where Ulf Högman was the industry supervisor. For the paper, the empirical material from the M.Sc. thesis was re-analysed by Ulf Högman. The paper was written by Ulf Högman, with the support of the co-authors.

Paper H: The study was carried out by Ulf Högman, who also wrote the paper, with the support of Hans Johannesson.

Table of Contents

1. INTRODUCTION 1

1.1. BACKGROUND 1
1.2. PURPOSE 4
1.3. DELIMITATION OF THE RESEARCH 5
1.4. THESIS STRUCTURE 5

2. FRAME OF REFERENCE 6

2.1. CLARIFICATION OF TERMS USED 6
2.2. CHARACTERISTICS OF TECHNOLOGY AND TECHNOLOGY DEVELOPMENT 7
2.2.1. Engineering design theory and technology 10
2.2.2. Systems engineering and technology 11
2.3. PLATFORM APPROACHES 15
2.4. NORMATIVE MODELS FOR TECHNOLOGY DEVELOPMENT 20
2.4.1. On innovation process models 20
2.4.2. On technology development models 23
2.5. IDENTIFIED KNOWLEDGE GAPS - RESEARCH OPPORTUNITIES 26

3. RESEARCH QUESTIONS 28

4. RESEARCH METHODOLOGY 30

4.1. ON KNOWLEDGE CREATION 30
4.2. ON RESEARCH STRATEGY 31
4.3. ON RESEARCH QUALITY 33
4.3.1. Reliability 33
4.3.2. Validity 34
4.3.3. Reliability and validity in case study research 35
4.3.4. Reliability and validity in participatory action research 36
4.4. THE CHOSEN RESEARCH APPROACH IN THIS THESIS 36
4.5. META-THEORETICAL RATIONALE 37
4.6. RESEARCH DESIGN 38
4.7. SAMPLING STRATEGY, DATA COLLECTION, AND ANALYSIS 43
4.7.1. Paper A 43
4.7.2. Paper B 44
4.7.3. Paper C 45
4.7.4. Paper D 46
4.7.5. Paper E 48
4.7.6. Paper F 49
4.7.7. Paper G 50
4.7.8. Paper H 52

5. RESULTS 53

5.1. PAPER A: TECHNOLOGY MANAGEMENT CHALLENGES FOR A SUB-SUPPLIER IN THE AEROSPACE INDUSTRY 53
5.2. PAPER B: PLATFORM STRATEGIES FOR A SUPPLIER IN THE AIRCRAFT ENGINE INDUSTRY 56
5.3. PAPER C: EXPLORING THE POTENTIAL OF APPLYING A PLATFORM FORMULATION AT SUPPLIER LEVEL – THE CASE OF VOLVO AERO CORPORATION 59

5.4. Paper D: The technology development process and its result – the case of Volvo Aero Corporation 61
5.5. Paper E: Applying stage-gate processes to technology development – experience from six hardware-oriented companies 64
5.6. Paper F: Technology development and normative process models 65
5.7. Paper G: Requirements on new technology and the technology implementation process 68
5.8. Paper H: Technology development practices in industry 70
5.9. Summarizing obtained results 71
5.9.1. Difficulties in technology development described in literature which are relevant for a supplier company characterized by small scale production and customer-specific product designs 71
5.9.2. Platform strategy for a supplier company characterized by small scale production and customer-specific product designs 71
5.9.3. Adaptations needed to facilitate the usefulness of the stage-gate model to manage technology development 71

6. DISCUSSION 73

6.1. Difficulties in technology development described in literature relevant for a supplier company characterized by small scale production and customer-specific product designs 73
6.2. Platform strategy for a supplier company characterized by small scale production and customer-specific product designs 75
6.3. Adaptations needed to facilitate the usefulness of the stage-gate model to manage technology development 79
6.4. Reflections on the research approach 81
6.5. Research Quality 81
6.5.1. Are the results reliable? 82
6.5.2. What is the validity of the results? 82

7. CONCLUSIONS 84

7.1. Academic Contributions 85
7.2. Industrial Contributions 85

8. FUTURE WORK 87

9. REFERENCES 88

APPENDICES

Paper A
Paper B
Paper C
Paper D
Paper E
Paper F
Paper G
Paper H

1. Introduction

This chapter provides an introduction of the topic area and research focus in this thesis. First, technology development and implementation is discussed from the industrial perspective of a supplier in the aero engine industry. After that follows a description of the research purpose, delimitations and an outline of the thesis.

1.1. Background

This research thesis has its roots in one company, Volvo Aero Corporation (VAC). The company is based in Sweden and is primarily active in the aero engine industry. Its main operations are as a subcontractor supplying its customers with components in a business-to-business relationship. It is an old company, dating back to the 1930s, with a strong tradition of technology development intended primarily for military applications. During the past 30 years, the company has gone through great changes. Today, its product portfolio has been broadened to include space propulsion components as well as engine components for most major types of civilian aircrafts, which today constitute the main business. The civilian component specialization has gradually evolved from make-to-print, without any design responsibility, to accepting design work under customer leadership, to taking on the full design responsibility for selected products. The company is in many ways very typical for the aero engine industry, and companies with similar development history can be found in countries like the USA, Germany, the UK, France, Italy, Belgium, and Japan. It has been a player in this particular market for a long time, with strong national roots, but has transformed and become highly international. Business is done in all engine life cycle phases, and the company enters into business relationships both as a Risk-and-revenue-Sharing Partner (RSP) and as a make-to-print supplier through Long Term Agreements (LTA).

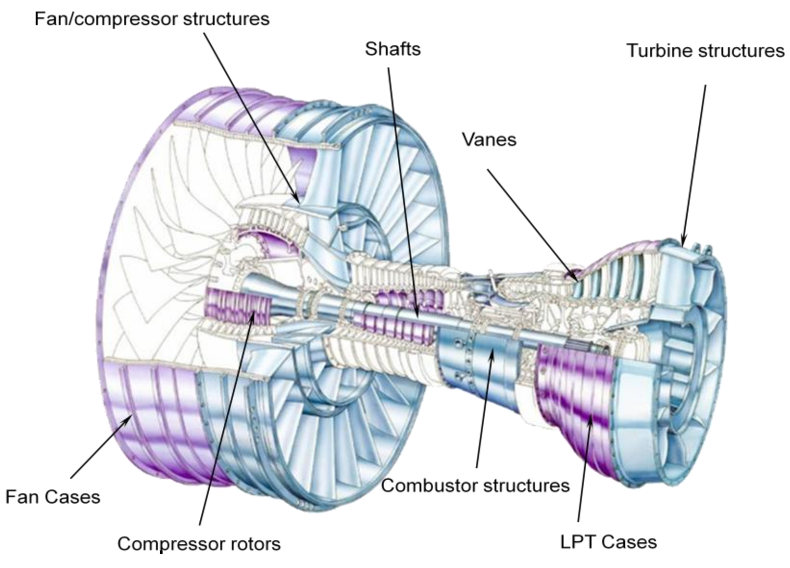

Figure 1. VAC civilian jet engine component specialization (source: VAC).

An aircraft engine is a multi-technology, multi-component product involving high costs and intensive engineering. The complex nature of the aircraft engine is reflected in the multi-tiered, multi-player aircraft engine industry. Unlike the traditional tiered buyer-seller model, the aircraft engine industry is characterized by six interdependent groups: the airlines, the airframers, the certification agencies and professional bodies, the government-funded laboratories and universities, the risk and revenue sharing partners, and the suppliers (Prencipe 2004) (see Figure 2). Developing a new engine today is too expensive to be carried out by one single company. This has driven the industry to organize new product development as a network of industrial partnerships where the partners share development costs and risks, and later also profits (thus Risk-and-revenue-Sharing Partnership). The “club” of partners that have both the will and the technical and financial capabilities to participate as RSP partners is quite small and consists of a number of old, large companies with extensive technical capabilities that have been built over time. The individual companies have developed product specialisations where VAC, for example, has focused on large static structures (see Figure 1). Even though the number of companies is quite limited, the competition for engine shares is fierce when new product development is initiated. This is particularly true if that engine is believed to have the potential to take a large share of the future market. The financial capabilities of a company will often decide how large a share that particular company will be able to opt for. The attractiveness of the product solutions and technologies that company has to offer for the particular engine will have a strong impact on the competitiveness of the company. Several authors have described the aero engine industry and some of its characteristics (Prencipe 1997; Prencipe 2004; Acha et al. 2007).

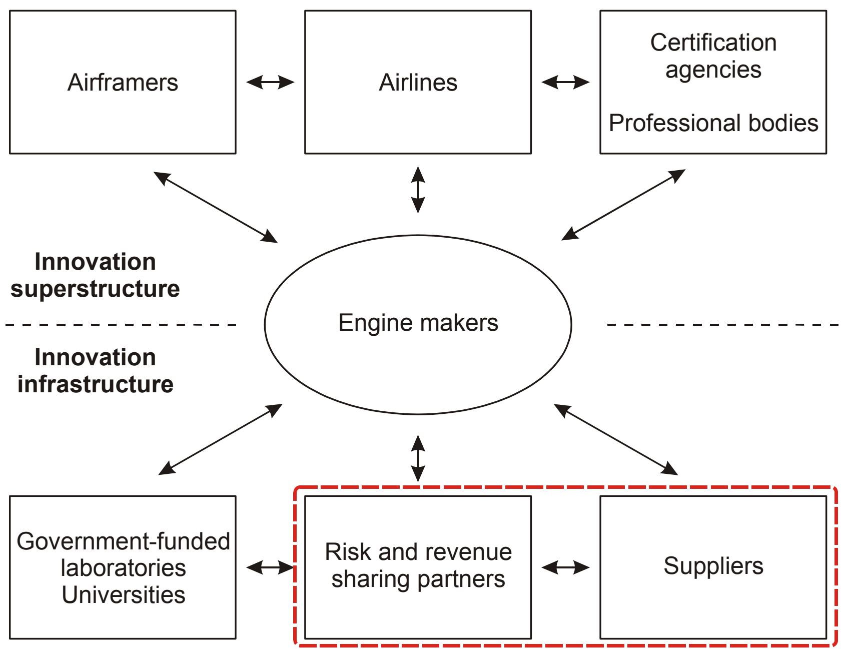

Figure 2. The aircraft engine industry meso-system (Prencipe 2004). VAC in red.

VAC normally acts on the first or second tier level, depending on their role in the program, and they quite naturally want to take part in the foreseen aircraft engine industry growth. However, financial restrictions limit the number and share of programs that can be entered. Access to personnel and competence is restricted, and the company will have a problem if it engages in too many new programs. Therefore, it is natural for the company to seek venues of synergy between different programs in order to utilize scarce resources with maximized efficiency. There is, consequently, a need to improve efficiency in the development programs in order to make it possible to accept larger program shares without increasing the financial investment. Additionally, the company strives to develop technologies that can benefit as many products as possible while, at the same time, constituting a basis for enlarging the product portfolio. A platform strategy is thought to achieve such internal and external benefits.

To develop new technologies in this industry and apply them to an engine is normally a lengthy process, requiring extensive testing, exemplified by (Peisen and Schulz 1999). Furthermore, since VAC does not control the product's architecture, they do not control the product requirements. As such, choosing concepts and technologies for development is a challenge. The architects are not always willing to share their views on future component requirements; rather, they expect their suppliers to independently explore and develop new technologies that will support new product concepts with attractive properties. In many cases, the architects themselves have only limited foresight into future needs and a fuzzy understanding of component requirements. Therefore, the supplier can only rely to a limited extent on support from system architects in defining future needs. Nevertheless, the company needs to decide on directions for developing new capabilities that facilitate innovation, with the strategic vision of building competitiveness and being able to supply attractive products in the future. Thus, the uncertainties regarding both future needs and the success of the technology development itself are high. Nevertheless, they need to be managed somehow.

In recent years, the pace of the development of new engines has increased. This has been driven by both the growth in air travel and the need to find technical solutions that are more fuel efficient and have a lower environmental imprint. To deliver such solutions, new technology has been developed and implemented in the various new products. The implementation of immature technology has, in many cases, resulted in the severe cost increase of the various development programs, as well as delays relative to the project schedule. More efficient models for identifying the needs of new technology, and developing and implementing that technology, are needed.

Furthermore, developing new technology is usually expensive, and, due to lead times, the return on investment may come many years after initiating the development. Ways of improving both efficiency and effectiveness in the development of new technology is therefore quite naturally of great interest to the organisation. Due to long lead times and the cost of technology development, there is in addition a need to find development models where the potential for the reuse of developed technologies is improved.

Even though extensive experience exists concerning technology development in VAC, little operational support in the form of structured development processes, methods or tools is available to researchers and engineers trying to develop new technologies. Traditionally, these early development phases have been dependant on dedicated individuals with high personal technical competence and vision to push new solutions forward.

In conclusion, the company has a need to find solutions that will support the development process of new attractive technology and to conduct this development efficiently. Two potential approaches identified to meet these needs are the development and implementation of a platform strategy and using a normative model for managing the development process.

Volvo Aero Corporation is characterized by having complex products with a high technology content, custom designed for particular systems and customers. Furthermore production rates are low, or even very low, in comparison with many consumer companies. Even though considerable resources are spent on R&D, most innovation and technology development is of an incremental nature. One reason for this are the strict safety considerations which are necessary in this type of industry. In general, this makes the technological change process slow with high requirements regarding verification and validation on all new technology introduced on aircraft and rockets.

As noted by Bryman and Bell (2007), for example, it is very common that researchers conduct research in areas of personal interest, and this thesis is no exception. I have a background in industry, where I have been working for over 20 years, often grappling with issues concerning technology development. Since 1995, I have been employed by Volvo Aero Corporation, where I have held various positions, mostly in engineering and project management. This means I bring extensive personal experience when approaching the research issues addressed in this research project. For me, this background knowledge is clearly an asset, even though, at the same time, I have to be prepared to confront “old truths”, which to me is a part of this learning experience.

1.2. Purpose

From the start, the purpose of the research has been to build knowledge concerning means which support companies in the pursuit of innovation and technology development. More specifically, the research has focused on the applicability of the stage-gate model for the technology development process, and on platforms as a means to leverage technology development. This research focus was not defined from the beginning, but grew out of the initial stages and was set during the second year.

1.3. Delimitation of the Research

Throughout the research, the industrial applicability and usefulness of the results have been strongly focused. It has been my intent to take practical knowledge of technology development into account when pursuing the research purpose. For this reason, I have chosen to conduct my research very closely to the industrial context where actual needs in industry strongly have guided the work. The research is focused on the context of suppliers working with complex products (Miller et al. 1995) in business-to-business settings. Since I have been a PhD student employed by Volvo Aero Corporation (VAC), this contextual delimitation has been a natural choice for me. However, to some extent during the project I have chosen to go outside of these delimitations, primarily in my last study, when exploring the external validity of results obtained in the chosen context.

1.4. Thesis Structure

Chapter 1 has provided you with a general view of the industrial background to this research, its importance, purpose, and delimitations.
Chapter 2 presents the theoretical foundation on which this research rests and with which I analyze the results I have obtained in the different studies.
Chapter 3 presents the research questions that have guided this research.
Chapter 4 then relates back to the previous three chapters and describes how I have chosen to approach my research questions, including assumptions regarding ontology and epistemology, quality criteria, research design, sampling strategy, data collection and analysis.
Chapter 5 presents the results from the different studies included in this thesis.
Chapter 6 considers the empirical results, and is both a reflection relating to existing theory (as described in Chapter 2) and a discussion of the results' trustworthiness.
Chapter 7 concludes the thesis by summarizing the main results obtained from this work, including a description of the academic and industrial contributions.
Chapter 8 indicates the need for further work and presents what is pursued in continued work.

2. Frame of Reference

This chapter presents a selection of theory that is relevant to the research scope and forms the framework I have used. In the initial chapters, characteristics of technology and the technology development process are discussed, as well as challenges therein. This part ends with a description of how technology is described in engineering design theory and systems engineering, an issue I have addressed in one of my studies. Since my focus has been on platforms and normative process models, the last part focuses on these topics. A discussion of platform theory and its relevance to the context focused on in this thesis precedes a description of different descriptive and normative models relevant to technology development.

2.1. Clarification of terms used

Technology and innovation have received substantial research attention from a multitude of perspectives the last 40 years. Still, some of the key concepts have not been defined consistently in research. Further, different vocabulary may be used to describe the same phenomena. To clarify what I mean, I provide a short description of definitions found in literature that can serve as a foundation for continued reading.

In the introduction to the first part of their book "Strategic Management of Technology and Innovation", Burgelman et al. (2004) describe some key concepts and how they relate to each other (see Figure 3).

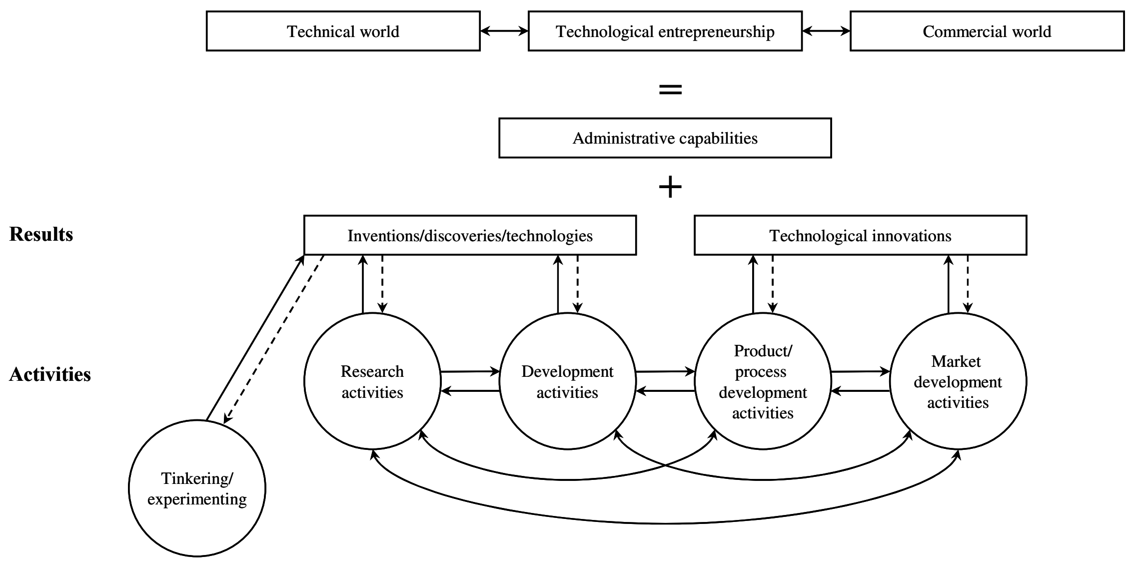

Figure 3. The relationship among key concepts concerning technological innovation, from Burgelman et al. (2004).

"Technology refers to the theoretical and practical knowledge, skills, and artefacts that can be used to develop products and services as well as their production and delivery systems. Technology can be embodied in people, materials, cognitive and physical processes, plant, equipment, and tools." (Burgelman et al. 2004)

"Innovations are the outcome of the innovation process, which can be defined as the combined activities leading to new, marketable products and services and/or new production and delivery systems." (Burgelman et al. 2004)

According to Burgelman et al. (2004), innovations can be related to technology in different ways. "Some innovations are *technology based* (e.g., disposable diapers, oversized tennis racquets, electronic fuel injection, and personal computers). Other innovations, such as new products or services in retailing and financial services, are *facilitated* by new technology (e.g., electronic data processing)." They cluster all these types under the heading "technological innovations".

Burgelman et al. (2004) further argue that "technologies are usually the outcome of development activities to put inventions and discoveries to practical use." This would mean that one of the outputs of product or process development is technology. I concur. However, when I discuss technology development, I normally mean a *directed effort* at developing new "knowledge, skills and artefacts" that in turn will facilitate product/process development (see Figure 4). The focus of that directed effort may very well be driven by the vision and objective of "putting inventions and discoveries to practical use".

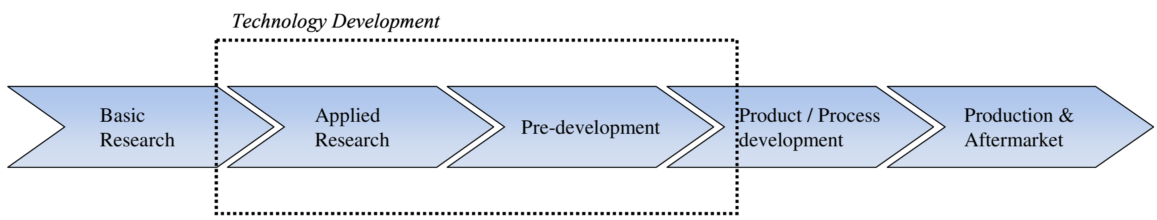

Figure 4. Adapted from Martin Karlsson (2004).

2.2. Characteristics of technology and technology development

The primary result of technology development is usually different compared to product development. Typically, technology development often has a fuzzy goal of building knowledge or demonstrating feasibility, while product development has a sharp goal of resulting in a commercial product (Nobelius 2002). Technology and product development differ in character in a number of dimensions regarding prerequisites, technical maturity, time horizon, competence needs, process repeatability and completion point (Iansiti and West 1997). Nobelius (2002) has summarized examples of differences in task characteristics between technology development and product development in relation to each other, and an adapted version of his summary is shown in Table 1 below.

Table 1. Adapted from (Nobelius 2002). Examples of differences in task characteristics between technology development and product development in relation to each other (synthesized from (Leifer and Triscari Jr 1987; Clark and Fujimoto 1991; Kusunoki 1992; Clausing 1994; Sheasley 1999; Burgelman et al. 2004; Nieto 2004)).

Dimension	**Technology development**	**Product development**
Prerequisites	Problem-focused, often unclear and with fuzzy target. Primarily exploration-oriented.	Solution-focused, and clearer in terms of targeted market niches as well as appointed development resources. Primarily exploitation - oriented
Technical maturity	The technology is to be evaluated and developed; problems are more of a component nature.	Major technological concepts are framed and chosen; the challenge is more of an integrative and systemic nature.
Time horizon	More long-term (e.g., targeting the product portfolio of tomorrow.	Ranging over a shorter period of time.
Competence needs	Unclear, depending on the nature of the problems, and harder to proactively schedule in time.	Clearer, project-based, and easier to predict.
Process repeatability	Low; greater uncertainty involved, and uniqueness, result in elusive processed with low commonality.	Higher; the process shows more routine tasks and is easier to formalize.
Completion point	Unclear; missions can be to build knowledge or to demonstrate a certain technology feasibility level.	Sharp, ending with commercialization and the launching of new products on the market.
Development result	Knowledge, competence, capability	Marketable product, service, manufacturing or delivery system

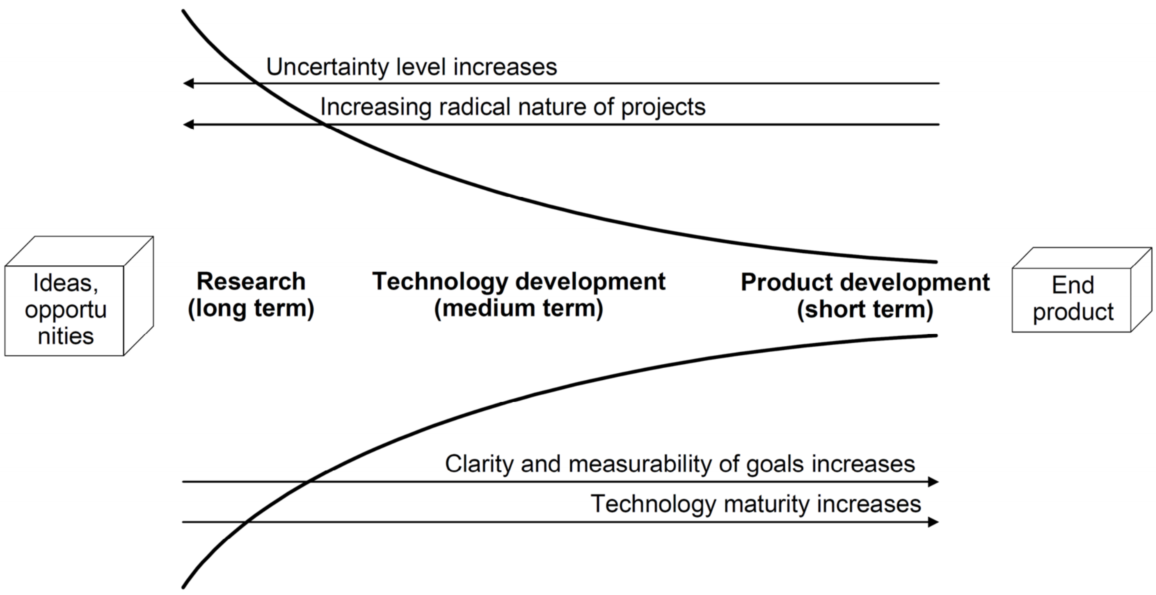

Figure 5. Nature of R&D at different phases, from (Aalto, Martinsuo et al., 2003). See also Wheelwright and Clark (1992).

Uncertainty in technology development is often very high initially (Wheelwright and Clark 1992; Groenveld 1997; Cooper 2006; Kähkönen et al. 2006), as indicated in Figure 5. As development progresses, clarity increases, and the company can down-select what initiatives to pursue to product development. Questions asked and focus shift from explorative to exploitative during the development, as exemplified by Groenveld (1997) (see Figure 6). As development continues and uncertainty decreases with increased learning, the company commits increasing amounts of resources.

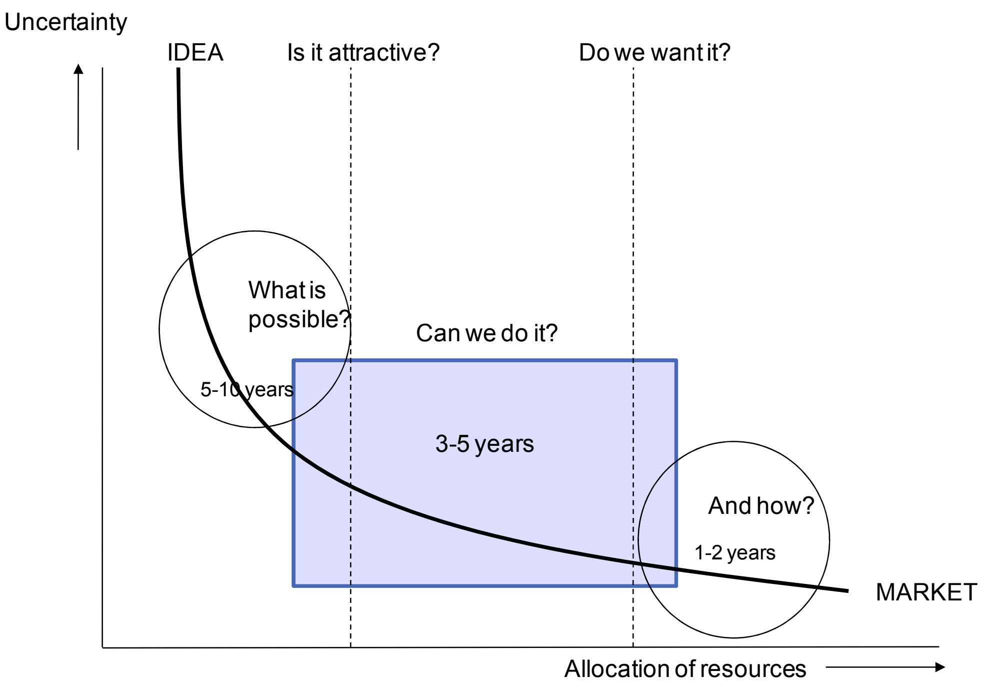

Figure 6 The Philips Blue-Box Model (Groenveld 1997)

As can be seen from Table 1, uncertainty and lack of clarity can be found in several dimensions. A high degree of uncertainty makes experimentation and iteration (to clarify both the objectives and the way to approach and meet them) necessary (Eisenhardt and Tabrizi 1995). Consequently, it is not surprising that technology development is primarily exploration-oriented, while product development is exploitation-oriented (Katz and Allen 1985). Experimentation as a means for exploration and problem-solving has been shown to play a crucial role in the corporate learning process when exposed to high levels of uncertainty (West and Iansiti 2003).

Adopting structure and normative models in this type of development is a balancing act between the rational needs of the corporation and the need for exploration and innovation. Eldred and McGrath (1997) state that "too much structure can inhibit creativity" and that "it is difficult to capture process experience and leverage for future technology development efforts." Research from highly dynamic corporate environments has shown that companies need to adopt flexible approaches to uncertain development. MacCormack and Verganti (2003) argue that the choice of specific development practices should be based upon their usefulness in resolving the specific types of uncertainty faced.

2.2.1. Engineering design theory and technology

In engineering design theory, development processes have been described and explored by various researchers, often with the objective of providing prescriptive support to product developers (Pugh 1990; Hubka and Eder 1992; Roozenburg and Eekels 1995; Ullman 2003; Ulrich and Eppinger 2003; Pahl et al. 2007). All these models are in principle similar in the sense that they divide the product development process into the following phases (even though terminology between different authors may differ):

- Product specification
- Concept generation
- Evaluation and selection of concept
- Detailed design and product layout
- Manufacturing adaptation

Design theory, describing a technical system, has been developed by Hubka and Eder (1988) and Andreasen (1992), for example. Andreasen describes how the Function-Means tree of the product gradually grows when going within and between domains from abstract to concrete and from general to detailed (see Figure 7). In axiomatic design, Suh (1990) describes product development as a successive definition of product functions realized through design means. The process is one of zig-zagging between the domains of customer needs, functional requirements, design parameters and process variables.

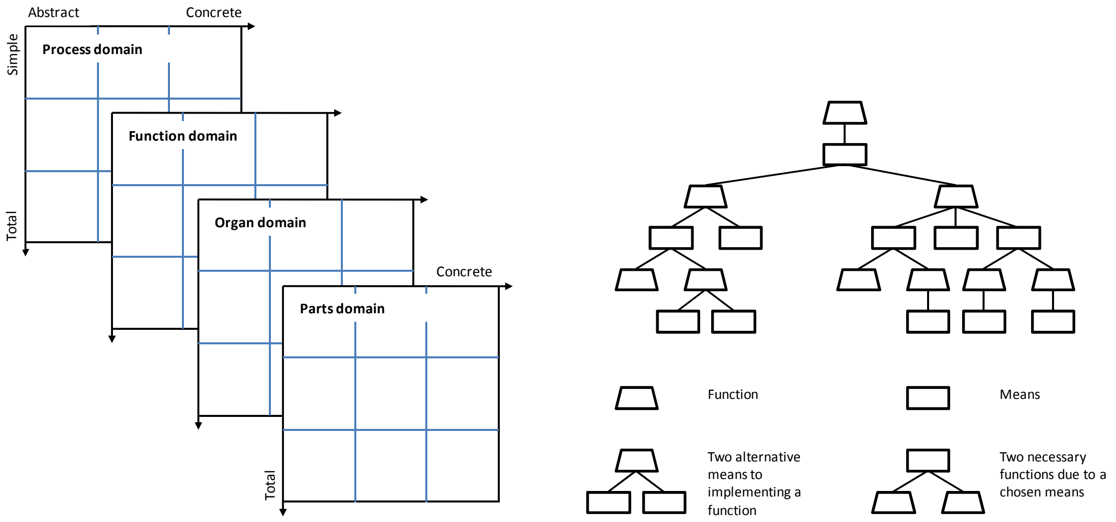

Figure 7. Development dimensions according to domain theory (Andreasen 1980) and the expanded Function-Means tree (Svendsen and Hansen 1993).

All these models aim to describe, and prescribe, how to design and manufacture a product. The models contain elements of iteration, even though an overall direction in development can be split in the various phases given above (Blessing 1995). Iteration between needs/requirements and possible solutions is conducted, in particular during concept generation/evaluation, to find a balanced design (Dorst and Cross 2001; Hansen and Andreasen 2007). It is common that activities have to be repeated when passing through the different iterative loops, with variations in input and constraints. Knowledge is built through the process. The element of exploration and learning in innovation processes has been studied by several researchers (e.g. Van de Ven and Polley 1992; Polley and Van de Ven 1996). Rothwell (1994) has described how the view regarding the innovation process has changed over the years and presents five models of innovation. A shift has occurred, going from a linear model to a network model. In most engineering design, model technology is seen as given inputs that define opportunities and constraints, not something that is to be developed. The development of the product is in focus, not the facilitating technologies.

2.2.2. Systems engineering and technology

Systems Engineering and the Vee-model (Forsberg and Mooz 1991), also called the V-model (Stevens et al. 1998), are commonly used in aerospace. The structured approach of successively breaking down top level requirements into the different components has provided a structured framework for development. Iteration of the system is an inherent part of the model, and is described by Stevens et al. (1998), for example. Stevens et al. relates a process for evolving the design of the system as an interaction of requirements and design at the different hierarchical system levels. The reasoning bears strong similarity with that found in, for example, axiomatic design or the Theory of Technical Systems (Hubka and Eder 1992). Similar to those areas of knowledge, technology in Systems Engineering is seen as a foundation and a constraint for the development of the system, or possibly as a by-product of the system development. Blanchard and Fabrycky (2006) state that technological growth occurs continuously as a response to some unmet need.

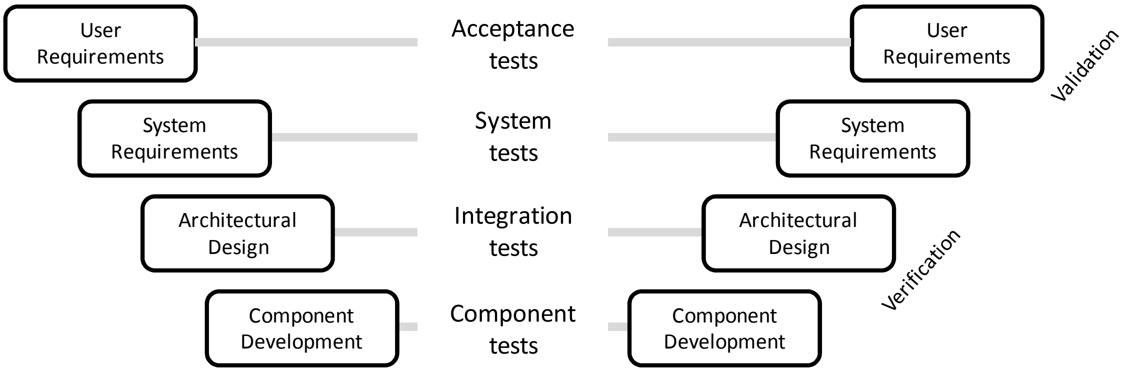

Figure 8. *The V-model, adapted from Stevens et al. (1998).*

Historically, the National Aeronautics and Space Administration in the USA has contributed methodology to support the development of complex systems. In their Systems Engineering Handbook (NASA 2007), they describe their view regarding developing and incorporating new technology in aerospace systems.

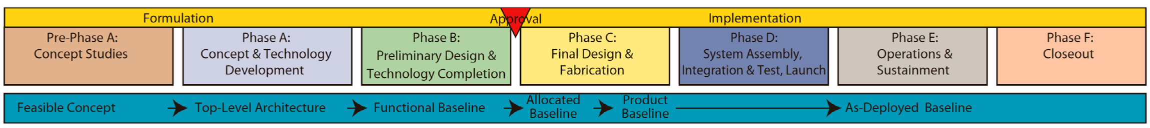

Figure 9. *The NASA project life-cycle process flow (NASA 2007).*

NASA divides system development into a series of phases where the first three incorporate technology development. The development process is described as a spiral motion, while passing the different phases, where the design of the system gradually materializes. A similar description is given in (Stevens et al. 1998; Jackson and Stevens 2000). There, the authors describe a spiral process in which the systems engineering process of the Vee-model is repeated for each iteration in the spiral. For each turn in the spiral, the level of detail and concretization increases, and risk exposure is evaluated in a stage-gate model employed by the organization. This spiral repetition of activities is a common process description also found in engineering design theory. Blessing (1995), for example, has described it, and compared different development models. In software systems engineering, the spiral model proposed by Boehm is commonly applied (Boehm 1988; Unger and Eppinger 2009).
An important component stressed by NASA (2007) is to assess the maturity of new technology incorporated in the system throughout the first three phases. They have defined a process for how this should be conducted. Maturity assessment is done relative to the Technology Readiness Levels (Mankins 1995) and for the different levels of the

system architecture. The methodology has been adopted and further developed by the US Department of Defense (2009). Further development of the assessment procedure has been proposed by several authors (e.g., Mankins 2002; Sauser et al. 2008).

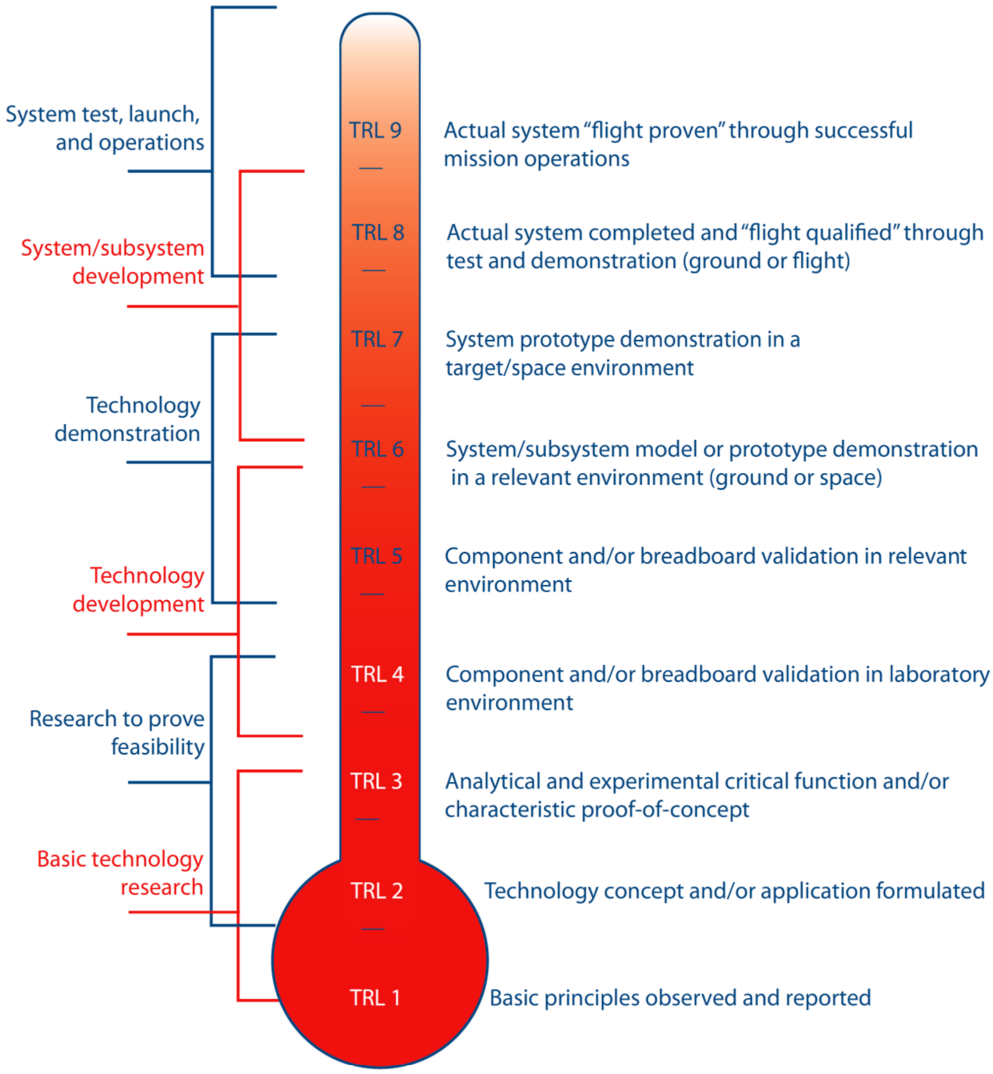

Figure 10 Technology Readiness Levels (Mankins 1995)

Clausing (1994) discusses the role of technology and its development and makes a clear separation between product and technology development. He argues that there are three main reasons for making this separation:

I. To enable time for creativity (without holding a product program hostage)
II. To provide a creative environment
III. To develop flexible (robust) technologies that can be used in several products.

He describes a technology stream running parallel with product development from which the individual product developments "fish out" new technology (see Figure 11). He proposed an approach with technology development conducted as a separate stream, which in turn feeds mature technologies into the product development process. The technological capabilities stream represent a continuous flow of knowledge and capabilities in the organisation which through the technology stream is converted into solutions possible to apply in the product stream.

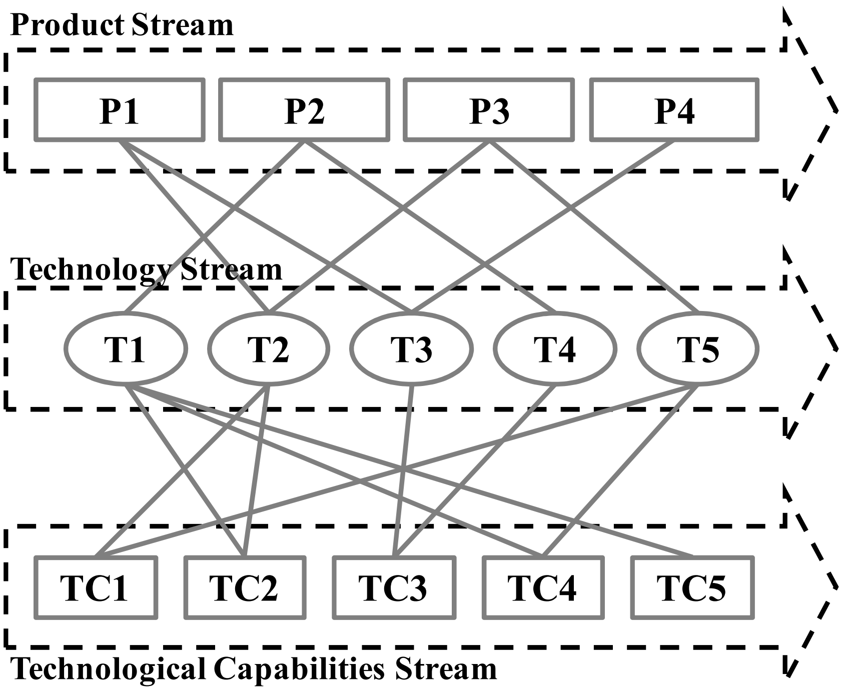

Figure 11 The three-tiered view introduced by Clausing (1994).

Schulz, Clausing et al. (2000) separate primary and secondary technologies. Primary technologies "directly enhance one or several functions of a system being introduced into this system in terms of a component, assembly, functionality, etc.". Secondary technologies enable the realization of the primary technologies and are of three different types: process, methods and tools, management and organizational (see Figure 12).

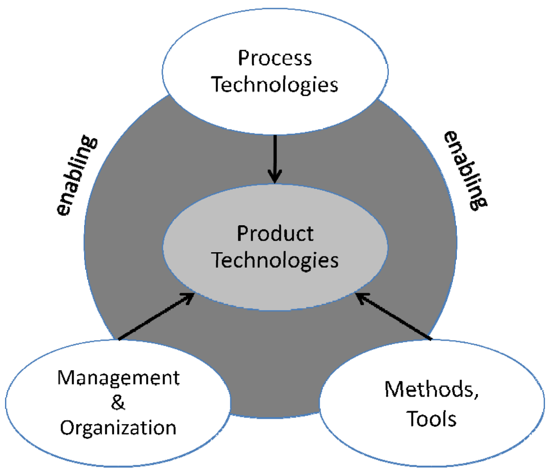

Figure 12. Secondary technologies as enablers for primary technologies (from, Schulz et al. 2000).

Clausing (1994) proposed a general process for developing new technologies in the technology stream, later further developed in (Schulz et al. 2000). Robustness optimization is primarily performed during technology development, in the Technology Stream (Figure 11), prior to introducing it into a product program. The robustness optimization is finalized during the design phase and verified in the total system during the system verification testing. After completion, the technology is ready for introduction into product development and is selected based on four criteria: a) superiority, b) robustness, c) flexibility, and d) maturity.

Based on project categorization from Wheelwright and Clark (1992), Kähkönen et al. (2006) use innovation management literature to summarize different ways to cope with uncertainty (see Figure 13).

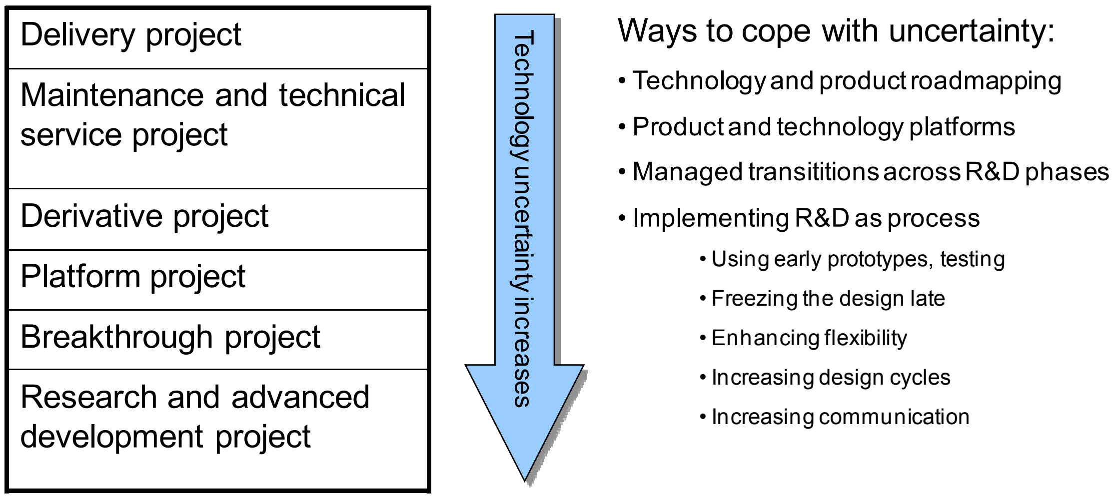

Figure 13 Managing uncertainty in R&D according to Kähkönen et al. (2006).

In the following paragraphs, several of the different ways of coping with uncertainty will be addressed, with special emphasis placed on platforms and process formulations.

2.3. Platform approaches

Applying platform strategies has received attention because of the strategies' potential to achieve advantages for internal and market leveraging. A multitude of different advantages from applying a platform strategy have been reported in literature. Some examples follow below:

- Increased efficiency in developing differentiated products, increased flexibility and responsiveness of manufacturing processes (Robertson and Ulrich 1998).
- Reduced cost and time of development and improved ability to upgrade products (Simpson et al. 2006).
- Promotion of learning across products and reduced testing and certification of complex products such as aircraft engines (Rothwell and Gardiner 1990).

– Improved design quality, offering coherence, referenceability and option value (Sawhney 1998).

There is, however, a range of different definitions of platforms. Simpson, Siddique et al. (2006) exemplify:

– "a set of common components, modules, or parts from which a stream of derivative products can be efficiently developed and launched" (Meyer and Lehnerd 1997)
– "a collection of common elements, especially the underlying core technology, implemented across a range of products" (McGrath 2001)
– "the collection of assets (i.e., components, processes, knowledge, people and relationships) that are shared by a set of products" (Robertson and Ulrich 1998).

In literature, leveraging the product platform is often found to be done through the realization of product families. Meyer, Tertzakian et al. (1997) define a product family as a set of products that share common technology and address a related set of market applications. Similarly, Simpson et al. (2006) define a product family as "a group of related products that is derived from a product platform to satisfy a variety of market niches." McGrath (2001) discusses the importance of implementing not only a platform strategy, but also a product line strategy (a concept similar to the product family) in order to reap the benefits of the platform formulation. The products within the product family can be seen as sharing a common gene pool (Sawhney 1998).

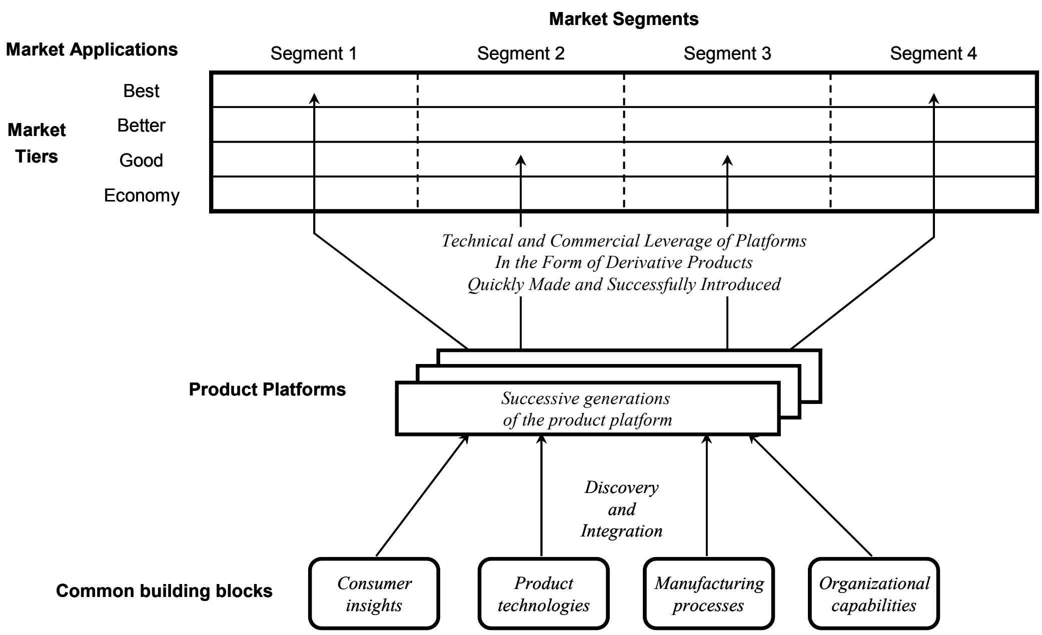

Figure 14. The Power Tower of Meyer and Lehnerd (1997).

Simpson et al. (2006) discuss the evolution of product families from the product platform. They also distinguish between modular or scalable products and refer to numerous examples of both types that can be found in literature. Well-known examples of modularized products include the Sony Walkman series (Sanderson and Uzumeri 1995) and the Hewlett Packard ink jet printer (Feitzinger and Lee 1997). Similarly, scalable products are represented, for example, by Black and Decker power tools (Meyer and Lehnerd 1997), the Rolls Royce RTM322 aircraft engine (Rothwell and Gardiner 1990), and Boeing commercial aircraft (Sabbagh 1996).

In order to discuss whether a product platform should be based on a modular or scalable assumption, one has to discuss product architecture. Product architecture has been defined by Ulrich (1995) as "(1) the arrangement of functional elements; (2) mapping from functional elements to physical components; (3) the specification of the interfaces among interacting physical components." Product architecture is classified as "either modular, if there is a one-to-one or many-to-one mapping of functional elements to physical structures, or integral, if a complex or coupled mapping of functional elements to physical structures and/or interfaces exists." (Simpson et al. 2006). Hölttä et al. (2005) concluded that if technical constraints (such as power consumption or weight) are the main drivers of design, an integral system will provide more suitable architecture than a modular system. Techniques for implementing standardization and modularity for resources within organizations are discussed in a number of publications, including (Baldwin and Clark 2000) and (Ericsson and Erixon 1999).

In addition, another category of platforms focusing on the production system, process platforms, has been proposed and explored by a few authors (see e.g., Jiao et al. 2000; Jiao et al. 2006; Jiao et al. 2007; Jiao et al. 2007).

As can be seen from the various platform definitions, the level of concretization varies quite a bit. Wider platform definitions have been proposed by a number of scholars. Sawhney (1998) defines platform thinking as "the process of identifying and exploiting the shared logic and structure in a firm's activities and offerings to achieve leveraged growth and variety". Apart from product platforms, he discusses brand, customer, process and global platforms. Sawhney argues that the selection of a proper platform should be based on a careful assessment of what is "core" and what is "variety" in the company offering, technologies, and customer segments. He argues that understanding the common strands that tie the firm's offerings, markets and processes together for the creation of leveraged growth and variety is the simple insight that is the foundation on which platform thinking lies.

Similar thoughts have been expressed by, for example, McGrath (2001). McGrath emphasizes the role of the product platform primarily as a definition for planning, decision-making, and strategic thinking. He stresses the importance of identifying what he calls "defining technologies" in product platforms as a foundation for uniqueness and a basis for product success. He argues that "in any product platform, one element above all others usually defines the real nature of that platform. It defines the platform's capabilities and limitations. It defines the unique characteristic of all products developed from that platform. The life cycle of the platform is usually dependent on the continuing strength of that element. We refer to this as the defining technology. While several technologies may be necessary to create a successful product, the defining technology is most critical."

Another type of platform discussed in literature is the technology platform. McGrath (2001) states that "a technology platform is a set of initiatives organized around a macro-level functionality that helps to manage and optimize technology investments across multiple product platforms." He further points out that the technology platforms represent, in a sense, the core competency for technology-based companies, which does not lend itself to the building block modules and interface structure of product platforms.

Similarly, Shapiro (2006) discusses technology platforms, arguing that they capture all the elements (physical and non-physical), unlike a product platform. Technologies within a technology platform can be combined to develop new products and product lines. A well-known example of a company that uses a technology platform to yield innovations is 3M. Their core strength is derived from 52 different technology platforms, such as adhesives, abrasives, and vapour processing (see (Shapiro 2006)).
Based on empirical data from the semiconductor industry, Kim and Kogut (1996) show that a firm's experience in platform technologies increases the likelihood of diversification when environmental opportunities are favourable. "Platform technologies represent the coincidence of market and technological opportunities." In addition, Kim and Kogut make an interesting observation regarding how to build the technology platform and to select what technologies to pursue. They state the following: "Freeman (1987) has observed that forecasting the class of future technologies has proven to be easier than identifying future markets and products. The implication of that seemingly innocuous observation is rather radical. Developing competence in new but broad-based technological skills is an investment in a platform to participate, by a process of expansion and diversification, in the evolution of future opportunities. In contrast, forecasting demand for specific products may lead to the development of capabilities poorly suited for the markets that eventually prove to be economically interesting." (Kim and Kogut 1996).

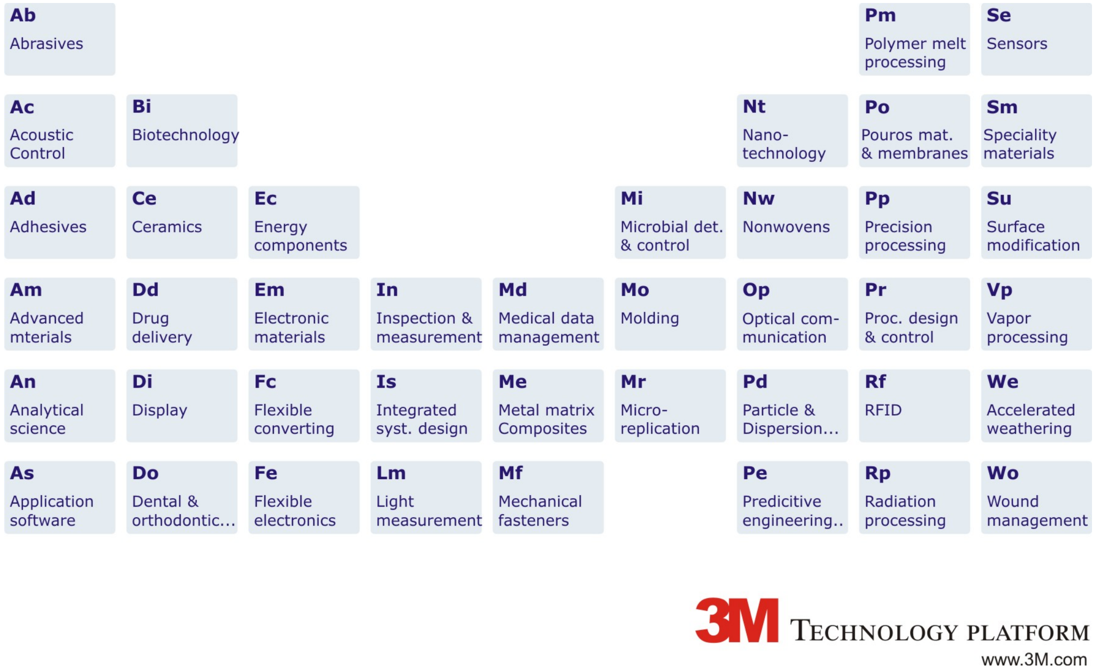

Figure 15. The technology platform of 3M, from the homepage of 3M and Shapiro (2006).

Jolly and Nasiriyar (2007) have proposed some definitions regarding technology platforms as a starting point for further empirical studies. They propose that "the technology platform represents the development of a set of technological competencies or capabilities that maps onto a wide variety of market opportunities. It concerns with reusing, redeploying and reconfiguring of existing technological assets within new context." They argue that a technology platform encompasses a set of technologies which are i) related, ii) common to different businesses and product families, and iii) distinctive and can provide competitive advantage. They argue that it is broader than product platforms, which primarily address efficiency in existing product lines, while the technology platform aims at expanding the product portfolio by leveraging the technological capabilities of the firm. Furthermore they discuss technology platform in relation to core competence (Prahalad and Hamel 1990), which based on their analysis is practically identical. One main difference though is that the technology platform to greater extent focus on technological competence exploitation.

When searching for research on technology platforms, little is found, with the references cited above as some of these few examples. However, when making a broad search on "technology platform", one can conclude that the term is used quite broadly, without any precise definition, in different research fields, ranging from materials science to medicine, biomedical engineering, radar technology, microelectronics, microbiology, etc. Furthermore, the term is used on quite different levels, in some cases as pan-European technology platforms encompassing a whole continent, and in some case as a new technology that can be used for a particular type of product. A deeper understanding concerning different uses and meaning of "technology platforms" seems warranted from this observation.

2.4. Normative models for technology development

The main purpose of this chapter is to describe some examples of normative and descriptive models in the technology development process that can be found in literature. A description of innovation models and some product development models is included to describe certain aspects explored in these areas that are relevant for technology development as well. Even though a division is made between innovation, technology development and product development, these three concepts are intimately related and in literature often intertwined. One explanation for this is that there is not really a common vocabulary in this research area (Nieto 2004), and different researchers mix the three concepts. Another explanation is the strong connection between these three perspectives. Innovation is realised through product and technology development. Product development itself should be innovative and relies on technology development, yet it also produces new technology. Finally, technology development is often driven by development activities that put inventions and discoveries to practical use (Burgelman et al. 2004).

2.4.1. On innovation process models

In Table 2, a number of different process models on innovation are summarized. Whether the model is primarily descriptive or normative (in my opinion) is indicated in the table. Here, descriptive means that the model is intended to describe the character of the process. Normative means how it should be done, or is done, in operative development or management. Models sprung out of academia are most often descriptive. On the other hand, models originating from industry tend to be normative, often with their origin from one particular context.

Table 2. Examples of innovation models in literature.

Author	**Year**	**Descriptive or Normative**	**Origin, Academia or Industry**
Rothwell	1994	Descriptive	Academia
Smith	1999	Normative	Industry (Alcoa)
Tidd et al.	2001	Descriptive	Academia
Verhaege & Kfir	2002	Descriptive	Academia
Hyland	2005	Descriptive	Academia
Miller	2006	Normative	Industry (ETAS Group)

Rothwell (1994) examined how the view of innovation has changed over the last decades, and presents five different generational models of the innovation process. The third generation model is shown in Figure 16 and was, according to Rothwell, state-of-the-art during the period early 1970's - mid-1980's. It is primarily a sequential model, an inheritance from generation one and two, but with feedback loops.

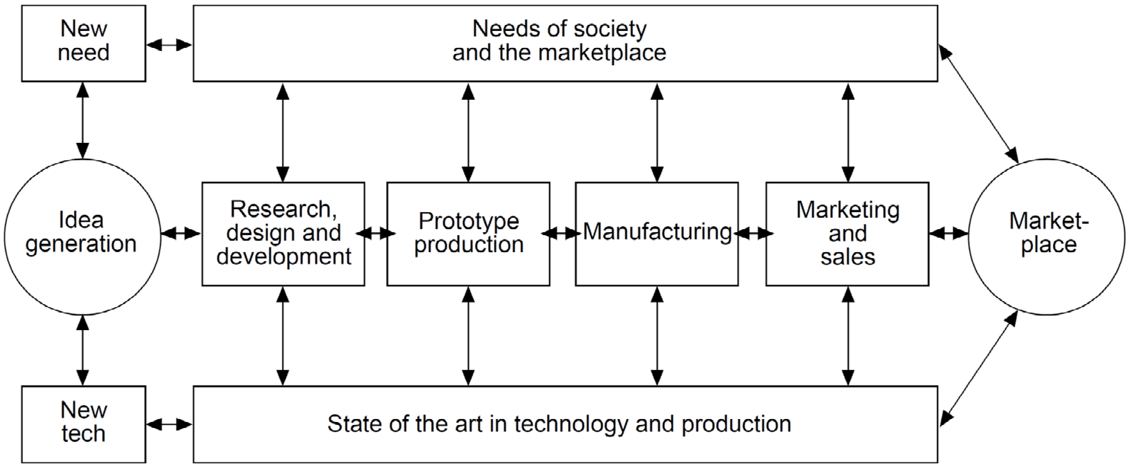

Figure 16 The "coupling" model of innovation (Third generation), from (Rothwell 1994).

In the fourth generation (early 1980's-early 1990's), the different steps in the third generation model were to a larger extent seen as parallel activities as views of concurrent engineering evolved. The fifth generation model abandons the activity-based process view. Instead, it describes a network in which the corporation builds its know-how in a learning process (see Figure 17). It is mainly an evolution of the fourth generation model that emphasizes parallel activity flow. However, it also emphasizes systems integration and networking aspects. The key aspects of the process are, according to Rothwell, integration, flexibility, networking, and parallel (real time) information processing. Tidd et al. (2001) present an innovation model that expresses similar ideas of innovation as an iterative learning process.

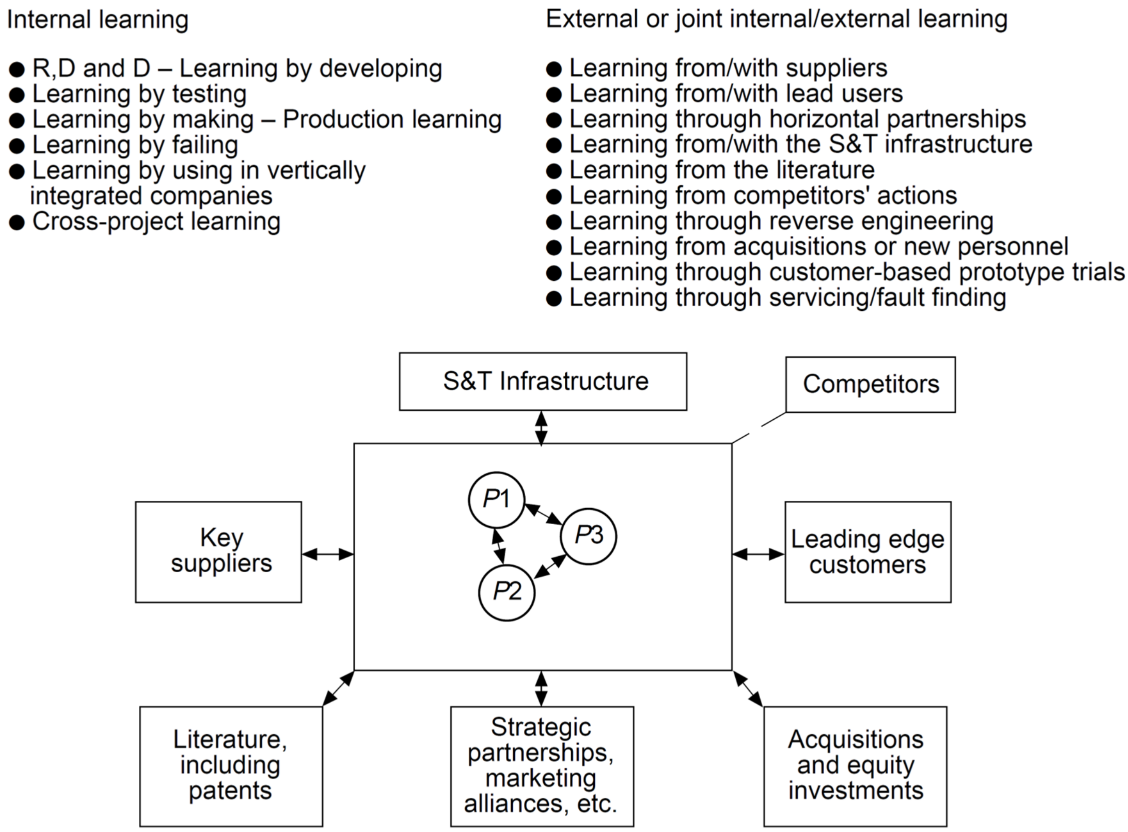

Figure 17. Innovation as a process of know-how accumulation (Fifth generation), from (Rothwell 1994).

Koen et al. (2001) developed a model describing the front end of innovation, the most important elements during this early stage and their relationships. They call it the New Concept Development Model (NCD) (see Figure 18). The activities covered by the NCD are those that come prior to the formal, well-structured activities that form product and process development. The model consists of three main elements:

- The inner area, defining the five key elements comprising the front end of innovation.
- The engine, which drives the five front-end elements and is fuelled by the leadership and culture of the organization.
- The influencing factors, or environment on the periphery, consisting of organizational capabilities, business strategy, the outside world and the enabling science that will be utilized.

They evaluated the importance of the different NCD elements to the innovative capabilities of 23 different companies. The elements that showed the strongest correlation to innovation excellence were high proficiency in company culture and leadership (what they call “the engine”), opportunity identification, and management of the technology development process. Koen et al. see culture and leadership as the crucial engine that drives corporate innovation.

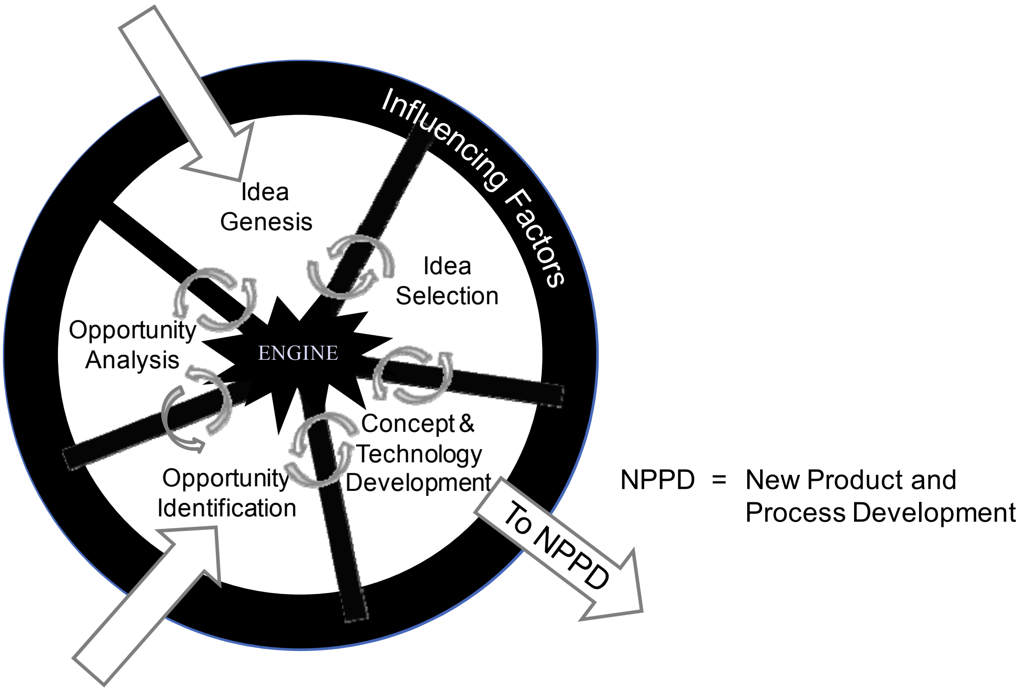

Figure 18. The New Concept Development Model (NCD) of Koen et al. (2001).

Tidd et al. (2001) state that a model for innovation development implemented in one industrial setting is usually difficult to transfer directly to another context and, therefore, needs to be adapted to that environment. The view Tidd et al. (2001) formulated that "routines are firm specific and must be learned" is therefore not surprising, and can be seen as representative of the current general view in academia.

2.4.2. On technology development models

Over the years, literature concerning the characteristics of product development, technology development and innovation has expanded. Different aspects have been researched, but the number of descriptions on normative models for technology development is quite limited. Most often these types of descriptions come from industry as testimonials regarding implemented models and experience from using them (Eldred and McGrath 1997; Cohen et al. 1998; Sheasley 2000; Koen et al. 2001; Lind 2006; Cáñez et al. 2007) .

Many of the developed models originating from academia are descriptive by nature but could probably be translated into normative models for operational application if one so wished. A common trait of technology development is its inherent uncertainty and the need for exploration and experimentation (Katz and Allen 1985; Eisenhardt and Tabrizi 1995). There is a risk that by employing normative process models, one restricts creativity and the ability to explore (Benner and Tushman 2002). It is therefore not surprising that few normative models have emerged from academia. Furthermore, "technology" may signify so many different things that defining one single process may be difficult, if not harmful.

At the same time, structure is needed for efficiency (Eldred and McGrath 1997; Cooper 2006), as witnesses from industry show. Further, the industrial need for rational processes for decision-making and prioritisation logically results in normative models, as exemplified by (Eldred and McGrath 1997; Cohen et al. 1998; Sheasley 2000; Koen et al. 2001; Lind 2006; Cáñez et al. 2007).

Table 3. Examples of technology development/management models in literature.

Author	**Year**	**Descriptive or Normative**	**Origin, Academia or Industry**
Eldred & McGrath	1997, 1999	Normative	Management consulting (PRTM)
Cohen et al.	1998	Normative	Industry (Exxon)
Sheasley	1999, 2000	Normative	Industry (Rohm and Haas)
Schulz et al.	2000	Normative	Academia
Koen & Ajamian	2001	Normative	Academia/Industry
Cooper	2006	Normative	Academia
Lind	2006	Normative	Industry (Boeing)
Cáñez et al.	2007	Normative	Industry (Mexican oil industry)

Eldred and McGrath (1997) argue that the technology development process of a company should implement a company's product strategy and transfer technology to the product development process. They argue that technology development should be managed through a review process where the maturation of the technology is followed and monitored, and they describe a model for this which they call TRAC (Technology Realisation and Commercialization). The main advantage gained from the experience of using this review process, according to Eldred and McGrath, is that the decision-making process for technology is improved.

The notion of gradual maturation and a structured review process is further supported by the propositions of both Ajamian and Koen and by Cooper (Ajamian and Koen 2002; Cooper 2006). Cooper argues for implementing a stage-gate model for technology development that is adapted to characteristics such as uncertainty. Furthermore, he argues that since differences in character and outcome from technology and product development are so large, applying the stage-gate model to technology development means that adaptation is necessary.

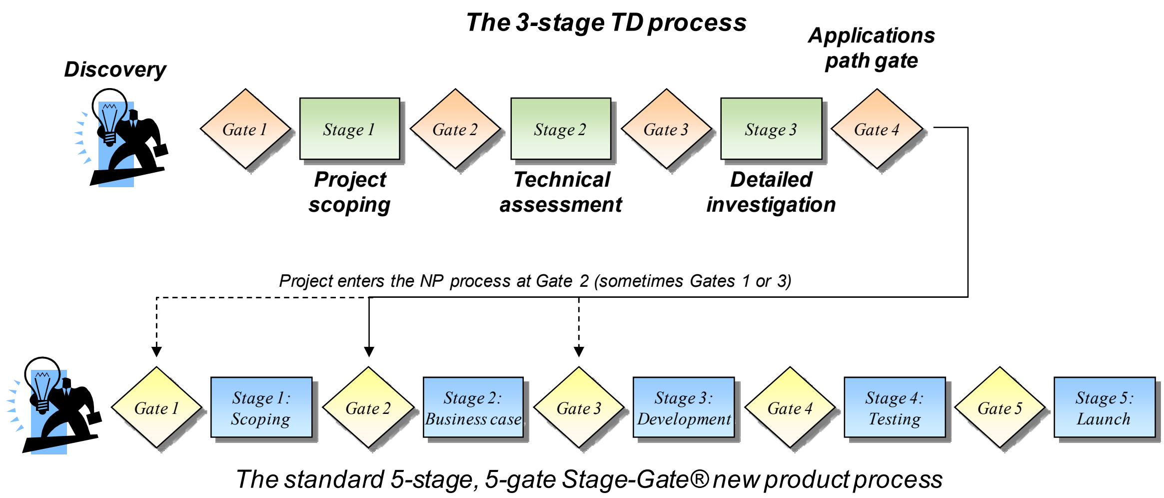

Figure 19. The technology development model by Cooper and its link to product development (Cooper 2006).

A few articles have been published with testimonials from industry describing their experience of implementing stage-gate models on technology development. Examples include Exxon (Cohen et al. 1998) and the Mexican petroleum industry (Cáñez et al. 2007). Sheasley (2000) describes the view adopted in the Room and Haas Company, where an options thinking is applied with a recurring review process. This is very similar to what is described as part of the stage-gate model. However, Sheasley emphasises the iterative learning process as central and does not frame technology development by a sequential process model, inherent in most stage-gate implementations. Lind (2006) describes the process implemented in Boeing, closely linked to the systems engineering V-model of Stevens et al. (1998).

These different models share many similar traits and experiences. One of the uniting characteristics is their purpose and what they describe. Their purpose is to manage technology development and to facilitate rational and balanced technological choices. They do not aspire to describe how new technology comes about or what the “real” process of technology development looks like. As has been seen in Chapter 2.2, it may be difficult to describe a repetitive process for technology development, and this may be a reason for this route, even though that is rarely stated in the different descriptions. However, all the Table 5 models attempt to some degree to consider the nature of technology development and how it differs from product development. It could be argued that these are practitioner accounts and thus not unbiased in their evaluation of the models. This may be true. However, they at least give an account of the perceived needs in these industries and how those needs have been addressed.

Engwall (2004) provides a description of the history of gated development models. In it, four cases of uncertain development are described. He describes different positive characteristics of the model that have led to its popularity. The model is easy to understand, there is a natural potential for control built into the model and it has a capacity to build trust. In addition, it forms a standard that facilitates the development of a common language, predictability and the creation of routines. However, in its original formulation, the model is based on an assumption of the separation of goal and action. In the early adaptations of the model, action is not initiated before goal formulation and resource allocation has been well-defined. According to Engwall, this basic assumption manifests itself in most of the literature on product development. This assumption should not be made for uncertain development. Such development should be regarded as a learning process, and the process description should reflect this, while still respecting legitimate management needs for control.

In the past, several other authors (in addition to Engwall) have stressed the importance of greater flexibility in design processes where a high degree of uncertainty is present (Bhattacharya, Krishnan et al., 1998 and MacCormack, Verganti et al., 2001).

Alternative models have been proposed in the past that are claimed to better cope with development uncertainty. Boehm (1988) proposed one of them, the spiral model. The spiral model was originally proposed as an iterative software development model. In it, development risk is managed through a series of product prototypes and requirements, and risks are successfully clarified and addressed. Unger and Eppinger (2009) compared the spiral model and the stage-gate model and their use in ten different corporate settings. He concluded that, depending on company context, companies tend to prefer one of the two. Unger and Eppinger found that both models can manage risk, but different types of risk. This is why the actual risk profile the company is exposed to may be used as a criterion for the selection of a suitable development model. In addition, he has seen that the ease of integration of samples or prototypes in testing is a clear indicator as to which model a particular company prefers. Companies exposed to high market uncertainty and where integrating prototypes is relatively easy tended to favour the flexibility offered by the spiral model. On the other hand, companies primarily facing technical uncertainty and where test product integration was harder tended to favour the stage-gate model. In the work by Unger and Eppinger, hardware companies seem to favour the stage-gate model while software companies tend to apply the spiral model.

2.5. Identified knowledge gaps - research opportunities

Extensive research has been conducted concerning models, methodology, methods, and tools for the development of technical systems and, in particular, for product development. Methodological support for technology development, similar to what is found for product development, is however largely lacking and in need of research. Still, technology and technology development are stressed time and time again in literature as crucial for the innovative capabilities of a company.

In the introduction of this thesis, different industrial problems were described, including needs concerning managing the uncertain process of developing new technology and achieving better focus in the reuse of new technology. One approach to addressing uncertainty proposed in literature is through normative processes, e.g. stage-gate. However, adopting normative process models on creativity-based activities is not without challenges. It has been discussed in previous paragraphs that routinisation, driven by process management practices, tends to result in increasingly exploitative behaviour, in turn resulting in primarily incremental innovation (Benner and Tushman 2002). At the same time, structure is needed for efficiency, which has resulted in suggestions of using the stage-gate model for managing the technology development process (Ajamian and Koen 2002; Cooper 2006). Examples from industry can be found in literature of such implementations. However, few accounts can be found regarding the difficulties encountered when applying a linear management model to technology development that is highly explorative. *Thus, a research opportunity exists to build knowledge concerning the applicability of these types of management models on highly iterative activities and how opposing needs could be resolved.*

Another route to addressing technology development is to apply a platform approach to development. Current research on platforms has primarily focused on product platforms, where in particular the concepts of modularization and scalable products have proven highly successful. However, most industrial examples of such platforms come from companies that can be described as system integrators, controlling the product architecture and the product requirements. Few examples can be found regarding platforms adapted for the needs of companies characterized as suppliers, not controlling the product architecture, not controlling product requirements, where production rates are low and the products are usually designed for unique customer needs. Could it be that a platform approach is not suitable in this type of company, or is it that conducted research on platforms simply has not addressed this type of context and therefore little prescriptive support exists? Could it be that other types of platforms are better suited to serve these types of companies? *My conclusion is that knowledge at present is largely lacking concerning the applicability of available platform theory in this type of context, which is why a research opportunity exists where these questions are addressed.*

Concerning both normative models and platforms, a challenge exists to balance between striving for efficiency and for effectiveness when adopting these approaches on technology development and innovation. Platforms have primarily been identified as a strategy for achieving internal and external leveraging through reuse, thereby achieving a larger potential for a wider product variety offer. Efficiency is sought in this sense. However, such efficiency may result in a company choosing to discard new innovations and technologies that do not build on the established and accepted platform. This, in turn, may result in a tendency toward increased incremental innovation and greater resistance for integrating new knowledge that challenges the accepted platform.

3. Research Questions

In the first chapter, the industrial problems were discussed from the perspective of one particular context. In the Frame of Reference available research considered relevant to the research purpose was discussed, ending with a discussion concerning opportunities for further research. In this part, I summarize the main research questions that have guided the work.

Earlier research proposed different approaches that may be suitable to address the issues described in the background and how to manage uncertain development. I have chosen to explore two of these routes, applying platforms and normative process models for technology development.

As described in Paragraph 1.3, the chosen context of this research is that represented by VAC (in other words, a tier one or two supplier perspective with low production volumes working on complex products usually tailored and where business is conducted as B2B with a limited customer base). However, to explore the external validity of the results obtained in this context, the research has been broadened towards the end to include five other companies.

Three main questions have guided the research.

RQ1: Which difficulties in technology development described in literature are relevant for a supplier company characterized by small scale production and customer-specific product designs?

This research question aims to describe in more detail the challenges a company meets when developing and implementing new technology in the selected context. In particular, it will serve to give more background regarding the chosen context.

RQ2: What kind of platform strategy is beneficial for a supplier company characterized by small scale production and customer-specific product designs?

As has been described in the theoretical framework, a substantial amount of research has been conducted regarding platforms. However, very little has been conducted regarding the applicability of current platform approaches to the type of context represented in this research.

RQ3: What adaptations are needed to facilitate the usefulness of the stage-gate model to manage technology development?

The amount of prescriptive support that can be found in literature concerning technology development is quite limited, especially when comparing to the progress made concerning similar support for product development. This justifies addressing this research question, in particular, since this is expressed as an industrial need.

These research questions are quite general, and different interpretations of them can be made. Consequently, different directions may be taken in the research and still give answers to the questions. As a part of the research, more detailed questions have been formulated in the individual studies. They are listed below, and are described in more detail in Paragraph 4.6. These detailed questions were not formulated from the very beginning, but have evolved as a part of the research process when new knowledge has been gained.

Research question 1 has been almost the same throughout the research project and is quite general in its formulation. The purpose of that question has been to map some of the main difficulties described in literature and found in VAC, where the answer would serve as a guide for the continued research project. Research questions two and three have evolved but were formulated in general form during the second year of the research process, when focus was placed on addressing two approaches of technology management, prescriptive processes and platforms. My research approach has been empirically driven, with identified industrial needs setting the direction. To address the three research questions, eight different studies have been conducted that are a part of this thesis. The different questions addressed in the individual studies have been defined in a step-by-step approach, meaning that a new question has been formulated for the following study depending on the results from a previous study. This has also meant that the overall research questions, primarily questions two and three above, have been modified in the process.

4. Research Methodology

The first three paragraphs, 4.1-4.3, discuss research in general, aiming at showing different strategies which are available to the researcher. Paragraph 4.3 introduce different quality criteria and discuss in particular quality considerations in case studies and participatory action research (PAR). In paragraph 4.4 and onwards, I describe the research approach which I have chosen when addressing the research questions of this thesis, and the rationale of this choice.

4.1. On knowledge creation

The aim of research is to generate knowledge. Approaching this task can be done in different ways depending on research traditions, which vary in different fields. The most common approaches are by adopting either a deductive or inductive position to knowledge creation.

Deduction is the classical approach to what is considered to be true science. It has its roots in the natural sciences, where the view is that the starting point of exploring a research question is in theory. Earlier research proven to represent the truth is used to generate hypotheses relating to the research questions at hand. The hypotheses can be verified or falsified through the gathering of empirical data, thereby contributing to theory.

Induction, on the other hand, starts from empirical data. Data is gathered, and general conclusions can be drawn pertaining to the research question after a comparison and search for patterns. Theory is a result of the empirical analysis. Even though deduction often is described as a scientific ideal, many of the great discoveries in natural science have employed extensive experimentation and observation, where inductive logic has constituted the foundation in theory creation.

Although the researcher may state that a deductive or an inductive approach is chosen, the creation of knowledge is usually somewhat more complex. Deductive logic often contains an element of induction, just as inductive logic often contains an element of deduction (Bryman and Bell 2007). The research process often entails a weaving back and forth between deductive and inductive logic in a process of iteration.

Applying deductive or inductive logic to research is intimately connected with the ontological and epistemological position of the researcher and the field of science.

Ontology concerns whether the social entities under study can be considered to have a reality external to social actors. The two opposing positions in social science are objectivism and constructionism. Objectivism claims that social phenomena have an existence independent of social actors. Constructionism, meanwhile, defends the view that social phenomena are accomplished by social actors and are in a constant state of revision (Bryman and Bell 2007).

Epistemology concerns the issue of what should be regarded as acceptable knowledge in a field. An issue of central importance in epistemology is whether social research can and should be studied according to the same principles, procedures, and ethos as the natural sciences. During the last century, the main battle has been between objectivism and interpretivism (Bryman and Bell 2007).

In philosophy, the debate regarding what knowledge is (and, correspondingly, what true science is) has been raging for hundreds of years. In the social sciences, the positivists represent an epistemological position that holds the natural science position of objectivism as the research ideal. The search for the general and objective truth is the scientific ideal. Positivists attempt to explain the social world and strive to find causal relations. Hermeneutic tradition, revived and developed in the latter part of the 20th century, opposes the idea of an objective truth, instead adhering to the view of interpretivism. Contrary to the positivist position, hermeneutic research does not attempt to explain the world through the search of causal relationships. Instead, it strives for understanding, and stresses the importance of the context in so doing (Arbnor and Bjerke 1997).

4.2. On research strategy

When deciding on research strategy, a position has to be taken as to whether a quantitative or a qualitative approach to the research questions should be used. This decision is not irrespective of the ontological and epistemological position of the research.

Quantitative research methods normally aim at answering questions such as “how often?”, “how many?”, and “when?” Through large data sets and statistical analysis, inductive conclusions can be drawn on causality and the search for general patterns. These can explain the phenomena under study and be formulated into “laws”.

Qualitative research methods normally aim at answering questions such as “how?” and “why?” Methods typically strive to provide rich description, resulting in understanding.

The common divide between qualitative and quantitative methodology and their relationship to ontology and epistemology is shown in Table 4.

Table 4. Fundamental differences between quantitative and qualitative research strategies, from (Bryman and Bell 2007).

	Quantitative	**Qualitative**
Principal orientations to the role of theory in relation to research	Deductive; testing of theory	Inductive; generation of theory
Epistemological orientation	Natural science model, in particular positivism	Interpretivism
Ontological orientation	Objectivism	Constructionism

Bryman and Bell (2007), however, state that even though it is helpful for clarification to describe the differences in approach in this way, one should be careful of driving a wedge between qualitative and quantitative research. This is because interconnections between the two positions are more complex than that. In later years, combinatory approaches have received a great deal of attention. Qualitative approaches have, for example, been advocated by researchers primarily adopting a positivist epistemology. Eisenhardt (1989) has argued that case studies involving qualitative methods are appropriate in exploratory research for theory generation and, in particular, as a way of generating empirically-based hypotheses in areas where limited theory exists.
In a similar way, researchers representing a hermeneutic tradition have advocated employing quantitative methods for exploring the possibilities of generalization and to what extent that is possible.Most research, however, tends to favour one of the two, a qualitative or a quantitative research strategy.

Within the research area of Engineering Design, Blessing has proposed a framework for conducting research that she calls Design Research Methodology (DRM) (Blessing 2002). Based on defined research criteria, prescriptive processes, methods and tools are developed through descriptive studies (DS1) to understand the problem at hand, prescriptive studies (PS) to develop suitable methods, and descriptive studies (DS2) to study the impact of the developed prescriptive methods. Throughout the research, iteration takes place between the different types of studies and the definition of research criteria to progressively find suitable constructions.

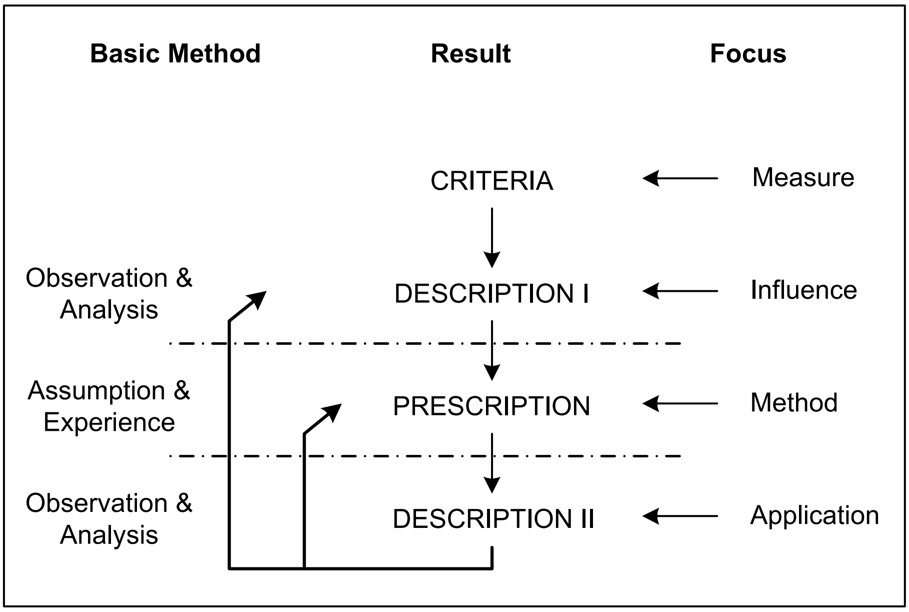

Figure 20. Design Research Methodology (DRM) from (Blessing 2002).

4.3. On research quality

Various quality criteria have been proposed by researchers relating to quantitative or qualitative research and different methodologies. They differ in interpretation and meaning depending on research tradition and ontological and epistemological position. From natural science, the positivist research tradition has adopted the quality criteria of reliability and validity. The most common meaning of reliability is as to what degree a study can be repeated, while validity concerns the degree of generalization. Applying these quality criteria to qualitative research is not readily accomplished, which is extensively discussed in literature (Arbnor and Bjerke 1997; Flick 2006; Bryman and Bell 2007) and reflected upon in the discussion below.

4.3.1. Reliability

The intention behind the reliability criterion is that it should be possible for another researcher to repeat the same study, make the same findings and reach the same conclusions. Bryman and Bell (2007) call this criterion external reliability. Flick (2006) discusses the reliability criterion in qualitative research and rejects the notion of repeatability of a study. Instead, he argues that reliability comes down to the need for explication in two respects. First, that it is possible to check what a statement of the subject is and what the interpretation of the researcher is. Second, that procedures in the field have to be made explicit in order to improve the comparability of different interviewers' or observers' conduct. He concludes that "the reliability of the whole process will be better the more detailed the research process is documented as a whole", reflecting that qualitative research usually incorporates researcher interpretation. Yin

(2003) argues in a similar way regarding reliability in case study research, and stresses the importance of documenting the different steps taken. He proposes several different strategies to facilitate the reliability of a case study, such as using case study protocols or databases in order to document the process as well as possible.

4.3.2. Validity

Validity is often split in different parts representing different aspects.

Validity in the sense of “the degree to which findings can be generalized across social settings” is called external validity by Bryman and Bell (2007). This aspect, contrary to internal validity, is usually a weakness of qualitative research (LeCompte and Goetz 1982; Bryman and Bell 2007). Case study research in particular is criticized on this account (Yin 2003). Yin argues, however, that this criticism is founded on an incorrect assumption. Critics, he claims, implicitly contrast case study research to survey research, in which a sample can be generalized to a larger universe. However, survey research relies on statistical generalization, while case study research relies on analytical generalization. “In analytical generalization, the investigator is striving to generalize a particular set of results to some broader theory.” The case study can be regarded as one test sample (Yin 2003).

Alternative quality criteria for external validity have been proposed by qualitative researchers. The notion of transferability (Guba and Lincoln 1994) is one such example. Guba and Lincoln argue that providing “thick description” provides others with a database for making judgements regarding the possibility of transferring findings to other milieux.

Internal validity is defined by Bryman and Bell (2007) as “whether or not there is a good match between researchers’ observations and the theoretical ideas they develop.” A similar criterion of this aspect is defined by Guba and Lincoln (1994), which they call credibility. However, the credibility criterion is somewhat wider. Establishing credibility incorporates ensuring both that research is conducted in accordance with good practice and that findings are submitted to the social world studied for confirmation that the investigator has understood that world. Techniques such as respondent validation and triangulation are recommended. However, whether research participants can validate a researcher’s analysis is questioned. This is because the researcher has to make a leap through the development of concepts and theories (Bryman and Bell 2007), the researcher interpretation. Respondent validation should therefore be limited to ensuring proper researcher understanding of the real world as perceived by the research respondents. Finally, internal validation is a typical strength of qualitative research. This is particularly true for case study and ethnographic research, where extensive effort normally is made to gain an in-depth understanding of the context.

4.3.3. Reliability and validity in case study research

Yin (2003) defines four quality criteria in case study research:

Construct validity: establishing correct operational measures for the concept being studied

Internal validity: establishing a causal relationship, whereby certain conditions are shown to lead to other conditions, as distinguished from spurious relationships (for explanatory or causal studies only, and not for descriptive or exploratory studies)

External validity: establishing the domain to which a study's findings can be generalized

Reliability: demonstrating that the iterations of a study – such as the data collection procedures – can be repeated, with the same results.

As can be seen, internal validity is not applicable to Yin's definition for descriptive or exploratory studies, and can in those types of studies be excluded, according to him.

Yin (2003) has proposed a series of steps (below) he argues should be made to ensure quality in case study research. The different steps are linked to the phases of a case study, and aim to ensure both reliability and validity.

Table 5. Case study tactics for four design tests, from (Yin 2003).

Tests	**Case study tactic**	**Phase of research in which tactic occurs**
Construct validity	– Use multiple sources of evidence – Establish chain of evidence – Have key informants review draft case study report	Data collection Data collection Composition
Internal validity	– Do pattern-matching – Do explanation-building – Address rival explanations – Use logic models	Data analysis Data analysis Data analysis Data analysis
External validity	– Use theory in single-case studies – Use replication logic in multiple-case studies	Research design Research design
Reliability	– Use case study protocol – Develop case study database	Data collection Data collection

4.3.4. Reliability and validity in participatory action research

Quality in action research has been debated for years. Herr and Anderson (2005) discuss the topic in detail and propose quality criteria relevant to this form of research that link to the purpose usually accompanying the approach.

Table 6. Quality criteria relevant to action research (Herr and Andersson 2005).

Outcome validity	The extent to which actions occur, which leads to a resolution of the problem that led to the study.
Process validity	To what extent problems are framed and solved in a manner that permits the ongoing learning of the individual or system.
Democratic validity	To what extent the research is done in collaboration with all of the parties who have a stake in the problem under investigation.
Catalytic validity	To what extent the participants and the researcher have been open to reorienting their view of reality as well as their view of their role.
Dialogic validity	To what extent the research has been peer-reviewed.

4.4. The chosen research approach in this thesis

Even though the results of technology development are usually measured against the quality criteria used in the natural sciences, the development process itself is a social process based on human creativity. The reality of technology development is often pragmatic, and how to conduct such development is often defined by the situation and the possibilities at hand. Seldom do we have a situation, at least in complex situations, in which true or false, right or wrong, is evident. Instead, it has to be analysed, discussed and agreed upon in the given context. Success criteria, when searching for prescriptive models, are often defined from whether the solution improves the situation and what is good enough.

In relation to my research questions, I adopt a qualitative research approach (see Table 7), which is appropriate when addressing “how?” and “why?” questions, as discussed in paragraph 4.2.

Table 7. Positioning my research concerning epistemology and ontology.

	Quantitative	**Qualitative**
Principal orientations to the role of theory in relation to research	Deductive; testing of theory	Inductive; generation of theory
Epistemological orientation	Natural science model, in particular positivism	Interpretivism
Ontological orientation	Objectivism	Constructionism

4.5. Meta-theoretical rationale

In technology development, context defines a suitable normative process, and this is likely to change as contextual factors change. My search for new knowledge in relation to the research questions, and in particular the second and third questions concerning prescriptive support, is primarily driven by abduction. The prescription that is the research purpose may be only one solution out of potentially several. Problems, needs and solutions are driven by the corporate setting I choose. They generate theory as a result, which can later be transferred to other, similar settings if perceived as useful.

It could be argued that a constructivist position is not possible to combine with the search for normative models. However, companies search for methods and tools that can serve as guidelines, support, to manage difficulties in their organizations. In fact, they search for normative models, but these have to consider the contextual factors in order to be effective. The "norm" is therefore only tentative and may become obsolete or need to be modified, due to changing circumstances. This contingent view of the "norm" as tentative, therefore, represents a constructivist view.

Generalized models may be applicable in many different settings. However, due to their general character, their operational usefulness is often very limited. They may serve as mental models for discussion, as descriptive models, or as a starting point for defining an operational model. However, they are rarely directly useful as practitioner support. In order to make models operational, they have to consider the contextual factors and be defined and tested in these settings. Results from an operational model may lead to results transferable to another context given that circumstances are similar. Models claimed to be general in character may be used as a starting point for adaptation to a particular context. However, this transformation is required in order to become operational. An operational model can be transferred to another context if the necessary adaptations are made. Given that this is done in repeated steps, generalization through induction can in some sense be accomplished by abstraction. It can then serve as a guide for the continued dispersion of a basically contextual model. In my view, generalization and contextualization can fertilize each other in this manner.

4.6. Research Design

When approaching the research questions, I have applied the Design Research Methodology (DRM) proposed by Blessing (2002) as a general guide when defining the different studies.

Figure 21 shows a classification of my studies in relation to DRM. The first research question has been addressed through descriptive studies. The second and third questions aim at developing prescriptive models but contain descriptive studies as well, and have been addressed by both descriptive and prescriptive studies.

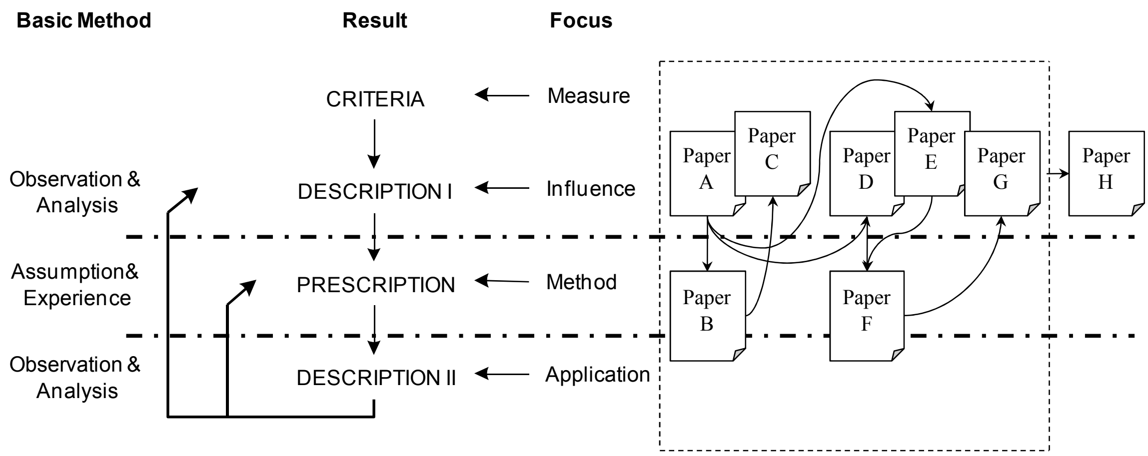

Figure 21 My research studies in relation to the classification of DRM

The research process has been iterative and inductive, where a step-wise adjustment of research questions has been made throughout the research project. Three general questions were defined initially that set a direction and reflected the general aim of the project. These questions are not identical to the research questions defined in this thesis and found in Paragraph 3; rather, they have evolved over time. An evolution of the research has modified the direction and is a result of an iterative process, where results from individual studies have influenced the direction in the following steps. In this process, the main research questions have also been modified. However, the main direction of the research reflected in this thesis was set during the second year, when the two paths regarding normative process models and platforms were selected. Results that came out of the first study, presented in Paper A, together with broad literature studies, resulted in the two main streams that have been followed.

During the course of my research project, the main research questions have been broken down into sub-questions through an inductive approach. In that approach, results from individual studies influence the formation of new questions. When answering the research questions in the different studies, they contribute to the main research questions. The process has been one of iteration between empirical results and reflection on these relative to available literature (see Figure 22). Reflecting on the individual results has resulted in a selection of research question for the next study to be conducted. The arrow between studies in Figure 22 indicates how reflection on results from one study feeds the formulation of the question for the following study. However, reflection has also been made relative to available research and possible ways to proceed. Together, they have defined the next research step.

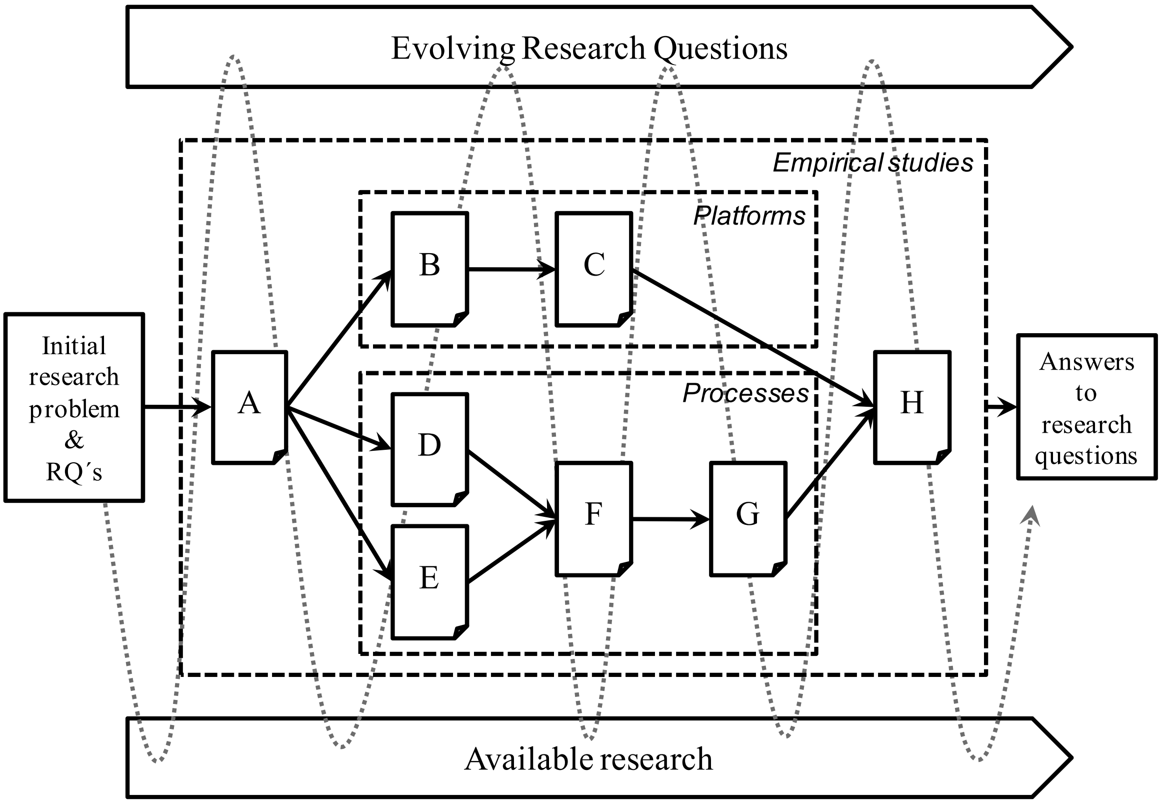

Figure 22 Iterative evolution of research questions and conducted studies.

In Table 8, the main research questions are given with the different sub-questions, or objectives, that have been addressed in the individual studies and contribute to the answers to the three main research questions. How this inductive process evolved and the rationale for the individual study questions is discussed below.

Table 8. The relationship between the main research questions and the questions, or formulated objectives, of the individual studies.

Study	Study questions	
Research question 1: Which difficulties in technology development described in literature are relevant for a supplier company characterized by small scale production and customer-specific product designs?		
A	A.1	Provide understanding for the general process for technology development at the company studied, including differences and similarities between departments.
A	A.2	Provide understanding regarding perceived problems and challenges in planning, developing and implementing new technologies.
A	A.3	Provide understanding regarding ideas for possible solutions.
Research question 2: What kind of platform strategy is beneficial for a supplier company characterized by small scale production and customer-specific product designs?		
B	B.1	What among current best practices on platform formulation could be applicable to a company like VAC, a supplier in a low batch production environment?
	B.2	Based on the needs from a company such as VAC, how could a suitable platform be formulated?
C	C.1	What is possible to reuse – between similar products in different sizes? – between different generations of the same product? – from similar components offered to different customers? – between products with different applications?
Research question 3: What adaptations are needed to facilitate the usefulness of the stage-gate model to manage technology development?		
D	D.1	Our aim in this work has been to build better understanding regarding how new technology is developed in a corporate environment and how this process can be described.
E	E.1	What is the experience from applying the stage-gate model to technology development in companies with operational differences, and what adaptations have been made to facilitate its usefulness?
F	F.1	The aim was to contribute experience gained from developing, implementing and using a normative model for technology development based on the stage-gate model.
G	G.1	What are the requirements on the maturity of technology when this technology is about to enter into the product development process?
External validity of results?		
H	H.1	Do obtained results from the unique context of Volvo, and especially that of Volvo Aero Corporation, apply more broadly in industry?

To explore the main research questions, I have mainly focused my research on one particular case company, Volvo Aero Corporation (VAC). Various research questions have been explored in a series of studies within this contextual setting, and different issues considered relevant to the main research questions were researched. Through this approach, “thick description” (Guba and Lincoln 1994) is achieved, facilitating transferability. However, in studies B, C, and H, the empirical base has been broadened to use a comparison between different cases and companies as a source for generating theory (Eisenhardt 1989) and to explore the external validity of results primarily obtained at VAC.

Study A was a descriptive study and largely explorative. The intent of the study was to paint a broad picture of technology development in the context of VAC and to gather issues perceived as important in different organizational functions of the company. Empirical results were compared to research reported in literature. This was the first study conducted, and the results were intended as a source for generating hypotheses as a starting point for continued research (Eisenhardt 1989). Within the framework of DRM, this study is type DS I.

Study B had a prescriptive aim, which is reflected in the research questions, but also contain descriptive results. Literature studies following Study A indicated that platforms was one possible approach to addressing some of the challenges discussed in the first study. However, little research was found addressing the supplier context. Therefore, the first question, B.1, was defined as a starting point and intended to map research reported in literature on the context of VAC. Based on the descriptive results obtained from the first question, study question B.2 addresses the study aim of generating a hypothetical platform prescription that can serve as the basis for continued research. Within the framework of DRM, this study is of type PS.

Study C is a retrospective study and descriptive. It was a follow-on study to study B, aimed at exploring the validity of the hypothetical platform that was proposed. Within the framework of DRM, this study is of type DS I.

Study D is a descriptive study, and was a follow-on study to A. While Study A had included a research question to map the development process, the answer that came out of the study primarily addressed the strategic management process. Limited insight into how new technology is developed in practice was obtained, which was the main rationale of Study D. The intent was to gain better understanding regarding the innovation process and how technology is developed. In addition, the results were intended as a source for generating prescriptive solutions for managing the technology development process in studies to follow. Within the framework of DRM, this study is of type DS I.

Study E is primarily a descriptive and comparative case study. Similar to Study B, literature studies following Study A indicated another possible route for addressing some of the issues revealed in the first study. The alternative route (to that of platforms) was to apply normative process models to technology development, primarily in the form of the stage-gate model. However, it was also found in literature that there were differing views concerning the value of such an approach. At this time, the planning of Study F had already started. Nonetheless, due to the differing views in available research, I felt at this time that deeper descriptive studies investigating issues with the approach were warranted. Six different companies were studied, with the objective of generating differences and similarities with respect to the research question. However, initially only two different companies were included in the study initially. It was not until later that another four company cases were added. This meant that only the results obtained from the first two companies were available when conducting the follow-on Study F. Since the stage-gate model is a prescriptive model, one could claim that Study E is a DS II study. However, since the stage-gate model has not been developed within this research, I would rather say that it is of type DS I, where descriptive results can later serve as input for generating new prescriptions.

Study F is primarily a prescriptive case study. The results from studies A, D and E were used as input into this action research study where the goal was to generate a normative model for technology development and experience from this process. Within the framework of DRM, this study is primarily of type PS. However, it also includes reflections that are of type DS II.

Study G is primarily a descriptive case study, and was a follow-on study to the previous ones (in particular, to F). When working with the action research group in study F, it was recognized that deepened attention was needed to explore requirements on deliverables from technology development to product development. The logic was that if we could define the deliverables better, the prescriptive process formulated in Study F could be made more concrete. The rationale was also supported by literature studies that showed the difficulties often encountered in transfer from technology development to product development. The study is of type DS I, with the intent of using the results to improve the process model that was the result from study F.

Finally, Study H is a descriptive study, and was the last study conducted in this research. The intent was to explore the external validity of the results in the other studies, which had primarily been gathered in VAC. The study and the interview questions were designed to test external validity. Parts of the results were also integrated in articles D and E.

As can be seen, the different studies are primarily descriptive, generating empirical knowledge from a particular context characterized by an intensive pursuit of new technologies. Prescription is generated in part, primarily concerning the application of platforms and using the stage-gate model of technology development. When the different studies have been conducted is indicated in Figure 23 .

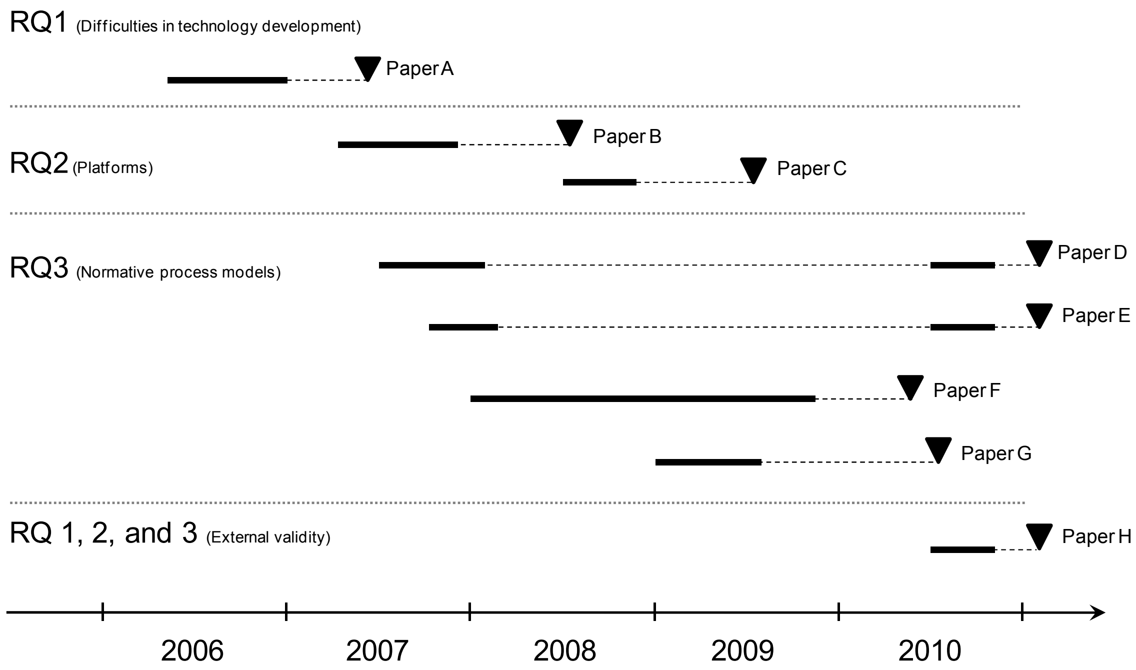

Figure 23. Empirical work (full line) and presentation of papers (triangle).

4.7. Sampling strategy, Data Collection, and Analysis

The selection of method should be defined by the research question at hand, the purpose of the study, and ontological and epistemological considerations. For this reason, I have chosen to discuss the suitability of different methods, with a starting point in the research questions explored in the different studies.
Different methods have been used in the studies, which is summarized in Table 9.

Table 9. Data collection methods used in different research studies

Main method	Study
Focus groups	A
Semi-structured interviews	B, C, D, E, G, H
Participatory action research (PAR)	B, F

4.7.1. Paper A

The intent of the study was to paint a broad picture of technology development in the context of VAC and to gather issues perceived important in different organizational functions of the company. This was the first study conducted, and the results were intended as a source for generating hypotheses as a starting point for continued research, as discussed, for example, by Eisenhardt (1989).

The chosen method of data collection was semi-structured interviewing in seven focus groups. The main reason for this choice was that focus groups typically are useful when orienting oneself in a new field and for generating hypotheses based on informant's insights ((Flick 2006), based on (Morgan 1988)). A general strength of the method is that the group discussion reveals diversity and difference and how people discuss and negotiate the topic at hand (Flick 2006). One of the main purposes of the study was to explore the differences between different organizational units. For this reason, homogeneous groups were chosen to concentrate on the differences in viewpoints of several departments on a given topic, rather than on similarities (Fern 2001). Another characteristic strength is the efficiency of the method. A large number of people can be interviewed with relatively limited effort (Lee 1999), another reason my research colleague and I chose this method.

A stepwise data reduction and information synthesis process was used to condense the material when conducting the data analysis. Summarizing content analysis, as described by Flick (2006), was done where answers from the focus groups were paraphrased and linked to the different questions. In the next step, the paraphrased answers from the seven groups were analysed and compared, and similarities and differences between the different groups were analysed and reflected upon. In the analysis, reiteration to the original, transcribed interviews were done in some cases in order to capture details lost when paraphrasing. The analysis resulted in a number of additional questions and hypothetical explanations that had to be verified or falsified. This was achieved through additional interviews with selected individuals at the two companies, thus improving clarity and eliminating error. In addition, a workshop was held with the group participants following the data analysis to verify or falsify conclusions the researchers drew. The complete analysis was done by the two researchers who conducted the interviews. The first researcher, who also asked most of the questions during the interviews, was an insider, while the second researcher was an outsider. The fact that the second researcher was an outsider meant that he could question the data with relatively fresh eyes.

4.7.2. Paper B

The aim in this paper was to answer two questions pertaining to the applicability of platforms to Volvo Aero Corporation (see Table 8). This study objective emerged, partly as a result from learnings from study A, as one possible route for the improvement of synergy between organizational units in the company, over product generations and across product families, and as a possible means for stability in the organisation. The literature review revealed a number of different platform formulations. However, the formulations' industry origins differed from the context we were interested in, which was why we were interested in exploring their validity in the context of VAC.

Empirical data was gathered through eight semi-structured interviews with key managers and strategists at VAC. The sampling strategy was the same as in study 1 (that is, purposeful), with the objective of getting the views from those believed to have "the greatest amount of insight" (Krueger and Casey 2000). Semi-structured interviewing is typically suitable in qualitative research when aiming to "seek out the world views of research participants" (Bryman and Bell 2007). The interviews were conducted by one of the researchers, who was an outsider to the organization. In addition, one of the researchers participated in a series of workshops inside the company where attempts were made to formulate a platform for one of the product families. Results from this action-research approach (Herr and Andersson 2005) were also fed into the reflections made regarding the results from the individual interviews.

In the data analysis, summarizing content analysis, as described by Flick (2006), was done, where answers from the focus groups were paraphrased and linked to the different questions. In the next step, the paraphrased answers were analysed and compared and similarities and differences were analysed and reflected upon. In the analysis, reiteration to the original interviews was done in some cases, to capture details lost when paraphrasing. Two people conducted the analysis, one being the interviewer and the other being an insider researcher. The results were discussed in workshops involving the interviewees.

The empirical results were later compared to the findings from literature, and an attempt to formulate a suitable platform was made. That platform served in the continued studies as a hypothesis for further research. Although study B primarily had a prescriptive aim, it was also descriptive and explorative in part. The first part of the study intended to map research reported in literature on the context of VAC. Based on the descriptive results, the second part in the study addressed the study aim of generating a hypothetical platform prescription that could serve as a basis for continued research.

4.7.3. Paper C

This paper describes a follow-on study to study B that sought to supply additional data as to whether the platform approach proposed in Paper B appeared promising. To achieve this, earlier experience in the company regarding the potential for reuse between different products was investigated. Reuse in four different dimensions was focused on through the four research questions given in Table 8. In this case, reuse was defined in a broad sense. It was an exploratory study, and we did not want to limit ourselves to, for example, design solutions or modules; rather, we were interested in mapping a broad picture of reuse at this stage.

The chosen research approach was retrospective. In it, the four reuse dimensions were explored based on the development experience from six different products within a particular product family. As is common in case studies (Yin 2003), different sources of data were used, such as company documentation, unstructured interviews, and workshops. Still, the chosen primary method was semi-structured interviews.

Empirical data collection was conducted in two steps.

Initially, a pre-study was conducted where four people were interviewed through semi-structured interviews regarding areas of reuse. These people were chosen to represent each of the four dimensions of the research questions. This first step resulted in eleven main categories of areas of reusability. Different aspects of enhancing and hindering factors that could arise when applying a platform strategy were identified and several elements of reusability were found (although at a fairly abstract level).
To increase concretisation, a retrospective longitudinal research approach was selected. In it, six different product developments conducted within a particular product family during the time period 1995-2008 were mapped. The reason for selecting this particular component was that extensive experience exists from different developments in different engine sizes and with different customers. In this second step of the study 12 in-depth, semi-structured interviews were conducted. The questions, formulated in an interview guide and based on the results from the pre-study and a workshop, were asked to ensure that five basic things were known: what was reused, how it was reused, where it was reused, why it was reused and where it came from. The people interviewed were selected based on their expected ability to contribute to the different aspects and dimensions explored in the different steps of the study (i.e., purposive sampling).

The transcribed interviews from the pre-study were analysed by each author individually, and important and interesting ideas and information were written down on Post-it notes. The notes were then grouped with notes containing similar information. This enabled us to distinguish different categories of interest. Those categories could then be used to present the findings from the pre-study. The procedure of discerning the interesting findings from the interviews was inspired by the concept of grounded theory (Glaser and Strauss 1967). There, key points in the data collected are to be marked with a series of codes, which are extracted from the text. The codes are then grouped into similar concepts in order to make them more workable. Categories are formed from these concepts, which then are the basis for the creation of theory.
The transcribed in-depth interviews were used to give a deeper understanding of each category of reusability in the matrix. These interviews were analysed differently from those in the pre-study. The important findings in each transcribed document were marked with a certain colour and thereafter grouped together with other related findings. The grouping was based on the reusability matrix developed in the pre-study and workshop, and focus lay on giving as much information as possible on the reusability situation in each category in the matrix.

4.7.4. Paper D

The goal of the study described in Paper D was to gain better understanding regarding the innovation process and how technology is developed. The results were intended as a source for generating prescriptive solutions for managing the technology development process.

The methodology chosen to accomplish this was through multiple case studies (Yin 2003). Case studies can be used for achieving different goals: to provide description, to test theory, or to generate theory (Eisenhardt 1989). In this case, the aim was to provide description. The research was conducted in five different companies. However, three different cases of technology development from Volvo Aero Corporation (VAC) supplied most of the empirical data and are described in detail in the article. The other four industrial cases were included primarily to explore the external validity of the results obtained in VAC. In these four cases, no particular projects were investigated. Rather, questions were asked in a general sense and were formulated based on the results obtained from VAC.

The primary method for collecting empirical data was through semi-structured interviews. Secondary data sources, such as company documents and physical artefacts, were also used. In total, fifteen interviews were conducted in VAC. Case A involved seven interviews, as did case B, and case C only one. Case C only contained one interview because its development was at a fairly early stage with very few people involved. This clearly limited the possibility of realizing triangulation in case C, but results could at least be compared with the other two cases. The interviewee selection was based on two criteria. The first was whether and to what extent they were believed capable of contributing knowledge. The second was whether a spread over time could be arranged in order to cover the whole development process, which in all cases had stretched over 10+ years. The interviewees all have held key positions in the different cases, as design engineers, design leads, project managers, technology strategists, or in marketing positions.

In the four additional companies (Companies A, B, C, and D), semi-structured interviews were conducted as well. Questions were formulated based on the results from VAC, aiming to explore the external validity of the VAC results. In Company A, three interviews were conducted; in Company B, three interviews; in Company C, two interviews; and in Company D, three interviews. More details concerning the research approach when studying these four companies can be found in the description of Paper H below.

It should also be stated that I, as one of the researchers, am an insider and have extensive personal experience from technology development within VAC. This has been another source of data that has also had an effect on the analysis made of the empirical evidence. Even though this clearly has been an asset in the study, there is a risk for bias. By involving external researchers, who have participated in all steps of the study, this risk has been minimized.

All interviews were transcribed. The three company cases from VAC were described in separate case reports and were thereafter compared, in search of similarities and differences. Conclusions were drawn from this data and formulated. These conclusions were compared to the interview results from the four validating companies A, B, C, and D.

4.7.5. Paper E

In Paper E, focus shifted from descriptive studies of the technology development process (Papers A and D) to normative models for managing such a process. The objective of this study was to gather practitioner experience regarding the suitability of applying the stage-gate model to technology development. The paper draws partially on results that have been reported in Papers F and H.

The paper was based on experience from six different companies, where data was gathered in three steps distributed over time. We limited ourselves to a corporate environment in which hardware development was in focus, and were in this selection influenced by the results from Unger and Eppinger (2009). The reason for selecting six companies was to generate knowledge through comparison. Contextual similarities and differences could explain similar or different experiences by applying the model in the six environments (Bryman and Bell 2007). All the companies, which are Swedish, were selected because they share some similar characteristics: they have a global presence, are world leaders in their respective specialisations, and have demonstrated a capability for sustainable innovation over many years. The rationale was that similarities found when comparing the different cases would serve to build external validity through replication (Yin 2003). Differences in results would be discussed based on the differences between the six companies and add to the richness of the results.

The three steps were conducted in sequence and are described below.
Step 1: A comparison of experience in two separate companies, Company 1 and 2, using the stage-gate model in technology development. This study was descriptive. Twelve semi-structured interviews were conducted, eight interviews in Company 1 and four in Company 2. All interviews were recorded and transcribed. Summarizing content analysis (as described by Flick (2006)) was done where answers from the semi-structured interviews were paraphrased and linked to the different questions posed in the interviews. The paraphrased answers were analysed and compared within the two company settings, and similarities and differences between individual interviews were analysed. The next step was to compare answers between the two company cases and analyze similarities and differences. In the analysis, reiteration to the original, transcribed interviews were done in some cases, to capture details lost when paraphrasing. The analysis resulted in a number of additional questions and hypothetical explanations that had to be verified or falsified. This was done through additional interviews with selected individuals at the two companies, thus improving clarity and eliminating error. Conclusions were drawn and fed into Step 2.

Step 2: Using an action research approach, a modified stage-gate model for technology development was developed and implemented in Company 1. Conclusions were drawn from the discussion that took place in the company during the development of the model, as well as experience from using the implemented model. The logic followed in the study agrees with the spiral of action cycles described by Herr (2005): 1) develop a plan of action, 2) act to implement it, 3) observe the effects of action, and 4) reflect on these effects. A detailed account of this study is given in Paper F.
Step 3: The external validity of the results obtained in Steps 1-2 was investigated by conducting 11 semi-structured interviews in four companies, "companies 3-6" in the paper. All of the interviews were recorded and transcribed. A detailed account of this study is given in Paper H.

Several different sources for gathering data were used, typical of case study research (Eisenhardt 1989). Examples included interviews, workshops, studies of company data (including written reports), presentations, minutes of meetings, planning documentation and company instructions. Quite a broad range of sources were available, especially in steps 1 and 2. This was due to the fact that, as an insider researcher, I had free access to both people and documentation.

The complete analysis was done by two researchers. One was the researcher who collected the empirical data, and the other was a researcher who only participated in the planning of the different studies and in the data analysis. While the first researcher was an insider in case company 1, the second researcher was an outsider in all cases. The fact that the second researcher was not part of data collection meant that he could look at the data with relatively fresh eyes. He could also question analysis that had been initiated in the first researcher's mind early on in connection with the data collection.

4.7.6. Paper F

The goal of the study reported in this paper was to generate a normative model for technology development and to gather experience from this process. This study was conducted during a two year period, from January 2008 till December 2009, as an action research study at one industrial company in the aero-engine industry. The company is located in Sweden.

The choice of research approach, action research, and the methodology followed were choices made based on the problem at hand, and were guided very much by the description supplied by Herr and Anderson (2005). Action research is a suitable method when trying to solve a real world problem in collaboration with practitioners, which was the main reason for choosing this approach. Typically, an insider researcher – insider practitioner constellation is suitable to contribute to the knowledge base on improved/critiqued practice or professional/organizational transformation (Herr and Andersson 2005). The logic followed in the study agrees with the spiral of action cycles described by Herr and Anderson (2005): 1) develop a plan of action, 2) act to implement it, 3) observe the effects of action, and 4) reflect on these effects. Work was conducted through a series of two-hour workshops during the time period January-November 2008. Apart from these working meetings, additional workshops and seminars were held during the period.

Different people were involved in the different stages. However, the core of the task was conducted by a team of seven to nine employees from the company, led by me. The number of people in the team changed during the course of development, as some people left the team and others joined. The team was cross-functional, with representation from business development & sales, engineering, quality and production. The team was selected by me, and the selection was based on two criteria: 1) cross-functional representation and 2) personal experience from technology development.

The process model was implemented and officially released in the "Operational Management System" (a web-based IT solution) of the company in November 2008. Gradually, during 2009, different technology development projects implemented and began to use the process. During 2009, I participated in a working group that focused on the issue of "How do we implement and make use of this normative model in our projects?" The team consisted of five project managers under whose leadership some of the major technology development efforts in the company were being conducted. Experience from using the model, as well as good practices, emerged during the year. One cycle in the spiral of action as defined by Herr was finally completed by reflecting on experience gained from developing the model, implementing it, and using it.

Data was recorded throughout the study in the form of short minutes of meetings distributed via e-mail to the participants and working material in the form of various documents, homepages, and reference material used by the group stored on a homepage dedicated to the team. The main result of the work, the normative process, has been formalised as a company routine in the corporate-wide Operational Management System (OMS). OMS is implemented as an IT solution in the company intranet. This system serves as the "law" in the company relative to which external and internal quality audits are conducted. The material used by the group (stored on the common homepage) and the results from the work of the group form the primary data used when conducting the analysis for this article.

4.7.7. Paper G

In the PAR study reported on in Paper F, it became clear that deeper understanding regarding what the technology development process needs to deliver had to be realized. To accomplish this, a qualitative research strategy (suitable in explorative research (Bryman and Bell 2007)) based on three study cases was chosen in the study described in Paper E. All three cases came from Volvo Aero Corporation. They were denoted Alfa, Beta and Gamma. Each case consisted of a group of designers and managers who had developed a new product design in which new technologies had been incorporated. The three cases were selected based on the fact that all of them had implemented new technologies. The bulk of data was gathered through 17 individual semi-structured interviews, all of which were recorded and transcribed.

In the study in Paper D, six main categories of technologies had been defined. These six categories were used in this study as a basic structure for selecting representative study cases, structuring the interview questions, and evaluating and analyzing the empirical data. The three product development projects, Alfa, Beta and Gamma, were selected because they all included new technologies from most of these categories (see Table 10).

Table 10. Categories of technology implemented in the three product development projects.

	Alfa	**Beta**	**Gamma**
Design solutions	x	x	x
Engineering methods	x	x	x
Manufacturing processes		x	x
Manufacturing methods	x	x	x
Materials		x	x
Test and control methods	x	x	x

The structure of the interviews followed the six technology categories in Table 10. For each category, the respondent was asked if there were any new technologies introduced in the project and to describe these. A series of questions followed for each of the stated examples. They concerned what requirements were seen as important for the successful use of the technology and whether that was met. Timing for each technology was also discussed, both when it was introduced and when the respondent felt it should have been introduced, with the required maturity level TRL 6.

Analysis was conducted through a step-wise data reduction. In it, data was clustered under common themes in a requirements breakdown structure. With the exception of grouping requirements in the six technology categories described in Table 10 this categorization was not conducted according to a pre-conceived structure. Rather, it grew out of the empirical data set in an approach similar to what is found in grounded research. The interpretation of the researcher has thus played an instrumental role when building the requirement structure. As an example, one respondent stated that an analysis had to be available regarding needed investments in machinery in order to implement a new manufacturing method. This was interpreted as a part of the “business case” regarding “manufacturing methods”.

4.7.8. Paper H

This paper presents the results from the last study conducted in this research. Its focus was on the exploration of the external validity of results obtained in the previous studies. A multiple case study approach was chosen in this study, involving four different companies. The chosen research approach and the different steps taken in this study were primarily based on recommendations from Yin (2003).

The companies were chosen based on the following facts: they are large with a global presence, they are world leaders in their respective specializations, and they have demonstrated resilience and the capability of sustainable innovation over many years. Three of the companies have their headquarters in Sweden. The exception is company D, which has been a part of a group of companies with group headquarters in the USA for the last ten years.

There are differences between the cases. They include types of products (automotive/paper /mechanical/electrical), customers (few/many, B2B/B2C), and positions in industry (component supplier/system integrator). The logic was that similarities found when comparing the different cases would serve to build external validity through replication (Yin 2003). Differences in results would be discussed based on the differences between the four cases and the VAC case, and would add to the richness of the results.

Several different sources for data gathering were used, typical of case study research (Eisenhardt 1989). However, the primary method chosen was individual semi-structured interviews. Three individuals were interviewed from each company case, with the exception of Case C, where two interviews were conducted. The interviewees were all selected based on their expected ability to contribute to the study topic (in other words, purposive sampling) through “snowballing” (Bryman and Bell 2007). All interviews were recorded and transcribed.

In the analysis, the first step was to link the different answers from the semi-structured interviews to the questions posed in the interviews. Next, the answers in the four company cases were analyzed and compared within the four company settings, and similarities and differences between individual interviews were examined. The step after that was to compare answers from the four companies with the results from Volvo and analyse similarities and differences between the different cases.

5. Results

In this chapter a summary is made of the results from the different studies which have been conducted. The summaries are held quite short since all papers are appended.

5.1. Paper A: Technology management challenges for a sub-supplier in the aerospace industry

The aim of this study was to explore the process of technology maturation and implementation in the selected case company in order to understand the perceived problems and challenges. Experience gained from aspects such as the identification, selection, planning, execution and introduction of new technology was discussed during the focus group interviews conducted. The study was structured, regarding both questions posed and the analysis made, under the different blocks of planning, development and implementation, and aimed to provide understanding of:
(i) The general process for technology development at the company studied, including differences and similarities between departments;
(ii) Perceived problems and challenges in planning, developing and implementing new technologies; and
(iii) Ideas for possible solutions.

Technology management in any company is heavily influenced by the context in which it operates. Therefore, a few remarks on the situation the studied company (Volvo Aero Corporation) is in are merited.
Customers of the aerospace company studied act primarily as system integrators. This means that the company studied is expected to take full responsibility for a component or sub-system, including developing new innovative technologies within their specializations. Prencipe (2004) has described the industry in which this particular company is one of several actors (see Figure 24). For a supplier, the global trends and general expectations of the industry may be reasonably clear. Nonetheless, how this should be translated into technology development is not necessarily clear-cut. This includes the anticipation of market trends, how the customers of the company position themselves in relation to global trends and regulations, the overarching system architecture that could be chosen by an aircraft supplier, and various forms of possible collaboration driven by market forces and political arrangements.

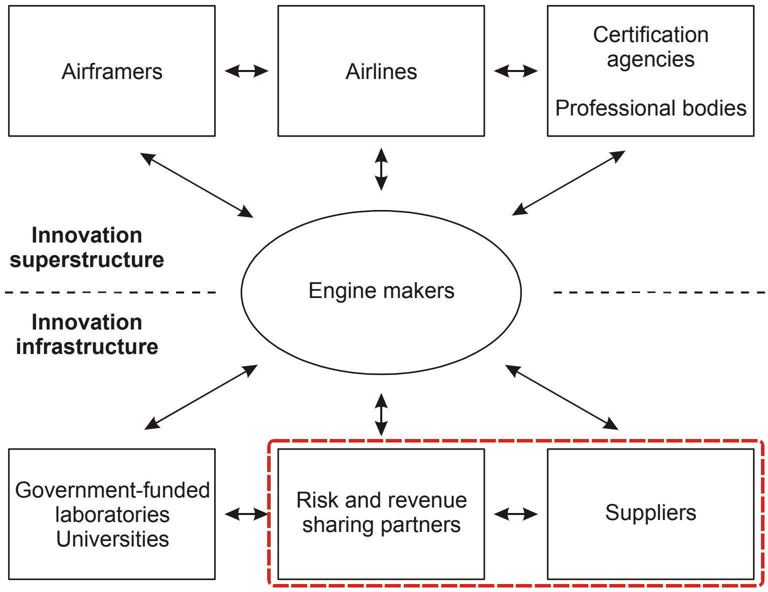

Figure 24. The aircraft engine meso-system (Prencipe 2004) with VAC operations in red.

For technology planning, it was shown that a problem exists: meeting the needs of long-term technology anticipation. Product planning was perceived as too short-sighted. It was said that typical technology development, prior to introduction, can be as long as 15 years. Meanwhile, product planning only has foresight that spans, at best, a few years ahead (and at worst far less). The reason claimed was that since the company does not control the system architecture (and therefore not the overall balancing between different sub-systems and components), future products at component level cannot be defined. At the same time, it was shown that formulating a product vision, when it was done, had been of great importance as a guide in technology selection and development.

Difficulties regarding priority and resource allocation exist for technology development. Historically, it has been very common that product development projects have been prioritized, at the expense of technology development projects. In addition, it was shown that the company has a problem making priorities when selecting technologies for continued development. This is likely linked to the difficulty of anticipation.

In literature, technology development is often described as a phase preceding product development. In this company, technology development feeds into all product life cycle phases, which are connected with the very long cycle and the way the company conducts its business (see Figure 25). The company conducts business addressing different phases in the product life cycle. It enters into business deals as a partner in new product development, a manufacturer from blue-print, and a supplier for the overhaul and maintenance of complete systems.

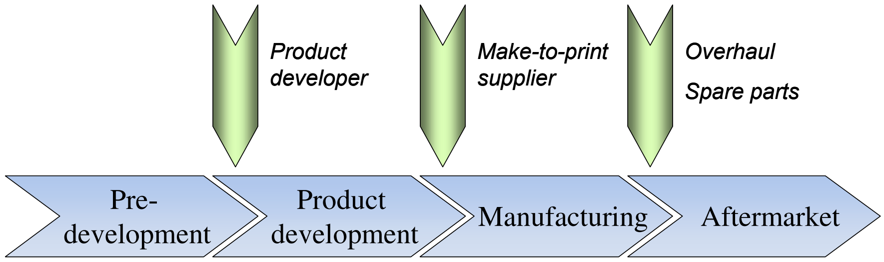

Figure 25. Different entries of new business.

New technology will have to address competitiveness for all these business entries. Thus, technology development feeds into all life phases of the product (see Figure 26). Although different business entries and different drivers of technology development exist, there are synergies of technology implementation. For example, a technology primarily developed for cost reduction in manufacturing can also be implemented in the next new product.

Concerning technology implementation, there was a wide-spread perception that the company had a poor track record. Different reasons were stated for this. Examples included deficiencies in planning capabilities, different priorities in different functional units, and poor coordination between functions.

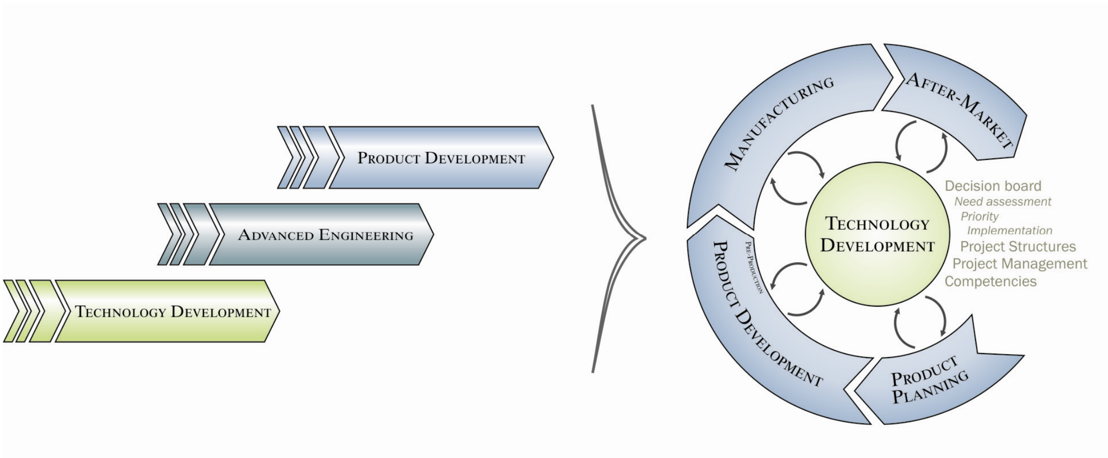

Figure 26. The multiple drivers of technology development in the company studied.

A number of different overall conclusions were drawn from this study:

- A well-formulated and communicated product plan or strategy has proven to be a vital platform for technology development. Two different business units were included in the study, and they approached this issue differently. This directly impacted on the clarity within technology strategy.
- It is important to consider at a fairly early stage of technology development how, when and where to apply new technology to simplify the implementation. Functions that will be stakeholders have to get involved at an early stage.

- Since technology development in a company tends to become incremental in specializations already fairly well-known, one has to make sure that the organization has the capability to generate and incorporate new kinds of knowledge.
- The business model of the company studied and the long cycle times of aerospace products mean that technology development efforts can be implemented at different phases of the product life cycle, instead of always going through all product development stages.
- It becomes necessary for a business-to-business component supplier to not only listen to the articulated needs of the customer, but also to anticipate future needs their customers have not yet formulated or communicated.

5.2. Paper B: Platform strategies for a supplier in the aircraft engine industry

As could be seen from the first study, new technology was implemented in all product life cycle phases. Furthermore, the product portfolio had been built over time, where corporate capabilities had been utilised as leverage to include new products. This is quite similar to the objective of implementing a platform strategy for asset leveraging. As discussed in Paragraph 2.3, platforms have been shown to provide a number of different advantages. The promotion of cross-product learning, increased efficiency in developing differentiated products, improved flexibility and responsiveness of manufacturing processes are among the pluses (Rothwell and Gardiner 1990; Robertson and Ulrich 1998; Simpson et al. 2005; Simpson et al. 2006). Consequently, the utilization of a platform strategy has become a competitive priority in many industries, most notably the automotive industry. Many firms in other industries are adopting this strategy as well, with different modifications and degrees of implementation. However, little research addresses the application of platform development in a supplier and/or small batch production environment. The adaptation of a platform strategy in such a setting was the focal point of this study. The case company selected was the same as in study 1.

Two research questions which were addressed in the study:

1. *What among current best practice on platform formulation could be applicable to a company like Volvo Aero Corporation (VAC), a supplier in a low volume business-to-business?*
2. *Based on the needs of a company of the type represented by VAC, how could a suitable platform be formulated?*

The starting point of the study was to approach the subject from the expected benefits of applying a platform strategy, internal leveraging and market leveraging, and discuss the potential for meeting these for the particular company. Market leveraging was linked to possible strategies for expansion and change (see Figure 27).

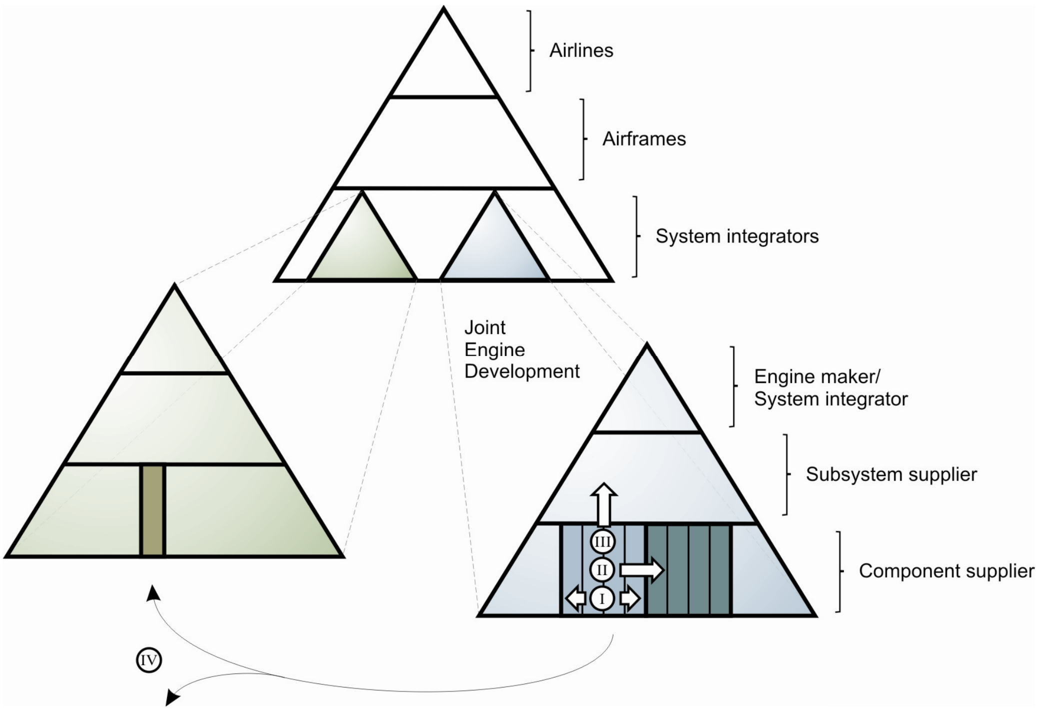

Figure 27. General strategies for the market leveraging for VAC.

The conclusion regarding the first research question was that current platform theory is applicable to sub-supplier companies in the low volume, high technology segment. However, it was also concluded that modularization through components, where designs are reused, may be difficult to realize at component level. Rather, design concepts at the more abstract level can form a common platform. Most product designs in the company are optimized for the particular application but are based on some generic design concept with underlying technologies to support its realization.

A technology platform is seen as a fundamental basis for a company like VAC. This is because attractive and verified technologies are essential for being selected for new engine programs. In addition, the company needs to have the ability to design and manufacture many various components utilizing different technologies to minimize their risk, since the selection of partners is made fairly late.

Therefore, formulating a product platform as one consisting of common modules or components is not seen as a fruitful strategy. The products are normally custom-designed for a particular application, primarily due to important design drivers such as minimizing mass or optimizing overall system performance. In addition, since VAC does not control the system architecture, there is always a risk of investing too much into methods and tools enabling design re-use connected to a specific architecture. Thus, one needs to balance this approach with more generic capabilities.

Therefore, when answering the study's second research question, a platform strategy was proposed where a product platform based on product lines and a technology platform co-exist. The difference between the two platform descriptions is that the technology platform is not connected to a specific implementation, while the product platform is the application of that technology to a specific product line. Therefore, the product platform is viewed as application-specific.

Based on the analysis of collected information, it was proposed that a possible platform strategy could include the following two items: a technology platform, incorporating general knowledge on core technology assets embodied in either humans, organizations, processes, information or methods, and a product platform, incorporating product specific elements that could be re-used when developing new components for a particular product line (see Figure 28). When developing a new product, knowledge and capabilities are drawn from both the formulated product platform and the technology.

The platform that was proposed as a result of this explorative study was formulated as a hypothesis. The benefits that could be achieved were not verified in this study; rather, they were in need of continued research.

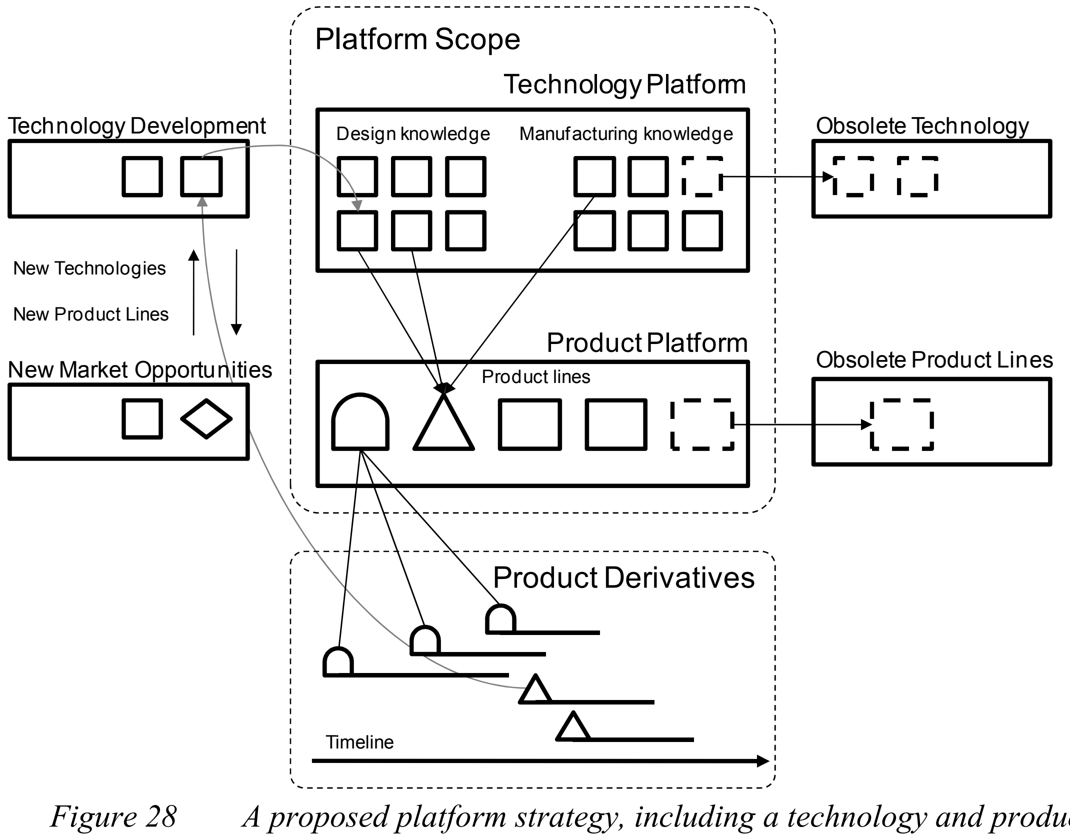

Figure 28 A proposed platform strategy, including a technology and product platform, serving different product derivatives.

5.3. Paper C: Exploring the potential of applying a platform formulation at supplier level – the case of Volvo Aero Corporation

The study described in Paper B proposed a platform approach to be tested in Volvo Aero Corporation. That proposal can be seen as a research hypothesis in need of further development and testing to be verified, falsified, or possibly modified. The study reported on in Paper C followed that of Paper B, and aimed at supplying additional data as to whether this approach appeared promising. To achieve this, earlier experience in the company regarding the potential for reuse between different products was investigated. Reuse in four different dimensions was focused on through the posing of four different research questions:

- *What is possible to reuse between similar products in different sizes?*
- *What is possible to reuse between different generations of the same product?*
- *What is possible to reuse from similar components offered to different customers?*
- *What is possible to reuse between products with different applications?*

Reuse was defined in this case in a broad sense. It was an exploratory study, and we did not want to limit ourselves to, for example, design solutions or modules; rather, we were interested in mapping a broad picture of reuse at this stage.

The research approach was that the four reuse dimensions were mapped based on the development experience from six different products within a particular product family. Empirical data collection was conducted in two steps. In the first step, eleven main categories of what has been possible to reuse were identified through four individual semi-structured interviews and a workshop. After that followed 12 individual semi-structured interviews where reuse in the four dimensions, within these eleven categories, was explored. What was found is summarized below for each research question.

Reusability between similar products in different sizes

The reusability between products in different sizes (in other words, the scalability of products) exists mainly in the underlying knowledge and core technologies possessed by the company. It is not the products themselves that have been possible to scale to different sizes by increasing or decreasing the shape of the product; it is the knowledge of how to design the product in the first place that has been reused for scalability. Even though the products have not been possible to scale themselves, it has still been possible to reduce the amount of work needed for derivative products, in accordance with the goal of applying a platform strategy.

Reusability between different generations of the same product
Most reusability can be found by looking at the projects over time, from generation to generation. This is not very surprising since much had to be developed for these projects specifically, allowing few elements to be taken from other areas or products.
The similarities between each generation of the product have allowed some product specific elements to be reused. Some of the basic structural design ideas developed for the first product generation have been used for all projects. However, some of the projects have been influenced by the customer, and different designs have been used according to their demands. Therefore, even though it has been possible to reuse some product-specific elements, most reusability can be found in the underlying knowledge, technologies and methods used to design the product.

Reusability between similar components offered to different customers
Reusability exists to some extent across customer borders. However, in the end, VAC depends so much on the requirements and solutions enforced by its customers that the full potential of reusability is impossible to reach. Even though many of the technologies and methods of VAC can be used repeatedly for different customers, it is still the customers who have the final say as to many of the methods, designs or technologies used. This limits VAC from using the method, design or technology that suits them best.
Furthermore, contractual restrictions exist that limit the possibility of transferring, for example, design solutions or design data between different customer products. Even though VAC is an independent component supplier to the "big three", these companies directly compete with each other. This has to be respected by VAC in order to maintain customer trust.

Reusability between products with different applications
The reusability of different product applications was found to be low. There are only a few categories in which elements have been found to exist in different products. Those elements that have been reused are not very product specific; instead, they lie on a higher level of abstraction and are a part of the product realisation, rather than being product specific elements. It is mainly the knowledge embedded in people coming from other areas that can be applied to and reused for the product in question. Those few elements that have been reused from other areas or products are mainly generic technologies, such as support systems and basic welding technologies that can be used on all products.
It was found that the uniqueness of the concept and its need for specially designed methods, technologies and design elements constituted the biggest hinder for the reusability between other areas and products. Therefore, only generic technologies, knowledge and competence from all parts of the company have been possible to reuse in the projects included in the study.

In conclusion, it was clear that the constant development and improvement of methods and solutions has impeded the reuse of product specific components. Instead, most

reusability has occurred in the form of experience and lessons learned. The experience lies in the realisation of the product and how to optimise it and obtain better quality. As such, much of the reusability can be found on a product design level. This has implications for the reusability between business areas and products with other applications, as many of the methods and solutions developed are specific for individual product families.
In summary, the article concludes that a platform built on reuse of design concepts and technologies appears most promising in a company like VAC, with low batch production and product designs driven by technical constraints (like weight and performance) and the optimization of product characteristics.

5.4. Paper D: The technology development process and its result – the case of Volvo Aero Corporation

While Paper A gave a broad overview of the challenges of technology development, Paper D aimed at building understanding regarding how technology development is conducted in practice. Mapping the real process was in focus, not the normative process as defined by the organization. The results were intended to be used as input for defining prescriptive support to technology development.

The research was conducted in the same context as in Paper A (i.e., Volvo Aero Corporation). Three different cases of technology development were studied in retrospect. Based on these results, conclusions were drawn and compared to experience from four other companies. This was done primarily to understand to what extent the results from VAC were valid in other contexts.

The three cases were all of a development type where the impact on the product architecture, and to the production system, was considerable. In fact, the developments were all of foundational character, where all product life-cycle phases have been affected. It was clear that this foundation did not address a single-application perspective, but, rather, addressed one or more product families with a variety of different products included. Therefore, the developments were rather of a platform character, where a set of different technologies were the result. These technologies are in an exploitation phase used to develop different product variants for different customers, in some of the cases spanning over different product families. All three cases can be seen as examples of the development of technology platforms.

Although the three cases all have followed their own distinctive path, some common patterns have been found. In all cases, a basic need, and a vision of a conceptual solution meeting this need, have defined and driven the technology development. The need for new technology is not fully known beforehand. Instead, it evolves and grows into a need-solution tree in a highly iterative process. This need-solution tree changes shape as target applications shift and new needs are encountered. The validity of the technology tree is assessed and further developed relative to different potential applications. Through this exploration and development, a platform is built from which a series of different products can be generated.

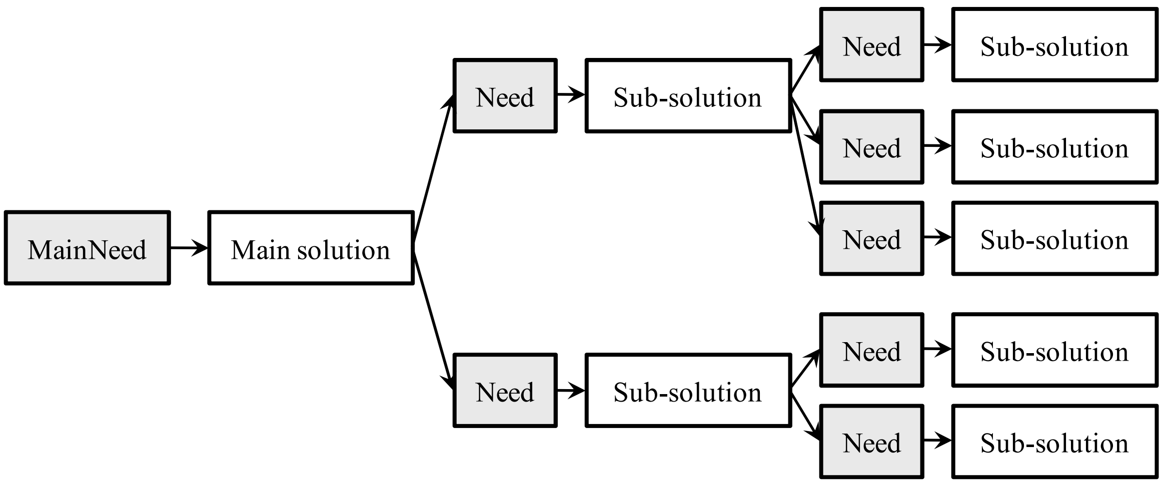

Figure 29. Vision/Need driven search for solutions.

The conceptual solutions embody the vision and help in making knowledge gaps, potential risks, real problems and needs more concrete. The iterative process builds knowledge concerning the applicability of the technology, thereby mapping the bandwidth of the developed technology platform.

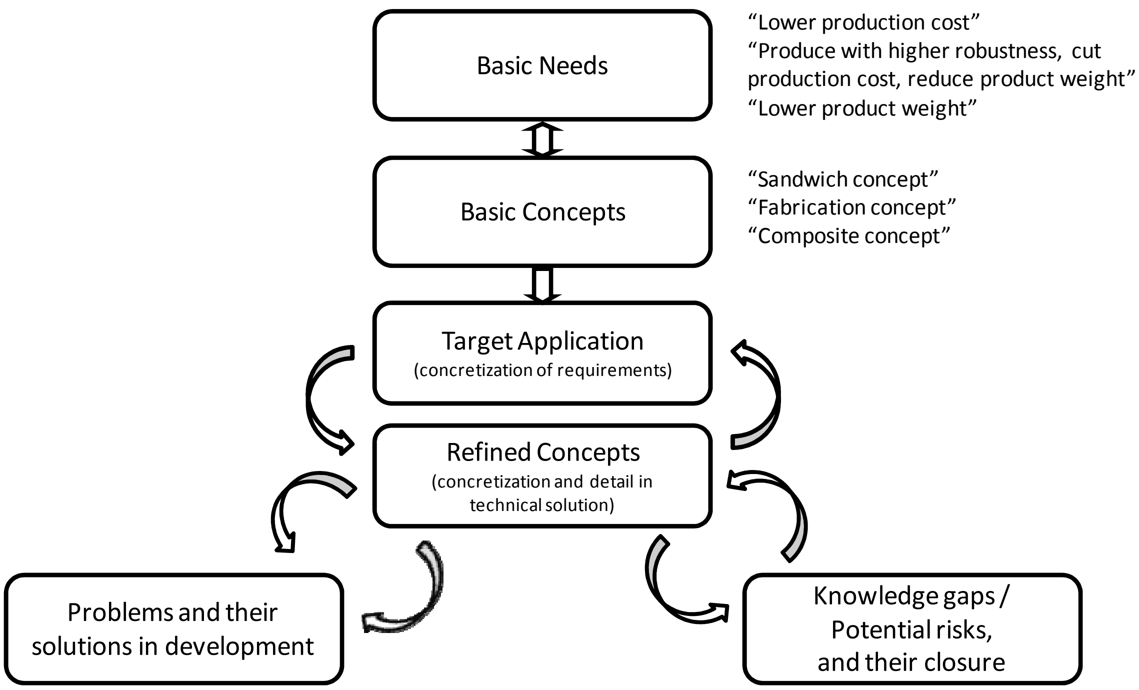

Figure 30. Forces driving the growth of the technology tree.

The technology development can be seen as a series of iterative design activities where new technology is explored and developed in order to realize a basic conceptual vision. When comparing the results to engineering design theory, a substantial amount of similarity was found. The technology tree is very similar to the Function-Means Tree as formulated by Andreasen (1980) as a part of the domain theory. Similarity is also found with axiomatic design, in the zig-zagging between functional, physical, and process domains (Suh 1990). The gradual evolution of needs and requirements as a part of the development that was found in the three cases is a trait in early conceptual development discussed by Hansen and Andreasen (2007) and Dorst and Cross (2001), for example.

Another perspective common in the aerospace industry is the Vee-model (or V-diagram) from systems engineering (see e.g., Forsberg and Mooz 1991; Stevens et al. 1998). The development process in the three studied cases can be described as passing through the Vee-model several times, initially with great uncertainty but gradually increasing the level of detail in the description of the requirements and their certainty. A similar description is given in Stevens, Brook et al. (1998) and Jackson and Stevens (2000). There, the authors describe a spiral process where the systems engineering process of the Vee-model is repeated for each iteration in the spiral. The level of detail and concretization increases for each turn in the spiral, and risk exposure is evaluated in a stage-gate model employed by the organization.

In conclusion, strong similarities were found between the three studied cases of technology development involving both engineering design theory and systems engineering. One implication of this result is that available theory base (including methods and tools) with origins in product design and systems engineering most likely can be applied successfully when developing technology as well, possibly with modifications. The elements of iteration, experimentation and learning are however more emphasized during the early stages of technology development.

The type of technology development included in this study has been shown to build a technology platform from which the company develops a range of different products. Knowledge concerning the bandwidth of the technology, and thus the technology platform, is explored in development by testing the validity of the technology for different applications. Bandwidth can be seen as a measure of the potential for commercial exploitation of the technology, and thus affects the "technology business case".

There are practical implications due to the fact that the deliveries from these early stages differ compared to later development stages. An organization developing new technology should broaden their view of technology development. It should include not only the validated technology realized through a product prototype, for example, but also the tools, capabilities and knowledge needed at the later stages to actually realize a marketable product. There is a strong tacit element during these early stages, and one of the "products" may actually be people having developed knowledge and skills relevant to the product realization.

5.5. Paper E: Applying stage-gate processes to technology development – experience from six hardware-oriented companies

In the previous studies A and D, the technology development process has been described without any ambition of delivering prescriptive support. In this paper, focus shifted to the prescriptive perspective. The stage-gate model is widely adopted in industry and applied to product development for the management of the process. It has also been proposed for use during the "fuzzy-front-end". However, as was seen in the theoretical framework, it is not evident that this necessarily is a fruitful approach. Therefore, this study aimed at exploring the applicability of the stage-gate model to uncertain development and to technology development in particular.
The formulated research question was as follows:
What is the experience from applying the stage-gate model to technology development in companies with operational differences, and what adaptations have been made to facilitate its usefulness?

In all six cases, it is evident that the companies regard technology development primarily as a stage of knowledge development. The development is seen as uncertain, with initially often fuzzy goal formulations that are gradually made more explicit.
We have found that all six companies use the Stage-Gate model to manage the technology development process. However, we have also found that the companies have considered that technology development differs on a number of accounts relative to product development when implementing and using the model.

Implemented models
The number of gates vary between the different cases, and it is not possible to say from our data that any specific number of stages is the optimum one. The companies have formulated generic check lists that are used as guides as to what should be delivered at the different gates. The check lists also have targets regarding level of detail or precision, for example.
In the initial stages, the goal formulation is accepted as being fuzzy. A clear requirements list usually does not exist at this stage. In the early stages, creativity, thinking in new ways and taking risks are often emphasized. The requirements on an initiative to pass the initial gates are set low in order to make it is easy to test new ideas and to not kill them prematurely. As development progresses, requirements on gate deliverables become tougher. In the later stages, focus is shifted towards proving feasibility and value and reducing risk levels so that they are acceptable for implementation in a first application development, product or production. An example from Company 2 is shown in Figure 31.

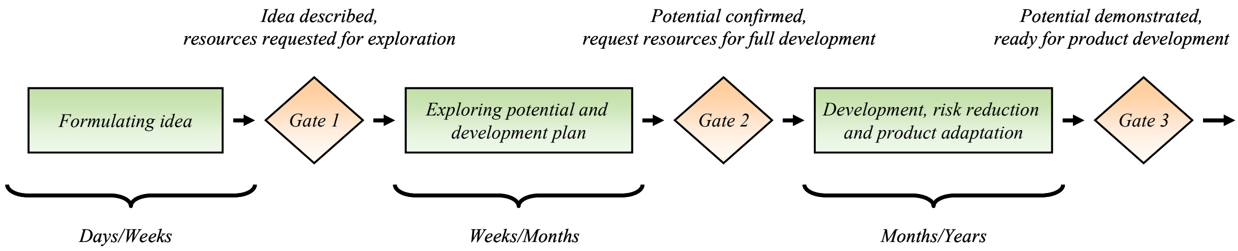

Figure 31. The implemented stage-gate model for technology development in Company 2.

Model use
Compared to product development, the model is used with greater flexibility. Gates are often softer with lower requirements regarding the detail and quality of the deliveries. Due to the high uncertainties in these phases, looping back in the technology stage-gate, modifying the direction, stopping and redefining the focus are all seen as something natural and a part of the explorative process. Other strategies found supporting flexibility include using the model recursively and defining technology development as a relay race of different projects where each individual project follows a stage-gate process.

A common result from all companies was that technology development should end with a proven concept that met some need. At this stage, feasibility and value had been proven and development risk had been reduced to levels acceptable to the organization. This was seen as the primary delivery to making a decision as to whether to start the development of a first application.

We concluded that adapting the model to the high level of uncertainty characterising technology development and its need for exploration had proven to be a successful strategy. Furthermore, we also found a more flexible use of the model than what is normally acceptable in product development.

All six companies included in this study have found ways to implement and use the stage-gate model in a modified form, both regarding its design and its practical application. In all six cases, despite great contextual differences regarding products and markets, for example, these modifications have rendered the model useful to the companies, providing effects such as logic, structure, and improved transparency.

5.6. Paper F: Technology development and normative process models

This study was initiated based on a need in VAC to implement an operational model for strategic technology development. A structured approach to down-selection and prioritization was sought. From a research perspective, the aim was to contribute experience gained from developing, implementing and using a normative model for technology development based on the stage-gate model.

The work was conducted as an action research study in a series of steps:

a) clarification of the task/problem, boundary conditions and requirements,
b) design of various models, down-selection, and detailing of a chosen model,
c) validation of the chosen model in the organization,
d) reworking after the first round of validation
e) re-validation after reworking
f) implementation in the IT management system at that company, and
g) implementation and testing in a couple of technology development projects.

During the course of the study, it became obvious that the developers and the management did not share a common view regarding the sought model. For the developers, one of the most apparent characteristics of technology development is the search for suitable solutions through iteration, which in their mind should be reflected by the model. Management, on the other hand, wanted a focus on a logic sequence of events leading to the desired outcome, developed technology. The solution finally chosen was actually a combination of two candidate concepts. When viewing the process at the first level of the IT solution, the classical stage-gate model with six stages comes up (see Figure 32).

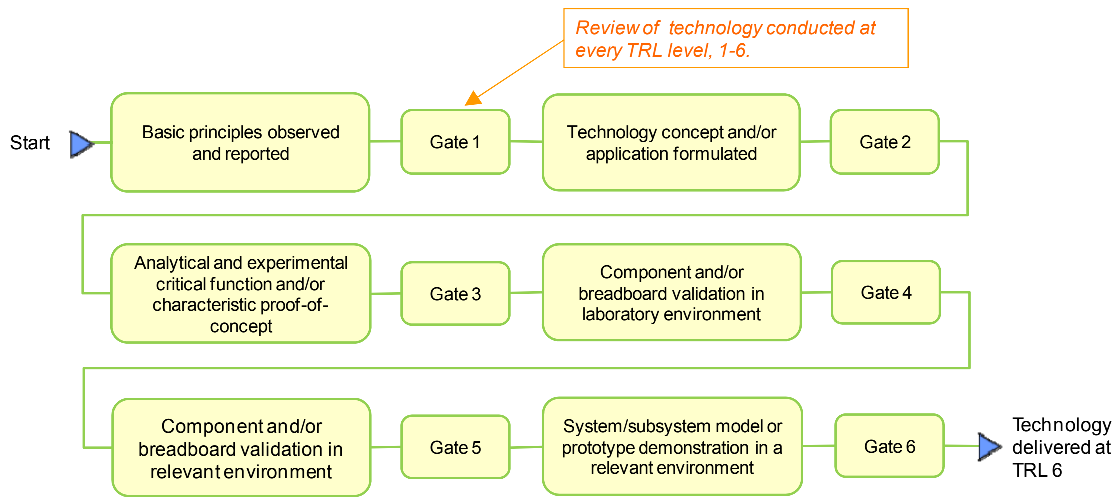

Figure 32. The normative process model for technology development in VAC.

This is a classic stage-gate model and quite similar to the model proposed by Cooper. One distinction, however, is that the model generated by the group contained six stages and gates, while Cooper's model contains three stages. The main reason for this difference was that the group chose to link the process model closely with the TRL scale (Mankins 1995) such that each stage corresponded to one TRL level. Six stages became the result of the simple “rule-of-thumb” that TRL 6 should be reached prior to application to product or process development.

Even though the model looks like a classical stage-gate, there are some aspects that separate it from the classic formulation.

a) When you “click” on one of the stage boxes, the same activity flow is found in four of the six stage boxes (TRL 3-6), while stages TRL 1 and 2 are simplified versions of the same flow. The philosophy represented in this model is simply that when technology development is conducted, activities are repeated, but the generated output contains a larger amount of detail with a higher level of concretization for each stage. This is a similar philosophy that can be found in the spiral model.
b) The second major principle of the model is that the process can call itself in a recursive manner. When new technology is being developed, new problems or needs will be encountered that were not anticipated. This is inherent in a highly uncertain development process. To solve these problems, additional new sub-technologies may have to be developed. To develop these new sub-technologies, the modelled normative process is used, thus the recursive philosophy.

An individual technology development project is usually confronted with a task involving a high degree of uncertainty. Iteration between customer/company needs, potential design solutions (product/process concepts) and technologies is conducted more or less continuously during the technology development process, and a “technology tree”, in accordance with the description found in Paper D, is gradually built.

The projects that used the model at VAC so far have adopted a practice where they describe the technology tree in a simple file as a list of technologies pursued. Different levels of technology readiness may have been achieved for different sub-technologies, which is indicated with links to supporting documentation. This description of the technology tree is updated as the project progresses and adapts to changing circumstances caused by, for example, new customer needs or new learning occurring in technology development.

Some conclusions can be drawn from learning gained from this first year of testing the process:

Advantages

- Achieved results and challenges are expressed explicitly, and adjustments to meet product/process plans can be made pro-actively.
- Clear structure makes it possible to better link to overall strategies and to adapt to changing circumstances.

Disadvantages/difficulties

- There is a risk of burdening projects with too much administration. Management has to show restraint and find a reasonable balance.

In general, the users at VAC appear quite satisfied with the model, even though a number of improvements clearly can be made to simplify its use.

5.7. Paper G: Requirements on new technology and the technology implementation process

In the study reported on in Paper F, the result was an operational process for technology development implemented in the organisation. The team developing the process spent considerable effort trying to formulate a checklist that could be used as a guide when passing the different gates. They did so because the common view deemed it more important to define what had to be delivered (in order to be able to decide on the next development step) than to define the process for getting to that point. In particular, the last gate at TRL 6 was considered especially important. That is because it is at that point the company has to decide to implement the new technology in an application development project. In addition, the study reported on in Paper A showed that there was a perception in VAC that the company had not been very successful in implementing new technology. This further emphasized the need to explore the implementation aspects.
To gain a better understanding of what had to be delivered at TRL 6, the study reported on in Paper G was conducted with the following research question in mind:

What are the requirements on the maturity of technology when this technology is about to enter into the product development process?

To answer the question, we studied the experience from three different product development projects that had been partly based on new technology. Semi-structured interviews were conducted with 17 designers and managers who had been involved in one or more of these projects. The "requirements" sought were defined in a broad sense and not purely technical.

Data on requirements was gathered and grouped in six different types of technology categories relevant to the studied company. The result was that each of these six categories contains 16 main types of requirements. The requirements are emphasized differently depending on technology category. The six technology categories were formulated in the action research study described in Paper F, even though these categories were not described in that paper. The categories were:

- Design solutions – Ways of designing a component or product.
- Engineering methods – Methods for modelling, simulation, calculation, etc (synthesis/analysis/simulation/evaluation).

- Manufacturing processes – Set-ups of production plants for manufacturing certain components/systems.
- Manufacturing methods - Methods of producing a component or product.
- Materials – Materials introduced in a component or product.
- Test and control methods – Methods for the testing and verification of components and methods.

Empirical data was grouped in 16 requirement groups under the six technology categories. These 16 groups were defined through a grounded research approach, and can be found in Figure 33, where clustering was made based on the empirical data generated in the interviews.

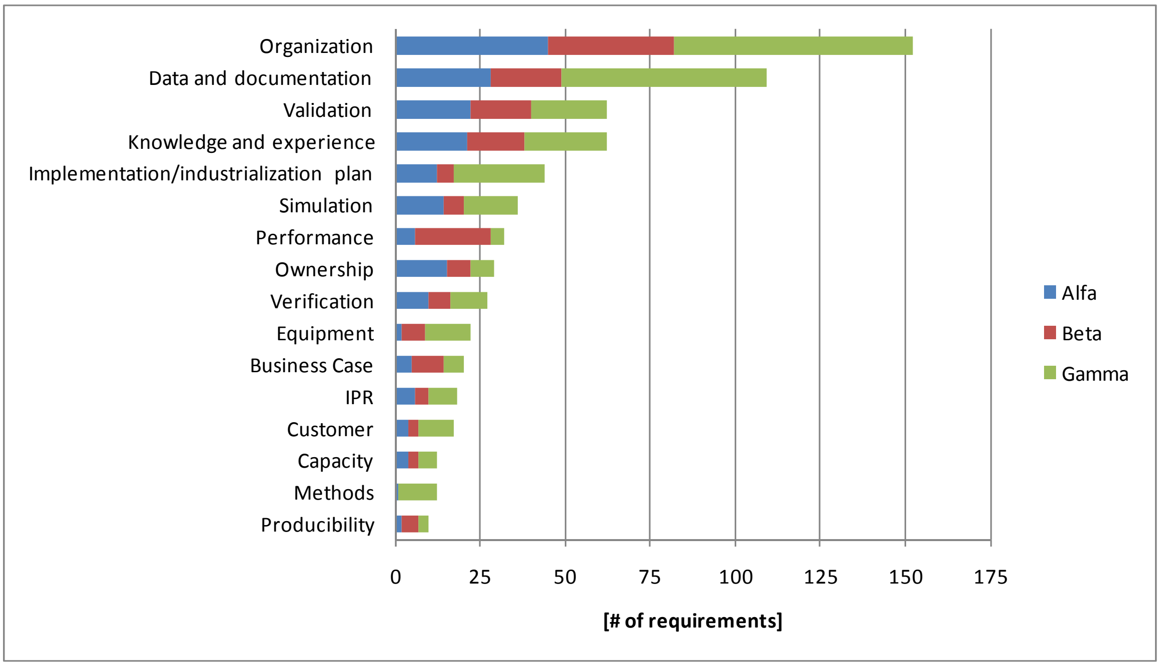

Figure 33. Distribution of the 16 main requirement groups.

It was found that requirements in these six categories differ substantially. For example, organizational aspects are most important when developing and implementing new manufacturing processes. However, such considerations are considerably less important when introducing new design solutions in which data and documentation carry more weight.

It was also found that the timing of mature technologies in relation to product design differs. Requirements on the maturity of new design solutions occurred earlier, relative to the product development process, than what was found for manufacturing methods. Manufacturing methods, on the other hand, push validation towards an overlap between product development and technology development. The reason was primarily one of efficiency. Validation tests have to be conducted on subjects similar to the real application environment. This means that real validation is often not obtained until actual application in a particular implementation occurs.

The conclusion drawn from these results was that, for successful technology implementation, it is important to identify what group of technology the development belongs to. Then what is really needed can be delivered at the appropriate point in time. Another observation made when analyzing the empirical data was that the requirements expressed in the interviews often address issues that do not directly concern requirements regarding the performance of the technologies or their characteristics. Instead, many of the requirements concern the development process and how new technologies are assimilated in the organization and made useful.
The conclusion from this observation was that attention during technology development should not only be paid to the capabilities of the technology itself, but also to how the organization builds new capabilities and integrates them in the organization. Approximately half of the identified requirements relate to aspects concerning the transfer of technology from applied research to implementation in the final application.

5.8. Paper H: Technology development practices in industry

All the previous studies have been conducted at Volvo Aero Corporation primarily, covering different aspects of technology development and implementation. External validity has been built mainly through a comparison with literature. However, in order to further investigate the external validity of the results, this last study was conducted. The research question we wanted to answer was the following:

Do obtained results from the unique context of Volvo, and especially that of Volvo Aero Corporation, apply more broadly in industry?

In order to answer the question, a multiple case study approach was chosen involving four different companies. Two to three people were interviewed in each company, and the questions were formulated such that falsification or verification of the earlier results would be possible.

The main conclusion from this study was that most of the results previously obtained in VAC were also found in the four companies, thereby verifying earlier results. The fact that these companies represent quite different types of products and contexts strengthens the external validity. Differences between the cases have quite naturally also been found, and some of those have been discussed in the paper.

Apart from providing an answer to the research question, the study has given a broader view of technology development than what is possible to achieve when conducting all studies within one context alone.

5.9. *Summarizing obtained results*

In this paragraph the main results from the various studies are summarized in relation to the research questions.

5.9.1. Difficulties in technology development described in literature which are relevant for a supplier company characterized by small scale production and customer-specific product designs

The identified difficulties are:

- Mismatch between engineers' needs for predictive long-term goal formulation (to guide technology development) and the capability, or even possibility, of producing such long-term anticipation.
- Difficulties with placing sufficient priority on, and allocating needed resources to, technology development.
- Difficulties to select technologies for continued development.
- Difficulties concerning technology implementation.
- Reliance on a few strong individuals advocating the incorporation and development of new technologies.
- Insufficient understanding for technology development as primarily a learning process, one of the traits which makes it different to product development.

5.9.2. Platform strategy for a supplier company characterized by small scale production and customer-specific product designs

- A component based product platform is unsuitable for this type of company.
- A platform approach has been proposed where a product platform, based on product lines, and a technology platform co-exist. The difference between the two platform descriptions is that the technology platform is not connected to a specific implementation, while the product platform is the application of that technology to a specific product line.
- The product platform is based on reuse of design knowledge, product concepts, and applied technology, for the different products in the company.
- The technology platform incorporates generic technological capabilities which are used in many different products, and is the foundation for product portfolio expansion.

5.9.3. Adaptations needed to facilitate the usefulness of the stage-gate model to manage technology development

- Developing simplified versions of the stage-gate model, relative to what is normally employed in product development, has been found to be a common approach.
- The different companies use their models with a greater degree of flexibility than what is normally acceptable in product development, including

    - loop backs,
    - modifying direction during development,
    - stopping and redefining the focus,
    - “soft gates”,
    - conducting technology development as a relay race between projects,
    - using the model recursively.
- Adapt the model to consider more holistic aspects concerning for example preparing the internal organisation for the new technology, assessing to what extent knowledge is built in the organisation regarding the new technology, how to apply the technology, and to ensure that technology implementation is properly addressed.
- Adapt the model to consider that technology development primarily is a learning process, e.g. through a flexible model design and use, and by reflecting this perspective in the questions addressed in the individual gates in the model.

6. Discussion

In the first three paragraphs of this chapter the obtained results are discussed in relation to the research questions and in relation to available research. Each paragraph ends with a reflection to what extent the research questions have been answered. In the last two paragraphs the quality of the conducted research is discussed.

6.1. Difficulties in technology development described in literature relevant for a supplier company characterized by small scale production and customer-specific product designs

The first research question was addressed primarily by studies A and H, but contributions to the answer can be found in the other studies as well.

In study A, the scope was to chart the general process for technology development in Volvo Aero Corporation and identify perceived problems and challenges throughout development, from initial idea to implementation. It was the first study that was conducted and gives a general picture of the perceived state in VAC at that time. The study was structured, regarding both questions posed and the analysis made, under the different blocks of planning, development and implementation.

One conclusion drawn was the importance of formulating a long-term strategy and linking it to a defined product plan. The importance to technology development of setting long-term goals and formulating visions and strategies for achieving them have been extensively discussed in literature from different viewpoints and perspectives (Roussel et al. 1991; Sheasley 2000; McGrath 2001; Tidd et al. 2001; Karlsson 2004). However, what came out of study A was that there appears to be a mismatch between engineers' needs for predictive long-term goal formulation (to guide technology development) and the capability, or even possibility, of producing such long-term anticipation. The shortcoming of the long range product planning in VAC was also found in the other five companies discussed in Article H. Two of the companies even stated that product planning had very little or even no impact on the selection of technologies to be pursued, at least not in the initial stages. The stated reason was that it is next to impossible to have any long range product planning with reliability; circumstances in the market may shift too quickly. In these cases, they rely to a great extent on the fact that the engineering organization has close contacts with the market. They have those contacts in order to build an understanding for needs and decide on long range technology development based on technology trends. Trends in society was another source for setting the direction.

Nonaka and Takeuchi (1995) discuss the role of middle management in facilitating the interpretation of a corporate vision on the working level. This is achieved through an iterative dialogue in which the tacit and explicit knowledge of the “front-line employees” is utilized to convert visions into reality. They argue that a company does not simply process external information in order to produce an output; it also generates new knowledge and, thereby, the capability to redefine both problems and solutions. Nonaka and Takeuchi see product visualization as an important means to access individual tacit knowledge and thereby generate innovation. Similar results have been reported by, e.g., Engwall (2004). This reasoning agrees with the results in Article D. There, it was found that a broad vision guided the initial development. The article also showed that new technology was generated through iteration between concept and technical sub-solutions and the path forward was successively clarified.
Dynamic capabilities (Kogut and Zander 1992; Teece et al. 1997; Eisenhardt and Martin 2000) and flexible planning (Verganti 1999) as means of adapting to uncertainty have been studied over the years, primarily from the product perspective. When reflecting on the empirical results and different perspectives in literature, a combinatory approach of anticipation and adaptive planning capabilities appears most feasible, considering the dynamics of the environment. How far into the future the product long-range planning can see with some level of accuracy is most probably very much set by the industrial context. Furthermore, the market position of the company is likely to impact forecasting precision simply because a market leader is in a position to set the direction for the whole industry, an aspect discussed in Article H.

Technology development in the company was found to be directed at all product life cycle phases. New technology will facilitate the development of new product properties and functionality, improve efficiency in the production of mature production programs, and support new ways of supplying customer product support on the aftermarket, for example. This is also quite natural, considering that the technology of the firm is “the stock of knowledge, competencies and capacities that a company has at a given moment in time” (Nieto 2004). Furthermore, Nieto states that “the innovation process includes a set of activities that contribute to increasing the capacity to produce new goods and services (product innovations) or to implementing new forms of production (process innovations)”. Given this view, the link between corporate technology development and business offerings is natural. In fact, many authors have expressed the importance of making this link clear in the company in the past (Fusfeld 1978; Roussel et al. 1991).

Another finding relating to technology development was that the company historically relied heavily on a few strong individuals advocating the incorporation and development of new technologies. Allen, Sloan, Katz and Tushman (Allen and Sloan 1970; Katz and Tushman 2004), for example, studied this important role of technology gatekeepers in literature. In time, however, the areas of expertise resulting from the success of these gatekeepers may develop into corporate rigidities. Ambidexterity in organizations, in order to conduct both incremental and radical development, has been advocated by Tushman and O'Reilly (1996), for example.

Implementing new technology was identified in Article A as a difficulty. This is not a new or unique problem, but has been reported and discussed by several authors (e.g.,Malik 2002; Nobelius 2002). Nobelius (2002) studied the transfer of technology to product development, and concluded that a number of factors have to be considered. He found that the proper management of technology transfer "provides benefits related to R&D efficiency and precision as well as securing quality throughout the process." In Article H, internal technology transfer was also described in the other five companies. In all companies, the application of the technology is usually a part of the development from the very start. A real need has to be formulated; otherwise, the idea will never be pursued. Furthermore, all companies put considerable effort into having the end users involved in the development, at least as a stakeholder influencing the development. The internal dialogue has proven especially important due to the explorative nature of uncertain technology development.

Has the main research question been answered?

The various aspects uncovered, mainly in studies A and D, served primarily as a contextual framework for continued studies aimed at addressing the second research question. However, it is clear that these aspects are probably in part general for this type of context and in part particular to the studied company. In general terms, the research question has been answered through the different studies.

6.2. Platform strategy for a supplier company characterized by small scale production and customer-specific product designs

The second research question is primarily answered by Articles B, C and H.

In Article B, a platform strategy was proposed where a product platform based on product lines and a technology platform co-exist. This proposal was based on literature studies on platform and their application in different companies, combined with both interviews and action research conducted at Volvo Aero.

Most research that can be found in literature concerns product platforms, which are based on a basic assumption of common modules or components (e.g., Baldwin and Clark 1997; Ericsson and Erixon 1999). However, this approach was not seen as a fruitful strategy in the studied company. The argument for this statement is that the products are normally custom-designed for a particular application. This is mostly due to important design drivers such as minimizing mass or optimizing overall system performance. Results from Hölttä et al. (2005), support this argument. They found that if technical constraints, such as power consumption or weight, are the main drivers of design, an integral system will provide more suitable architecture than a modular system.

Nevertheless, one can identify features and solutions that are re-usable among different products. These are usually, however, at a more abstract conceptual level, where design and manufacturing knowledge is reused. So, rather than having a modular product platform, one could talk about a product platform more supporting product realization.

Applying a technology platform at the company is considered a more promising approach than a modularised product platform. One fundamental aspect of a technology platform is that focus is not placed on a particular implementation (for example, the simulation of a weld sequence on a specific component); rather, it is on a more general implementation, such as the simulation of weld sequences on hot structures. The most well-known example of an implemented technology platform is that of 3M (Shapiro 2006). 3M has built, and continues to build, a series of different platforms around specific technologies from which niche applications are developed. The company maintains a product focus and a focus on developing new, or improving already existing, technology platforms. Historically, VAC has leveraged existing capabilities and knowledge to generate new business and expand its product portfolio, similar to the development at 3M. There is, however, one big difference between the strategy of VAC and 3M. While 3M use their platform as a set of core capabilities they apply more or less to any type of products, VAC define themselves as a jet engine company. The product portfolio at VAC is much more narrow.

To further explore the possibility of reuse and the validity of the hypothetical platform approach proposed in Article B, the study described in Article C was conducted. The study concluded that reusability primarily was found over generations within the product family and in different sizes. Reusability across product family borders was found to be considerably more limited. The results from this study support the hypothesis formulated in Article B. The reuse found within families is supported by the product platform, even though it is on a more abstract level than what is found in a majority of available research. The technology, or knowledge, platform is seen as more promising for leveraging corporate assets, both internally and on the market, across product family borders.

In the platform approach proposed in Article B, it is shown that the platform consists of product and process capabilities adapted to different product families and integrated into the product platform. After further discussions within the research group and with VAC, a modified approach was proposed to the company in October 2009. A process platform (in VAC called “production platform”) at a similar level of concretization as the product platform was added (see Figure 34). The rationale behind this modification is to be found in the way the company conducts business. Article A describes how the company not only develops products that are later manufactured, but also conducts business as “make-to-print”. This means manufacturing products not developed by the company themselves, but usually by their customers. This business is based on the fact that externally developed products have a good match with the production system of the company. The production system is de facto reused. Another argument for adding process platforms was that it was believed that commonality in the production system probably could be found without being limited to staying within particular product families. The modified approach thus has three different types of platforms: the product platform, the process platform and the technology platform. This approach was presented to the company in October 2009, and they decided to use this approach as a framework for further development. Three different mid-level managers were made responsible for the continued development of the three platforms. Work has continued in VAC, and product platforms have so far been formulated for three different families of products. Furthermore, the process platform has been further explored and formulated in the company. In addition research is being pursued at Chalmers to investigate some of the aspects of the approach. One part of this work focuses on exploring the concept of technology platforms and their description. As mentioned in the theoretical framework, a very limited amount of research has been conducted on this type of platform previously. More research is needed if operational support is to be provided in the future. Furthermore, the interface and connection between the product and process platforms, is explored through continued research at the department at Chalmers by attempts to model this link with the CC concept. The CC concept refers to “Configurable Components”, and is an information modelling concept to support the development of generic, autonomous, configurable systems (Claesson 2006).

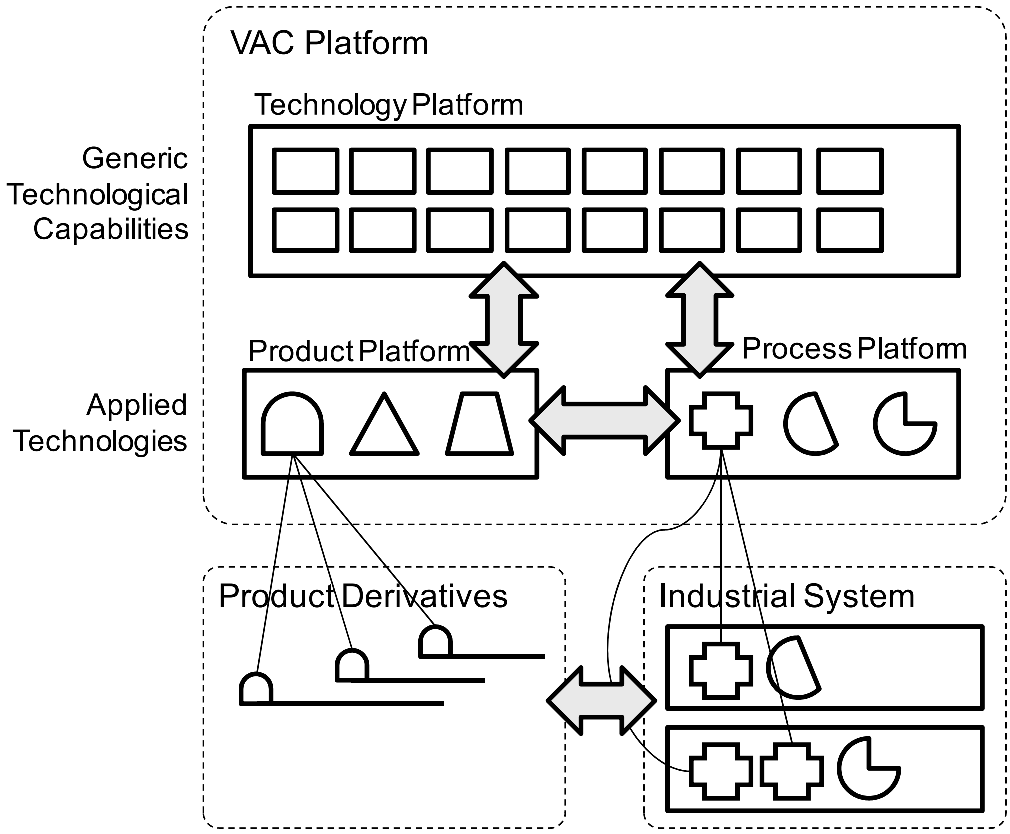

Figure 34 The modified platform approach pursued in VAC.

The results presented in Article H support the modified platform approach. Different platform approaches were found in the different companies, and a comparison was made with the context of the different organizations relative to that of VAC. Company B had chosen to implement a process platform. Similar to the situation in company B, lead time and cost in the development projects at VAC are often driven by production aspects. Furthermore, production has to support a range of different products in different families. That is also similar to what was found in Company B. This would indicate that a process platform, as chosen by Company B, may actually be a viable approach for VAC.
In *Company C,* a technology platform approach had been chosen. In it, five different platforms are included. The company has a strategy of offering tailor-made customer solutions, similar to that of VAC, by drawing on the capabilities of the five platforms.

When reflecting on this proposed platform formulation, some difficulties need to be addressed. A platform in the form of the modules is concrete, and the potential benefit can be seen almost intuitively. The formulation proposed for VAC is more abstract. Technology is an abstract definition and, as can be seen in Chapter 2.2, is often described as knowledge. The formulation thus becomes a form of explaining and structuring knowledge, a research area in itself. One challenge this platform formulation may present is going from abstract theory to concrete reality if the potential advantages are to be realized. This is work that has to be pursued and indeed is being done at both VAC and Chalmers.
The approach of combining three different types of platforms proposed to VAC is not that common. In fact, I have not found any other example where this is done. This approach is one of the scientific contributions of this research, with the potential of addressing different perspectives concerning the strategic intent of the company. The product and process platforms aim primarily to give advantages concerning product families already in the corporate portfolio, while the technology platform gives a foundation for product portfolio expansion.
Few examples have been found in available research of platforms developed and implemented in the industrial context explored in this research, customer-specific products in small production series. The research presented in this thesis contributes with knowledge on applicability of platform theory in this context and on possible routes to follow.

Has the main research question been answered?
The studies conducted contribute to the applicability of platforms to companies with products developed for specific systems and customers, which also are produced in small series. However, I cannot claim to have a final answer to the research question. In Article B, a hypothetical platform was formulated, and support for this approach has been found in Articles C and H. However, proof in the form of company benefits has not yet been confirmed. Work is ongoing, both at Chalmers and at VAC, to develop and implement the

suggested approach which should give more evidence concerning benefits and drawbacks.

6.3. Adaptations needed to facilitate the usefulness of the stage-gate model to manage technology development

When addressing the question regarding a “normative process” for technology development, I have focused primarily on the stage-gate model as a normative approach. Primarily five studies have addressed this topic, and they are reported in Papers D, E, F, G and H.

While Article A provided a broad picture of technology development, Article D focused on describing the technology development process. The process was described as one of exploration and iteration, where new technology was sought to meet different needs that emerged in the process. The conceptual solution as central to clarifying the needs was emphasized, and a comparison was made with engineering design and systems engineering theory. Approach and methodology in the studied technology developments were largely based on what is applied in product development. Iteration was conducted by passing through several small “product developments”. This resulted in paper concepts or the embodiment of hardware enabling testing on different levels of system complexity. Design theory, represented here primarily by the Theory of Domains and Systems Engineering, therefore compares and applies well to the three cases. However, one major difference in this theory base concerns process output. In our cases, the main result from the development process is more than the product design solutions. New knowledge, competence or capabilities (Nieto 2004), concerning both needs and solutions, are the primary results that can be utilized in later development phases to realize a product. In these early development stages, the developing organization builds knowledge based on the characteristics and limits of the pursued design solutions. The learning perspective is reflected in several of the models describing innovation (e.g., Tidd, Bessant et al. 2001) or development of technology (e.g., Sheasley 2000). This is also reflected in the results from study G, which showed the requirements on the results of technology development, where organizational learning and acceptance was emphasized.

Normative practices for managing technology development were found in all six companies that participated in the different research studies. Some form of stage-gate model has been employed in all the cases. Practitioner experience as to the suitability of the stage-gate model in early development has also come from some other corporate contexts (Cohen et al. 1998; Cáñez et al. 2007). Cooper (2006) advocates the use of a model dedicated to technology development, and refers to additional industrial applications where the model has been successfully implemented. Similar models have been reported on from, for example, Boeing (Lind 2006). Finally, Eldred and McGrath (1997) argue for a process quite similar to Cooper’s. As was discussed in the framework, it is not obvious that the model is suitable for managing technology development. Leading management researchers in the field of innovation in product development argue the importance of flexibility, adaptability, and dynamic capabilities (Verganti 1999; Eisenhardt and Martin 2000). This casts doubt on the model, which has been criticized for being inflexible and bureaucratic. Examples of unsuccessful model implementations were recently reported by Cooper (2008). In them, inflexibility and bureaucracy were two of the main problems encountered. In addition, results have been conveyed regarding how the use of the model limits learning (Sethi and Iqbal 2008). This is in direct contradiction of the purpose of conducting technology development. Engwall reports on the failure of the stage-gate model when applied to uncertain development, and strongly advocates a "new grammar" (Engwall 2004). According to him, one basic problem is not the model in itself, but whether one believes the final development goal can be articulated and locked prior to initiating development. The challenge in management is to accept that a decision to initiate this kind of development has to be based on limited and possibly erroneous initial data, and that re-evaluation is a part of the learning process of the development.

What was found in the six cases was that all six companies included in this study have found ways to implement and use the stage-gate model in a modified form, both regarding its design and its practical application. In all six cases, despite great contextual differences regarding, for example, products and markets, these modifications have rendered the model useful to the companies, providing effects such as logic, structure, and improved transparency. Flexibility and adaptability have been accomplished through various strategies, as described in the results section of Paper E. It could be argued that the companies have rendered the basic idea of the stage-gate useless by introducing these adaptations. However, that is obviously not their experience. The results from Article G, showing the great variety regarding both timing and requirements linked to the different technology categories, further support the need for the adaptive and flexible use of the model.

An alternative approach that has been discussed is the spiral model (Boehm 1988), which has been claimed to give greater flexibility and more successfully manage uncertainty and risk. The companies included in my research are all hardware companies, and the conclusions from Unger and Eppinger would rather suggest that the spiral model is not a fruitful approach in these types of companies. However, it could be argued that the companies have in practice introduced a spiral model in technology development through their flexible use of the stage-gate model. A mature concept was seen in the six companies as the main outcome from the technology development phase. Different types of prototypes are used to build knowledge and capabilities concerning the different technology selection criteria suggested by Shulz et al.(2000) (superiority, robustness, flexibility, and maturity), thereby reducing risk.

Has the main research question been answered?
The studies conducted contribute knowledge concerning the applicability of the much-used stage-gate model to this type of uncertain development. It has been shown that the model is useful even for this type of uncertain development, provided adaptations are made concerning both model implementation and use. Experience from six different contexts has been gathered and compared supporting the external validity of the results. However, alternative models have been proposed in literature that may provide equally good results, or perhaps even better ones. Exploring the potential in alternative answers to the question is another issue that should be pursued. However, in my research, I have never expressed the ambition to supply one final solution to the question. Instead, I seek a contribution to one possible solution out of potentially many. Through the work conducted in this research, at least one step in the direction of supplying an answer to the second main research question can be claimed.

6.4. Reflections on the research approach

The chosen research strategy has generated fruitful results. Starting with a broad initial study to gain an overview of the issues the chosen case company is struggling with has guided the continued work, and has thus been valuable. The subsequent studies have focused on two different approaches for addressing uncertain development, and have both given new insights. By applying a qualitative research strategy and focusing primarily on one company, a rich description from various aspects has resulted. Some disadvantages can be seen when focusing on one single company. First of all, as a researcher (and, in particular, as an insider researcher), I run the risk of not being objective. My history with the company may mean that I am biased in some sense. However, this has been balanced by the fact that outsider researchers have been involved in all studies as well. Thus, the analysis has not been left to me alone. Secondly, as an insider researcher with an industrial background, I run the risk of solving operational company issues, rather than producing scientific knowledge. I have to admit that this has in part been one risk which I have not fully managed to avoid, and this is partly reflected in my focus on normative support for technology development and its exploitation. Still, as an insider reserarcher I have had access to an industrial context which would have been difficult obtain as an outsider. Thirdly, by studying more companies, a broader picture of both problems and potential solutions could have been explored. However, this needs to be balanced with the depth of the individual case descriptions.

6.5. Research Quality

The different empirical studies conducted within this research are all case-based, employing different qualitative research methods. Many of the strategies for ensuring reliability and validity in case study research proposed by Yin (2003) have been adopted. In addition, best practices for conducting qualitative research (regarding sampling, data gathering and data analysis, for example), as described by Bryman and Bell (2007), have been employed.

6.5.1. Are the results reliable?

Reliability in research is primarily ensured through the proper application of methodology, a coherent research strategy, and a correct choice and application of methods. As was shown earlier, substantial effort has been made to have a coherent research strategy and employ methods suitable to qualitative research.
The different steps taken in the individual studies have been documented during the research. This has been done in various ways. The ways have included writing research plans, writing questionnaires used in interviews, recording and transcribing semi-structured interviews, writing and validating notes from unstructured interviews, storing reviewed company documentation, and documenting the different steps taken during data analysis. Reliability in the meaning of "possibility to repeat the research" has thus been facilitated. However, the research has been carried out in real world settings that undergo continued change. It is not possible to rewind the organisation, and the people who have been involved, to the exact state that prevailed when doing these studies. Having another researcher repeat the study and reach the same results may therefore be difficult. This is a common criticism against case study research. Since this research process has been well-documented, it is, however, possible to review all the empirical data and revisit the analysis done, if required.

Throughout the research, effort has been made to distinguish between empirical material and researcher interpretations and report that clearly in the individual studies. Furthermore, the documentation of the research process facilitates a comparison of results to those from other researchers. Both these steps serve to ensure reliability (Yin 2003; Flick 2006). Furthermore, involving both insider researcher and outsider researchers in all studies supports reliability (Bryman and Bell 2007).

Due to the various steps taken during the research to ensure that the procedural best practices advocated in methodology literature were taken, the reliability of the results can be considered to be high.

6.5.2. What is the validity of the results?

Research validity is ensured by applying steps in the research process that methodology literature considers sound and by comparing findings to previous research, as well as between company cases.
In this research, several actions have ensured internal validation. The different steps taken in the different studies have been documented and are described in the appended articles, as well as in Chapter 4. Both respondent validation and data triangulation have been employed. Therefore, internal validity can be considered high.
It is clear from the conducted studies that, due to the choice of a qualitative research strategy (case study research), statistical generalization is impossible. Analytical generalization is more realistic. However, according to (Yin 2003), this is not automatically achieved; rather, it is realised by adapting the theory to different contexts

where replicating the results will lead to analytical generalization. Analytical generalization can be claimed, at least to some extent, primarily through the study described in Paper H. In addition, external validity has been sought, by comparing results with those reported from earlier research.

Finally, transferability, and not generalization, has been sought in this research. Through in-depth case studies, partly adopting an ethnographic approach, applying different methods for data collection, and providing a thick description of the studied cases, it has been my ambition to support transferability in accordance with the proposal of Guba and Lincoln (1994). Whether I have been successful in this intent can only be judged by the reader.

7. Conclusions

Technology development and its management have received extensive attention from the research community during the last 40 years. Despite this, it is still often regarded as a new area of research.

In this research, two different approaches proposed in literature to manage the inherent uncertainty in technology development have been explored, primarily in the context of one particular company. The first approach involves applying a platform formulation, and the second entails applying the stage-gate model to the technology development process.

Given the context of a company characterized by low production volume, complex custom designed products, the following conclusions can be drawn from this work:

- Several difficulties relating to technology planning, development, and implementation have been found:
  - Mismatch between engineers' needs for predictive long-term goal formulation (to guide technology development) and the capability, or even possibility, of producing such long-term anticipation.
  - Difficulties with placing sufficient priority on, and allocating needed resources to, technology development.
  - Difficulties to select technologies for continued development.
  - Difficulties concerning technology implementation.
- A component based product platform is unsuitable for this type of company context. Instead a combined platform formulation, including product, process, and technology platforms, has been proposed that appears both feasible and useful based on the empirical evidence. The product platform is based on reuse of design knowledge, product concepts, and applied technology, for the different products in the company. The technology platform incorporates generic technological capabilities which are used in many different products, and is the foundation for product portfolio expansion.
- Normative process models based on the stage-gate model can benefit technology development, given that they are adapted to the explorative nature of such uncertain development and used with a higher degree of flexibility. Strategies to achieve flexibility that have been found include, for example, soft gates, loop-backs, stopping projects and redefining the focus, using the model recursively, or defining technology development as a relay race of different projects where each individual project follows a stage-gate process. Furthermore, the adapted model should consider a more holistic perspective where technology development as a learning process, more so than e.g. product development, is reflected.

The reliability of these conclusions can be considered to be high, due to the various steps taken during the research to ensure that best practices advocated in methodology literature have been followed.

The internal validity can be considered to be high, not the least due to the selection of a qualitative research approach, but also through the different steps taken during the research, including respondent validation and data triangulation, for example.

The external validity of qualitative research, and not the least in case based research, is usually a weakness. That is also true for this research. Nonetheless, effort has been made to achieve external validity by comparing the research to literature and by comparing the results from the different company cases. Further, the transferability of the results is supported through a thorough description of the studied companies (in particular, Volvo Aero Corporation) and their industrial context.

Finally, the formulated research questions have been answered, even though it is clear that more research would have been beneficial. This will have to be left to future work.

7.1. Academic Contributions

This work has contributed knowledge regarding the management of technology development, using primarily one industrial case in which different aspects have been explored.
The main contributions concern

- prescriptive considerations concerning adaptation and use when applying normative stage-gate processes to technology development, and
- prescriptive platform approaches in the studied context.

7.2. Industrial Contributions

From an industrial perspective, the prime contributions can be found regarding the applicability of platform formulations and stage-gate models.

Both platform implementations and applying the stage-gate model to technology development have been shown to hold promise for companies similar to VAC.

Ultimately, both platform and process formulations are strategies for managing uncertainty, and, when combined, can address different aspects of technology development and the facilitation of innovation.

In the course of the work, a normative stage-gate model for technology development has been developed and implemented at VAC that is in operational use today. Experience from this work has been adopted in part by other Volvo companies. In addition, based on this experience, a decision has recently been made to implement the TRL scale in the entire Volvo Group. Furthermore, results have been reported to VINNOVA and the Knowledge Foundation, for example, who have decided to implement similar approaches as in VAC in some of the research programmes.

In October 2009, the adapted platform approach presented in the discussion of the thesis, Paragraph 6.2, was selected by VAC top management as the company platform approach. Work inside the company on platforms has been pursued in accordance with this model, though substantial work remains in order to reap the expected benefits.

8. Future Work

Several opportunities for additional research have been identified. Some examples are the following:

On descriptive models

- In my work, I have sought a more concrete description of "technology" and requirements on this entity. However, more work is needed. It may be that descriptive models of technology based on TTS would be interesting to explore. For example, relating "technology" to the Organ model of Andreasen is a venue that may prove fruitful for supplying a stronger theoretical foundation.

On normative process models

- One objective of the thesis has been to supply normative support for technology development. Applying the stage-gate model has proven to be one possible route. However, alternative approaches to the Stage-Gate model should be explored as well. It could very well be that alternative models may provide better results concerning managing technology development.
- The formulated Stage-Gate model would benefit from more details concerning, for example, deliverables for the different gates, how they interact with the strategic decision process in the company, and timing relative to product development.
- Further exploration of how methods and tools developed in Systems Engineering could be adapted and used for technology management would be of great interest. For example, propositions presented by NASA, as well as from Clausing, would be interesting to pursue. NASA discusses how "technology" interacts with system development, and that is an aspect that would contribute insight into how requirements on technology may evolve in the development process.

On platforms

- A theoretical framework for the different platforms, and in particular for the technology platform, is needed where concretization also should be made more explicit.
- The interaction and relationship between the three platform elements (technology platform, product platform, and process platform) need more work..
- Additional testing of the hypothetical model in a real setting, to make the description more concrete and to explore its potential benefits, should be conducted.
- Finally, the interaction between, on the one hand, the technology development process and, for example, the product development process and, on the other hand, the platform approach is another issue that would benefit from additional research.

9. References

Aalto, T., M. Martinsuo, et al. (2003). Project portfolio management in telecommucincations R&D. Handbook of Product and Service Development in Communication and Information Technology. T. O. Korhonen and A. Ainamo, Kluwer Academic Press: 99-147.

Acha, V., S. Brusoni, et al. (2007). "Exploring the miracle: strategy and management of the knowledge base in the aeronautics industry." International Journal of Innovation and Technology Management 4(1): 15-39.

Ajamian, G. M. and P. A. Koen (2002). "Technology stage gate: A structured process for managing high risk, new technology projects." The PDMA Toolbook for New Product Development: 267-295.

Allen, T. J. and A. P. Sloan (1970). "Communication Networks in R and D Laboratories." R & D Management 1(1): 14-21.

Andreasen, M. M. (1980). Syntesmetoder på Systemgrundlag - Bidrag till konstruktionsteori. Lund, Lund University. PhD.

Andreasen, M. M. (1992). The Theory of Domains. EDS Workshop on Understanding Function and Function to Form Evolution. Cambridge.

Anemo, M. and H. Persson (2008). Applying a platform strategy in a low-volume, business-to-business company - A study in four dimensions at Volvo Aero. Department of Product Development. Gothenburg, Chalmers University of Technology. M.Sc.

Arbnor, I. and B. Bjerke (1997). Methodology for Creating Business Knowledge. Thousan Oaks, CA, Sage Publications.

Baldwin, C. Y. and K. B. Clark (1997). "Managing in an age of modularity." Harvard business review 75(5): 84-93.

Baldwin, C. Y. and K. B. Clark (2000). Design Rules, Vol. 1: The Power of Modularity. Cambridge, MA, MIT Press.

Bengtsson, D. and S. Stetz (2009). Deliveries from Technology Development, A study of requirements at the Volvo Aero Corporation. Department of Technology Management and Economics. Gothenburg, Chalmers University of Technology. M.Sc.: 63.

Benner, M. J. and M. Tushman (2002). "Process Management and Technological Innovation: A Longitudinal Study of the Photography and Paint Industries." Administrative Science Quarterly 47(4): 676-706.

Berglund, F., D. Bergsjö, et al. (2008). Platform strategies for a supplier in the aircraft engine industry. ASME 2008 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, IDETC/CIE 2008, Brooklyn, New York.

Bhattacharya, S., V. Krishnan, et al. (1998). "Managing New Product Definition in Highly Dynamic Environments." Management Science 44(11): S50-S64.

Blanchard, B. S. and W. J. Fabrycky (2006). Systems Engineering and Analysis. Upper Saddle River, New Jersey, Pearson Prentice Hall.

Blessing, L. T. M. (1995). "Comparison of Design Models Proposed in Prescriptive Literature." Conference Article, COST A3 / COST A4 International Research Workshop, Lyon February 1995, Perrin & Vinck (eds.), Social Sciences Series, European Committee 5: 187-212.

Blessing, L. T. M. (2002). What is this thing called Design Research? International CIRP Design Seminar, Hong Kong.
Boehm, B. W. (1988). "Spiral model of software development and enhancement." Computer 21(5): 61-72.
Bryman, A. and E. Bell (2007). Business Research Methods. Oxford, UK, Oxford University Press.
Burgelman, R. A., C. Christensen, et al., Eds. (2004). Strategic Management of Technology and Innovation. New York, McGraw-Hill.
Cáñez, L., L. Puig, et al. (2007). "Linking Technology Acquisition to a Gated NPD Process." Research Technology Management 50(4): 49-55.
Claesson, A. (2006). A configurable component framework supporting platform-based product development. Product and Production Development. Gothenburg, Chalmers University of Technology. PhD.
Clark, K. B. and T. Fujimoto (1991). Product Development Performance. Boston, Harvard Business School Press: 169.
Clausing, D. (1994). Total Quality Development. New York, ASME Press: 317-341.
Cohen, L. Y., P. W. Kamienski, et al. (1998). "Gate system focuses on industrial basic research." Research Technology Management 41(4): 34.
Cooper, R. G. (2006). "Managing technology development projects." Research Technology Management 49(6): 23-31.
Cooper, R. G. (2008). "Perspective: The stage-gates® idea-to-launch process - Update, what's new, and NexGen systems." Journal of Product Innovation Management 25(3): 213-232.
Department of Defense (2009). Technology Readiness Assessment (TRA) Deskbook.
Dorst, K. and N. Cross (2001). "Creativity in the design process: co-evolution of problem-solution." Design Studies 22(5): 425-437.
Eisenhardt, K. M. (1989). "Building Theories from Case-Study Research." Academy of Management Review 14(4): 532-550.
Eisenhardt, K. M. and J. A. Martin (2000). "Dynamic capabilities: What are they?" Strategic Management Journal 21(10-11): 1105-1121.
Eisenhardt, K. M. and B. N. Tabrizi (1995). "Accelerating Adaptive Processes - Product Innovation in the Global Computer Industry." Administrative Science Quarterly 40(1): 84-110.
Eldred, E. W. and M. E. McGrath (1997). "Commercializing new technology-I." Research Technology Management 40(1): 41-47.
Eldred, E. W. and M. E. McGrath (1997). "Commercializing new technology-II." Research Technology Management 40(2): 29-33.
Engwall, M. E. (2004). Produktutveckling bortom kunskapens gräns, Mot en osäkerhetens grammatik. Lund, Sweden, Studentlitteratur.
Ericsson, A. and G. Erixon (1999). Controlling Design Variants: Modular Product Platforms. Dearborn, MI, Society of Manufacturing Engineers.
Feitzinger, E. and H. L. Lee (1997). "Mass customization at Hewlett-Packard: The power of postponement." Harvard Business Review 75(1): 116-121.
Fern, F. E. (2001). Advanced Focus Group Research. Thousand Oaks, Sage Publications.
Flick, U. (2006). An introduction to qualitative research. London, UK, SAGE Publications.
Forsberg, K. and H. Mooz (1991). The relationship of Systems Engineering to the project cycle. First Annual Symposium of the National Council On Systems Engineering (NCOSE). Chattanooga, TN.

Fusfeld, A. R. (1978). "How to put technology into corporate planning." Technology Review 80(6): 51-55.
Glaser, B. G. and A. L. Strauss (1967). The Discovery of Grounded Theory: Strategies for Qualitative Research. Chicago, Aldine.
Groenveld, P. (1997). "Roadmapping integrates business and technology." Research Technology Management 40(5): 48-X.
Guba, E. G. and Y. S. Lincoln (1994). Competing Paradigms in Qualitative Research. Handbook of Qualitative Research. N. K. Denzin and Y. S. Lincoln. Thousand Oaks, CA, Sage Publications.
Hansen, C. T. and M. M. Andreasen (2007). Specifications in early conceptual design work. International Conference on Engineering Design, ICED'07, Paris, France.
Herr, K. and G. L. Andersson (2005). The Action Research Dissertation, A Guide for Students and Faculty. Thousand Oaks, California, Sage Publications.
Hubka, V. and W. E. Eder (1988). Theory of Technical Systems: A Total Concept Theory for Engineering Design. Berlin, Springer-Verlag.
Hubka, V. and W. E. Eder (1992). Engineering Design: General Procedural Model of Engineering Design. Zürich.
Högman, U., D. Bengtsson, et al. (2010). Requirements on New Technology and the Technology Implementation Process. NordDesign 2010, Gothenburg.
Högman, U. and F. Berglund (2007). Technology management challenges for a sub-supplier in the aerospace industry. IAMOT 2007, Miami Beach, FL.
Högman, U., D. Bergsjö, et al. (2009). Exploring the Potential of Applying a Platform Formulation at Supplier Level - The Case of Volvo Aero Corporation. International Conference on Engineering Design, ICED'09, Stanford University, CA, Design Society.
Högman, U. and H. L. Johannesson (2010). Technology development and normative process models. 11th International Design Conference - Design 2010, Dubrovnik - Cavtat, Croatia, Design Society.
Högman, U. and H. L. Johannesson (2011). Applying Stage-Gate Processes to Technology Development - Experience from Six Hardware-oriented Companies. Gothenburg, Chalmers University of Technology.
Högman, U. and H. L. Johannesson (2011). Technology development practices in industry. Proceedings of International Conference on Engineering Design, ICED11, Copenhagen, Denmark.
Högman, U. and H. L. Johannesson (2011). The Technology Development Process and its Result - The Case of Volvo Aero Corporation. Gothenburg, Chalmers University of Technology.
Hölttä, K., Suh, E S, de Weck, O (2005). Tradeoff between modularity and performance for engineered systems and products. International Conference on Engineering Design. Melbourne.
Iansiti, M. and J. West (1997). "Technology integration: Turning great research into great products." IEEE Engineering Management Review 25(4): 16-25.
Jackson, K. and R. Stevens (2000). "Systems engineering models." Computing and Control Engineering Journal 11(4): 187-194.
Jiao, J., T. W. Simpson, et al. (2007). "Product family design and platform-based product development: A state-of-the-art review." Journal of Intelligent Manufacturing 18(1): 5-29.
Jiao, J., M. M. Tseng, et al. (2000). "Generic Bill-of-Materials-and-Operations for high-variety production management." Concurrent Engineering Research and Applications 8(4): 297-321.

Jiao, J., L. Zhang, et al. (2006). Process Platform and Production Configuration for Product Families. Product Platform and Product Family Design - Methods and Application. T. W. Simpson, Z. Siddique and J. Jiao. New York, Springer: 377-402.
Jiao, J., L. Zhang, et al. (2007). "Process platform planning for variety coordination from design to production in mass customization manufacturing." IEEE Transactions on Engineering Management 54(1): 112-129.
Jolly, D. R. and M. Nasiriyar (2007). Technology platform exploitation: definition and research boundaries. 16th International Conference on Management of Technology, IAMOT 2007, Miami Beach, FL.
Karlsson, M. (2004). "Organizing Technology Planning - A contingent approach." Doktorsavhandlingar vid Chalmers Tekniska Hogskola(2164).
Katz, R. and T. J. Allen (1985). Organizational Issues in the Introduction of New Technologies. Management of productivity and technology in manufacturing. P. R. Kleindorfer, Plenum: xiv+331.
Katz, R. and M. L. Tushman (2004). A study of the influence of technical gatekeeping on project performance and career outcomes in an R&D facility. The human side of managing technological innovation. R. Katz. New York, Oxford University Press: 309-324.
Kim, D.-J. and B. Kogut (1996). "Technological Platforms and Diversification." Organization Science 7(3): 283-301.
Koen, P., G. Ajamian, et al. (2001). "Providing clarity and a common language to the "fuzzy front end"." Research Technology Management 44(2): 46-55.
Kogut, B. and U. Zander (1992). "Knowledge of the Firm, Combinative Capabilities, and the Replication of Technology." Organization Science 3(3): 383-397.
Krueger, R. A. and M. A. Casey (2000). Focus Groups: A Practical Guide for Applied Research. Thousan Oaks, CA, Sage Publications, Inc.
Kusunoki, K. (1992). "The dilemma of technological leadership." Hitotsubashi Journal of Commerce and Management 27: 63-79.
Kähkönen, K., K. Artto, et al., Eds. (2006). Managment of uncertainty. Helsinki, Unpublished course material.
LeCompte, M. D. and J. P. Goetz (1982). "Problems of reliability and validity in ethnographic research." Review of Educational Researcher 13(5): 20-30.
Lee, T. W. (1999). Using Qualtitative Methods in Organizational Research. Thousand Oaks, Sage Publications, Inc.
Leifer, R. and T. Triscari Jr (1987). "Research versus development: Differences and similarities." IEEE Transactions on Engineering Management EM-34(2): 71-78.
Lind, J. (2006). "Boeing's Global Enterprise Technology Process." Research Technology Management 49(5): 36.
MacCormack, A. and R. Verganti (2003). "Managing the sources of uncertainty: Matching process and context in software development." Journal of Product Innovation Management 20(3): 217-232.
Malik, K. (2002). "Aiding the technology manager: A conceptual model for intra-firm technology transfer." Technovation 22(7): 427-436.
Mankins, J. C. (1995). Technology Readiness Levels: A White Paper, Advanced Concepts Office, Office of Space Access and Technology, NASA.
Mankins, J. C. (2002). "Approaches to strategic research and technology (R&T) analysis and road mapping." Acta Astronautica 51(1-9): 3-21.
McGrath, M. E. (2001). Product Strategy for High Technology Companies, Accelerating Your Business to Web Speed, McGraw-Hill.

Meyer, M. H. and A. P. Lehnerd (1997). The Power of Product Platforms: Building Value and Cost Leadership. New York, The Free Press.
Meyer, M. H., P. Tertzakian, et al. (1997). "Metrics for Managing Research and Development in the Context of the Product Family." Management Science 43(1): 88-111.
Miller, R., M. Hobday, et al. (1995). "Innovation in Complex Systems Industries: the Case of Flight Simulation." Ind Corp Change 4(2): 363-400.
Morgan, D. L. (1988). Focus Groups as Qualitative Research, Sage Publications, Inc.
NASA (2007). Systems Engineering Handbook. Washington D.C., National Aeronautics and Space Administration: 340.
Nieto, M. (2004). "Basic propositions for the study of the technological innovation process in the firm." European Journal of Innovation Management 7(4): 314-324.
Nobelius, D. (2002). Managing R&D Processes - Focusing on Technology Development, Product Development, and their Interplay. Operations Management and Work Organization. Göteborg, Chalmers University of Technology. PhD: 91.
Pahl, G., W. Beitz, et al. (2007). Engineering Design - A Systematic Approach. London, Springer.
Peisen, D. J. and C. L. Schulz (1999). Case Studies: Time Required to Mature Aeronautic Technologies to Operational Readiness. Jenkintown, Pennsylvania, SAIC.
Polley, D. and A. H. Van de Ven (1996). "Learning by discovery during innovation development." International Journal of Technology Management 11: 871-882.
Prahalad, C. K. and G. Hamel (1990). "The core competence of the corporation." Harvard Business Review 68: 79-91.
Prencipe, A. (1997). "Technological competencies and product's evolutionary dynamics a case study from the aero-engine industry." Research Policy 25(8): 1261-1276.
Prencipe, A. (2004). The changing boundaries of the firm, Empirical evidence from the aircraft engine industry. The economics and management of technological diversification. J. Cantwell, Gambardella, A, Granstrand, O. London - New York, Routledge.
Pugh, S. (1990). Total Design: Integrated Methods for Successful Product Engeneering. Wokingham, Addison-Wesley.
Robertson, D. and K. Ulrich (1998). "Planning for product platforms." Sloan Management Review 39(4): 19-31.
Roozenburg, N. J. M. and J. Eekels (1995). Product Design: Fundamentals and Methods. Chichester, John Wiley and Sons.
Rothwell, R. (1994). "Towards the Fifth-generation Innovation Process." International Marketing Review 11(1): 7-31.
Rothwell, R. and P. Gardiner (1990). Robustness and product design families. Design management: A handbook of issues and methods. M. Oakley. Oxford, UK, Blackwell.
Roussel, P., K. Saad, et al. (1991). Third Generation R&D. Boston, Harvard Business School Press.
Sabbagh, K. (1996). Twenty First Century Jet - The Making and Marketing of The Boeing 777. New York, NY, Scribner.
Sanderson, S. and M. Uzumeri (1995). "Managing product families: The case of the Sony Walkman." Research Policy 24(5): 761-782.
Sauser, B., J. E. Ramirez-Marquez, et al. (2008). "A systems approach to expanding the technology readiness level within defense acquisition." International Journal of Defense Acquisition Management 1: 39-58.

Sawhney, M. S. (1998). "Leveraged high-variety strategies: From portfolio thinking to platform thinking." Academy of Marketing Science. Journal 26(1): 54.
Schulz, A. P., D. P. Clausing, et al. (2000). "Development and integration of winning technologies as key to competitive advantage." Systems Engineering 3(4): 180-211.
Sethi, R. and Z. Iqbal (2008). "Stage-gate controls, learning failure, and adverse effect on novel new products." Journal of Marketing 72(1): 118-134.
Shapiro, A. R. (2006). "Measuring innovation: Beyond revenue from new products." Research Technology Management 49(6): 42-51.
Sheasley, W. D. (1999). "Leading the technology development process." Research Technology Management 42(3): 49-55.
Sheasley, W. D. (2000). "Taking an options approach to new technology development." Research Technology Management 43(6): 37-43.
Simpson, T. W., Z. Siddique, et al., Eds. (2005). Product Platform and Product Family Design - Methods and Application. New York, USA, Springer Science+Business Media. Inc.
Simpson, T. W., Z. Siddique, et al. (2006). Platform-based product family development. Product Platform and Product Family Design, Methods and Application. T. W. Simpson, Z. Siddique and J. Jiao. New York, Springer.
Stevens, R., P. Brook, et al. (1998). Systems Engineering - Coping with Complexity. London, UK, Prentice-Hall.
Suh, N. P. (1990). The Principles of Design. New York, Oxford University Press.
Svendsen, H.-K. and T. C. Hansen (1993). Decomposition of Mechanical Systems and Breakdown of Specifications. International Conference on Engineering Design, ICED 1993, Den Haag, NL, The Design Society.
Teece, D., G. Pisano and A. Shuen, (1997). "Dynamic Capabilities and Strategic Management." Strategic Management Journal 18(7): 509-533.
Tidd, J., J. Bessant, et al. (2001). Managing Innovation - Integrating Technological, Market and Organizational Change. Chichester, England, John Wiley & Sons.
Tushman, M. L. and C. A. O'Reilly III (1996). "Ambidextrous organizations: Managing evolutionary and revolutionary change." California Management Review(4): 8-30.
Ullman, D. G. (2003). The Mechanical Design Process. New York, McGraw-Hill.
Ulrich, K. (1995). "The Role of Product Architecture in the Manufacturing Firm." Research Policy 24(3): 419-440.
Ulrich, K. T. and S. D. Eppinger (2003). Product Design and Development. New York, McGraw-Hill.
Unger, D. W. and S. D. Eppinger (2009). "Comparing product development processes and managing risk." International Journal of Product Development 8(4): 382-402.
Van de Ven, A. H. and D. Polley (1992). "Learning While Innovating." Organization Science 3(1): 92-116.
Verganti, R. (1999). "Planned flexibility: linking anticipation and reaction in product development projects." Journal of Product Innovation Management 16(4): 363-376.
West, J. and M. Iansiti (2003). "Experience, experimentation, and the accumulation of knowledge: The evolution of R and D in the semiconductor industry." Research Policy 32(5): 809-825.
Wheelwright, S. C. and K. B. Clark (1992). Revolutionizing Product Development: Quantum Leaps in Speed, Efficiency, and Quality. New York, Free Press.
Vigfusdottir, A. M. and E. Rääk (2008). The Technological Innovation Process at Volvo Aero: Hindering and Enhancing factors. Department of Technology Management

and Economics. Gothenburg, Chalmers University of Technology. Master of Science in Engineering: 114.

Yin, R. K. (2003). Case Study Research, Design and Methods. Thousand Oaks, CA, Sage Publications.