Radical Technological Innovations within the Mechanical Engineering Industry

An Empirical Study for Successful Realization

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List of Abbreviations

ANOVA	Analysis of Variance
B2B	Business to Business
B2C	Business to Customer
BSC	Balanced Score Card
CAD	Computer Aided Design
DIN	Deutsches Institut für Normung (German Industrial Standard)
DOD	U.S. Department of Defense
EFA	Explorative Factor Analysis
EU	European Union
FVA	Forschungsvereinigung Antriebstechnik (Research Association for Power Transmission Engineering)
GDP	Gross Domestic Product
HP	Hewlett Packard
ICE	International Conference on Engineering, Technology and Innovation
ICETI	International Conference on Engineering, Technology and Innovation
ICPS	Innovation Context Process Success
ISPIM	International Society for Professional Innovation Management
JSF	Joint Strike Fight program
KIT	Karlsruhe Institute of Technology
KMO	Kaiser Mayer Olkin criterion
MCC	Microelectronics and Computer Technology Corporation
MCAR	Missing Completely at Random
MSA	Measure of Sampling Adequacy
NASA	National Aeronautics and Space Administration
NPD	New Product Development
OECD	Organization for Economic Cooperation and Development

OEM	Original Equipment Manufacturer
PCA	Principle Component Analysis
PDA	Personal Digital Assistant
PFA	Principal Axes Factor Analysis
R&D	Research and Development
RQ	Research Question
SKF	Svenska Kugellager Fabriken
TOMP	Technology Organization Market Process
TRL	Technology Readiness Level
TTI	Technologie-Transfer-Initiative (Technology Transfer Initiative)
UK	United Kingdom
U.S.	United States
USA	United States of America
VDMA	German Engineering Federation (Verband deutscher Maschinen & Anlagenbauer)
WWW	World Wide Web

1 Introduction

1.1 The Mechanical Engineering Industry: Characteristics and Trends

The mechanical engineering industry is primarily concerned with the industrial application of mechanics and with the production of tools and machinery (Webster dictionary). It is a very heterogeneous branch with a variety of sub-sectors. Correspondingly, the respective market environments impose fundamentally different requirements on the companies' competences and their strategic direction (VDMA, 2015, p. 30; Vieweg, 2012a, p. 5). Approximately one third of the industry's output is intermediary products that are delivered to other companies, such as bearings, gears, taps, valves, and engines. Many of these goods are intra-sectoral and made for other mechanical engineering companies while further target industries of these products are electrical engineering, automotive industry, precision instruments, and others. However, the majority of output consists of capital goods dedicated to a broad range of industries. There are sub-sectors that produce products for specific client industries such as textile, pulp and paper, construction and mining, and agricultural industry. Other capital goods manufacturers provide products with a broader range of applications like handling equipment and machine tools (Vieweg, 2012a, p. 10).

In general, the mechanical engineering industry is recognized as an enabling industry which means that the industry supplies machinery and equipment, as well as process know-how, to all its customer industries, enabling them to produce their respective goods and services. The industry is one of the largest industrial sectors in the European Union (EU) economy in terms of number of enterprises, employment, production, and the generation of added value. The sector is characterized by smaller family-owned companies with a typical firm size between 500 and 2,000 employees. In the EU, it employs approximately three million people and is similarly one of the sectors in the manufacturing industry with the highest requirements of staff qualification (European Commission; Vieweg, 2012b, pp. 2–9).

Mechanical engineering is responsible for 9.5% of all the production in EU manufacturing industries and compared to other industries, the manufacturing depth is relatively high. Moreover, a broad range of activities is needed to finalize the products, e.g. engineering, research and development (R&D), production, and a growing supply of services. Additionally, the industry is characterized by a sophisticated division of labor between companies and complex value chains. This structure of the industry is notably different from its automotive and aerospace counterparts. Therefore, original equipment manufacturers (OEM) do not benefit from the same level of purchasing power.

There are several larger suppliers to final product manufacturers that possess a strong position in the market, based on their technical expertise and ability to produce components with unique characteristics (European Commission; Vieweg, 2012b, pp. 4–7).

According to Statista, China is by far the leading country in mechanical engineering based on revenue in 2014. With the accumulated revenues of all mechanical engineering companies in the country, China achieved 826 billion €, followed by the USA with 324 billion €, Germany with 249 billion €, Japan with 222 billion €, and Italy with 109 billion € (Statista, 2015). This is the result of a huge growth momentum of China over the past two decades. Moreover, deliveries to emerging economies have grown much stronger than domestic markets and are thusly becoming more and more important for developed economies. For the EU-economy, the exports to China are of similar size like those to the USA. Additionally, exports from emerging economies, above all China, are gaining shares in the global market. Therefore, it is expected that China will be clearly dominating the world output of mechanical engineering products within the next decade. However, the growth rates of the Chinese mechanical engineering industry exhibited a perceptible decline during 2015 (Industriemagazin, 2016, Vieweg, 2012b, p. 11, 2012a, pp. 14–15).

Moreover, a structural change of economic activities of the developed countries and Asia is expected in the coming years. In the face of the increasing globalization, this structural shift has already started and is driven by a specialization in comparative advantages. In the developed economies, workplaces have already been lost to low-value added areas and new opportunities have been created for the more qualified labor. In general, Asian deliveries consist above all of large batch, medium-tech products, whereas in the developed countries, small batch production, and customization as a share of total output, grows. This division of labor provides the developed countries with opportunities to remain price competitive (Vieweg, 2012a, pp. 10–14, 2012b, p. 10).

The mechanical engineering industry has to cope with more severe market fluctuations than most other branches. As one of the prime supplying industries of capital goods, the industry is highly dependent on the investment activities of the purchasing companies. These investment decisions are highly sensitive to developments in the overall economy and are a response to actual or expected changes in capacity utilization, earnings, financing costs or general market conditions. The resultant fluctuations in investment activity have a crucial effect on the cyclical up- and downturns of the economy as a whole. Thus, the mechanical engineering industry is almost inevitably at the core confronted by boom and recession periods. Correspondingly, the global financial and economic crisis hit the industry in 2009 harder than other industries and production fell by more than one fifth, on average, for all EU member states. However, the mechanical engineering industry directly benefitted from an early recovery and high growth momentum in 2010. Nevertheless, since 2013, the industry has to withstand a slight economic downturn (Kautzsch and Sitte, 2016; VDMA, 2015, p. 29, Vieweg, 2012a, p. 6, 2012a, p. 14).

Regarding the development and application of high technology, the mechanical engineering industry evolved as a leading branch. Many products from the industry combine mechanical technologies with even more advanced technologies, ranging from optoelectronics to new materials, and the like. The engineering ingenuity at the creation of innovative products, that combine different technologies, is one of the strengths of the EU mechanical engineering industry. Moreover, firms of the EU mechanical engineering industry strive for an expansion of their product programs to become full-value suppliers. This has increased the need for system engineering and caused a broader focus on product, as well as process innovations. Accordingly, the innovation intensity of the European mechanical engineering industry, as measured by the share of innovation expenditure of total sales, is higher than the major competing economies, and also higher than the average of other EU industries. Furthermore, the industry is leading others in terms of the number of patent filings (Vieweg, 2012b, pp. 7–8, 2012a, p. 17, 2012a, p. 4).

Especially the structural change of economic activities due to globalization, the increasing competition from Chinese manufacturers, and the ambition of becoming a full-value supplier, forces mechanical engineering companies from developed countries to be innovative, to not just gain advantage in the market, but to stay competitive. Competitiveness demands superior solutions to problems that are based on market-conforming, promising products and services. On a long-term basis, it is not enough to only create incremental improvements or innovations. In order to reach fundamentally better products, lower costs, and new product features, radical innovations are needed (Bullinger, 1994, p. 39).

Radicalness might be conceived as the combination of newness and the degree of differentness. The most radical innovations would be new to the world and exceptionally different from existing products and processes (Schilling, 2010, pp. 50–51). Thus, the level of risk is high, but simultaneously the correlated market opportunities of radical innovations are better (Bullinger, 1994, p. 34). What is of particular note, especially in consideration of the current global market dynamics in the industry, is that radical innovations open up huge differentiation potential. In general, radical innovations are often linked to the employment of new technologies. As technological development and successful market introduction have independent success parameters, the arising challenges for companies are obviously both technical and entrepreneurial in nature (Bullinger, 1994, p. 39). Hence, the capability to develop and exploit radical technological innovations needs to be interpreted as a complex concept influenced by a variety of factors, internal and external, to the organization (Terziovski, 2007, p. 19).

To study the realization of radical technological innovations within the mechanical engineering industry is sensible, as their implementation is risky, costly, and time-consuming (Vahs and Brem, 2012, p. 68). This thesis helps to reduce the existing complexity and serves as guidance for the actual implementation of radical technological innovations within the mechanical engineering industry. Therefore, critical success factors for the realization of the innovation process were derived. Moreover, distinct innovation archetypes were detected that are based on the project-specific contextual circumstances, and which predetermine the concrete implementation of the respective innovations. Finally, an operational framework was developed that contains concrete recommendations for actions regarding forthcoming innovation projects.

1.2 Structure of the Thesis

The thesis is divided into nine chapters. Figure 1 depicts an overview of the structure of the thesis. The first sub-problem *critical success factors* is addressed by the chapters 4, 5, and 6, the second sub-problem *innovation archetypes* by chapter 7, and the third sub-problem *operational framework* by chapter 8. In the following, a brief description of each chapter is given.

Chapter 1 contains an introduction to the thesis. Therefore, the characteristics and trends of the mechanical engineering industry are outlined, specifically those characteristics which cause the demand for radical technological innovations. Furthermore, the structure of the thesis is described. Lastly, in this first chapter, related work and related publications are documented and presented.

Chapter 2 highlights the state of the art analysis and the corresponding problem statement. First, basic concepts and terms are introduced that underpin the theoretical background. Then, the results of previous studies and related conceptual frameworks are presented. The resulting open questions form the underlying basis for the formal problem statement. The three derived sub-problems, outlined in the problem statement, determine the central research questions of this doctoral work.

Chapter 3 provides the overarching research approach. The methodology of design science is described. Then, the corresponding application of the general design science research guidelines for the current study is delineated.

Chapter 4 outlines the heuristics and model building for the initial version of a *critical success factor* framework. As a first step, the methodology of secondary case study analysis is described. Next, the TOMP-Framework as the central finding of this first research step is presented. In wrapping up this chapter, the results and the respective limitations are more thoroughly discussed.

Chapter 5 contains the qualitative validation and modification of the TOMP-Framework as an initial critical success factor framework. The results of the conducted literature review, expert interviews, and primary case study research are delineated in this chapter.

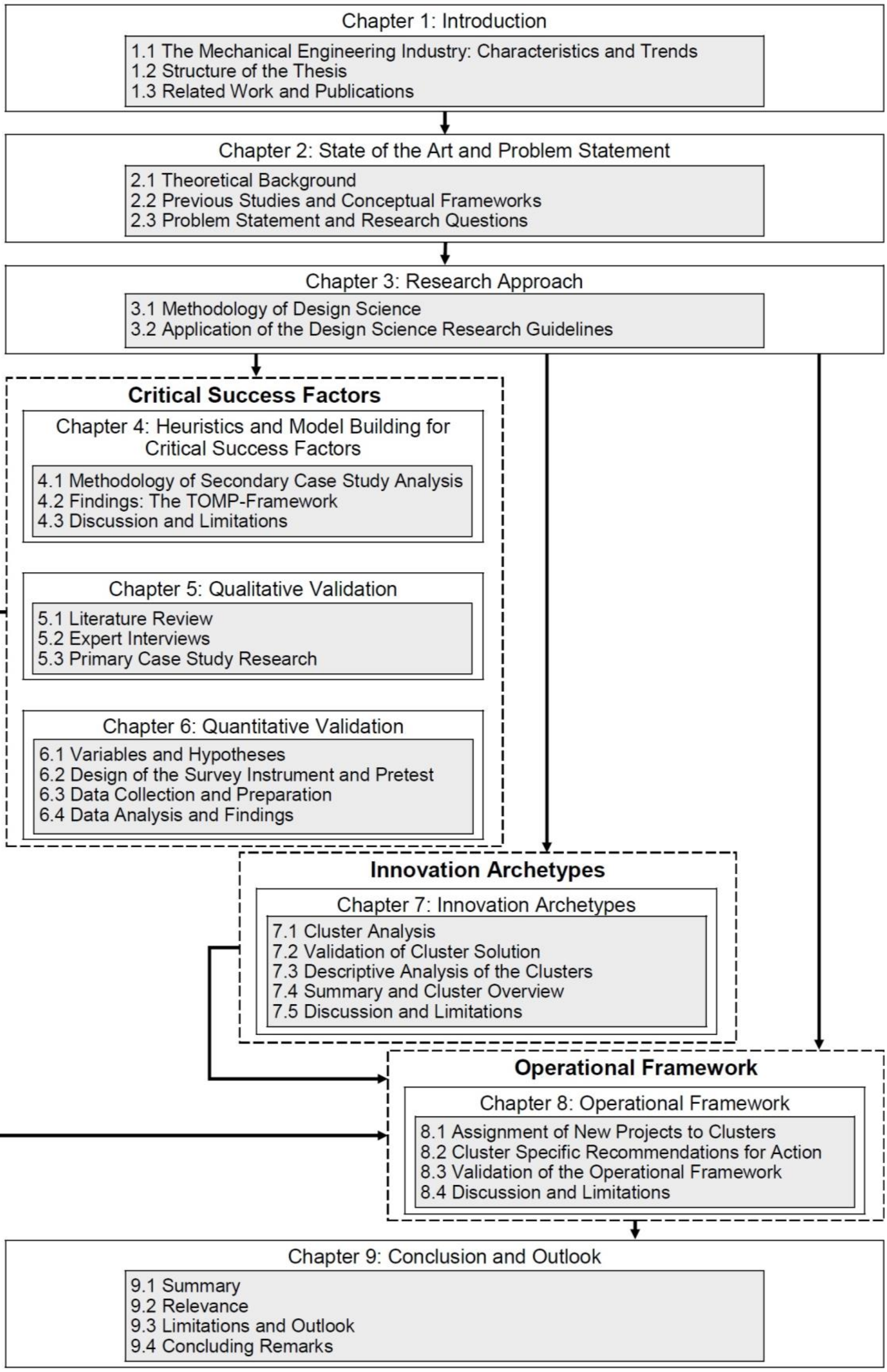


Figure 1: Structure of the Thesis

Chapter 6 presents the quantitative validation of the critical success factor framework. Variables and statistically testable hypotheses are outlined. Subsequently, the design of the survey instrument and the correlated pretest are described. Thereupon, a delineation of the data collection and preparation processes follows. Finally, the data analysis and the eventual findings are depicted.

Chapter 7 addresses the second sub-topic: *innovation archetypes*. First, the cluster analysis as the underlying methodology is described. Then, the validation of the cluster solution and the descriptive analysis of the clusters are presented. Afterward, a summary and a cluster overview are delineated. The chapter concludes with a discussion and limitation section.

Chapter 8 synthesizes the preceding findings into a coherent *operational framework* as an answer to the third sub-problem. This framework suggests a systematic way to deal with the challenge of realizing a radical technological innovation within the mechanical engineering industry. The derived *critical success factors* and *innovation archetypes* are utilized in the generation of this operational framework. As the first step, the assignment of new projects to clusters is presented. Thereupon, cluster specific recommendations for action are outlined. Afterward, the qualitative validation of the generated operational framework is described. Finally, the results and limitations of this chapter are reflected.

Chapter 9 is the final chapter of this thesis. Therefore, the results are summarized and the limitations are discussed. Moreover, the relevance of this thesis is highlighted and an outlook suggests potential areas for future research. The chapter ends up with several concluding remarks.

1.3 Related Work and Publications

Several contents of this thesis have been presented and discussed at international scientific conferences. The corresponding papers were published in the respective conference proceedings. Furthermore, some contents of the thesis have been published as working papers. Additionally, the author has involved several master students, who contributed with their master theses to the elaboration of this thesis.

Therefore, parts of chapter 1.1 and chapter 2.2, as well as the core contents of chapter 4 were presented at the International Conference on Engineering, Technology and Innovation (ICE) 2014 in Bergamo and were subsequently published in the conference proceedings (Wohlfeil and Terzidis, 2014). Moreover, the main contents of chapter 5.1 were presented at the International Conference on Engineering, Technology and Innovation (ICETI) 2015 in Istanbul and were published afterward at the International Science Index of the World Academy of Science, Engineering and Technology (Wohlfeil *et al.*, 2015). In addition, the results of the conducted expert interviews, reported in chapter 5.2, were presented at the ISPIM (International Society for Professional Innovation Management) Conference 2015 in Budapest. The respective paper was published in the ISPIM conference proceedings (Wohlfeil and Terzidis, 2015a). Findings of the primary case study research, outlined in chapter 5.3, were presented at the R&D Management Conference 2015 in Pisa and subsequently published in the conference proceedings (Wohlfeil and Terzidis, 2015b). Furthermore, for each case, an individual case study report was elaborated and published in the KIT Scientific Working Paper series. The case study of the P1.18 bicycle transmission by Pinion was published in this series as paper number 28 (Wohlfeil, 2015c), the case study of the Friction Disc by SKF as paper number 42 (Wohlfeil, 2015b), and the case study of cryogenic machining by 5ME as paper number 29 (Wohlfeil, 2015a). All case studies can be found in Appendix III. Similarly, parts of the chapters 6.4, 7, and 8 were published in the KIT Scientific Working Paper series as paper number 39 (Wohlfeil, 2015d).

As mentioned above, several students contributed with their master theses to the overall research project. Hellmann and Yakubovich were involved in the conduction of the expert interviews, reported in chapter 5.2 (Hellmann, 2014; Yakubovich, 2014). Additionally, parts of chapter 5.1 were reported by Hellmann (Hellmann, 2014). Dahl was involved in the creation of and Hilgers in the analysis of the quantitative survey. Therefore, parts of the chapters 2.2, 9.2, and 6 were reported by Dahl and Hilgers in their master theses (Dahl, 2015; Hilgers, 2015). However, if contents of these student theses were used, this was indicated by clear quoting and reference of their work.

2 State of the Art and Problem Statement

2.1 Theoretical Background

The following section provides a brief overview of the theoretical background of this thesis. Essential underlying terms and theories will be discussed. To some extent, there are different and even contradictory definitions and explanations of the central concepts presented in the literature. To ensure a common understanding and to avoid misinterpretations when reading the thesis at hand, these definitions and descriptions will be outlined that have been followed in this work.

2.1.1 Basics of Technology

2.1.1.1 Concept of Technology

According to Bullinger, the concept of technology describes a target-mean-relation. Its application is meant to solve technical problems. Consequently, technology is rarely a product or a process but can be embedded within a product or a process by its application. Along the research and development value chain, Bullinger clarified three concepts that should be differentiated: *theory, technology*, and *technique* (Bullinger, 1994, pp. 32–34).

Theories display general cause-and-effect relationships and are generated by basic research (Bullinger, 1994, p. 32). The aim is to gain fundamental new scientific knowledge regarding the origin of phenomena and observable facts. Future commercial usage or applicability is mostly neglected (Vahs and Brem, 2012, p. 25). In contrast, *technology* is the knowledge about potential approaches to solving technical problems (Bullinger, 1994, p. 34). They are instructions for technical proceedings to reach an intended goal and are produced by applied research based on theory. The fundamental applicability of the technology is a focus (Vahs and Brem, 2012, pp. 25–26). The concept of *technique* relates to the material results of the problem-solving process, its production and application (Bullinger, 1994, p. 34). The technique includes the systematic application of technologies to reach new or improved materials, artifacts, products, processes, systems, and services (Vahs and Brem, 2012, p. 25). Thus, a technical innovation corresponds to a concrete technique as it has been realized and implemented within practice (OECD, 2005, p. 25; Vahs and Brem, 2012, p. 2).

2.1.1.2 Technology Performance

Many technologies show an s-curve when the relation between effort (e.g. accumulated R&D expenses) and resulting performance is illustrated in a diagram (Foster, 2006, p. 39). Each development trajectory represents a path of incremental innovations along the lifetime of a technology. Typically, the performance graph initially exhibits slow improvement as the fundamentals of the technology are poorly understood and potential applications may not be apparent (Schilling, 2008, p. 54).

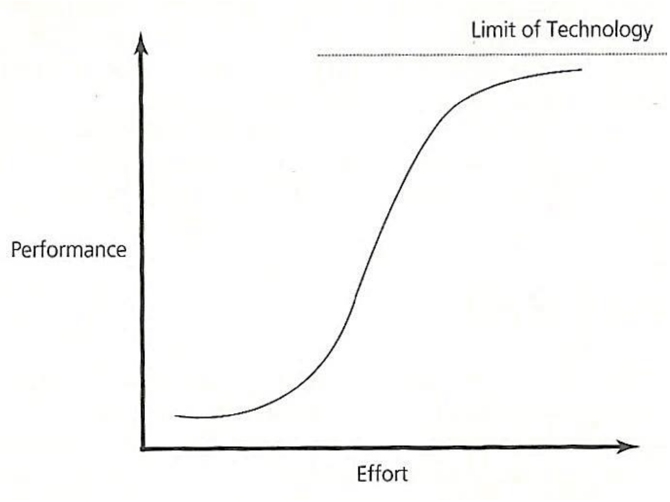


Figure 2: S-Curve of Technology Performance (Schilling, 2010, p. 54)

Until the technology has established a degree of legitimacy, it is difficult to attract researchers or companies to cooperate and participate in its development. However, once this has been achieved, the technology's potential will be recognized and a deeper understanding will be acquired. Consequently, performance increases rapidly. At some point, the technology reaches its limits; the cost of each marginal improvement increases, and as a result, the curve flattens (Schilling, 2008, p. 54).

This chronological progress of technology maturity can be classified into four phases: *embryonic* or *emerging, growth, mature,* and *aging*. Nevertheless, not all technologies go through the entire cycle. Some technologies, due to unprofitable development, are abandoned in the early stages (Caragay, 1983, p. 1641).

In the early phases of technology development, the effort that is invested in a new technology may gain lower returns than the effort that is invested in the current technology (cf. Figure 3). Thus, firms are often reluctant to switch technologies. Only when the new technology reaches a higher performance level, potential users are willing to adopt it. At a certain point, this may turn and the returns for the effort invested in the new technology are much higher

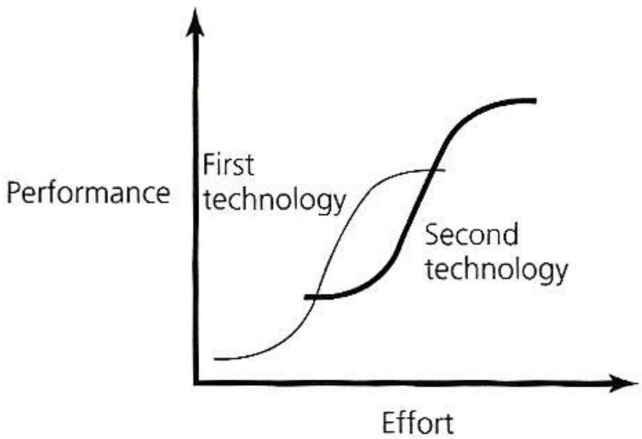


Figure 3: Substituting Technology (Schilling, 2010, p. 57)

than the effort invested in the incumbent technology. When it happens, the rate can vary significantly (Schilling, 2008, p. 56).

Several authors have suggested using the s-curve model as a tool for predicting the time when a technology will reach its limits and whether a firm should move to a new technology (Schilling, 2010, p. 59). Indeed, s-curves can provide an important perspective on what happens to performance trajectories at average and aggregate levels. However, when s-curves are used to plan technology development at the firm level, caution is important (Christensen, 1992, p. 365). As a prescriptive tool, the s-curve model has serious limitations. It is seldom that the true limits of a technology are known in advance as unexpected changes in the market, component technologies, or complementary technologies can shorten or extend the life cycle of a technology (Schilling, 2010, p. 59). Most of the time, only in retrospect, it will be clear which technological decisions have been correct. The future development of a technology s-curve is unknown in advance and thus, a high level of uncertainty is associated with the deployment of the s-curve model as a prescriptive tool (Bullinger, 1994, p. 128).

2.1.1.3 Classification of Technologies

Technology Readiness Levels

The realization of technological innovations depends on the maturity of the underlying technology. A certain level of technology maturity is a precondition for a feasible utilization within a concrete innovation project. Therefore, a sound assessment of technology readiness is sensible. The concept of Technology Readiness Levels (TRLs) can serve as a helpful standard for this assessment.

The nine scale TRLs (cf. Figure 4) have been introduced by the National Aeronautics and Space Administration (NASA) in the mid-1970s as a discipline-independent, systematic approach for effective assessment and communication regarding the maturity of new technologies. Later on, Mankins (1995) articulated the TRL scale for each level. The TRLs have been used by the U.S. Department of Defense and numerous other organizations. Mankins emphasized that the TRLs have proved to be highly effective in communicating the status of new technologies among sometimes diverse organizations (Mankins, 1995, 2009, p. 1217).

According to Mankins, *TRL 1* is the lowest level of technology maturity. At this level, basic scientific research has resulted in the reporting of basic principles, and thus, more applied research and development begins (Mankins, 2009, p. 1217). At *TRL 2*, Mankins delineates that the concepts for practical technology applications could be formulated, but remain on a speculative level. When *TRL 3* is achieved, active research and development have been initiated. This includes analytical and laboratory-based studies to physically validate the predictions. These studies and experiments should constitute "*proof-of-concept*" validation of the concepts formulated at *TRL 2*. At *TRL 4*, the basic technological elements have been integrated into a coherent system and validated in a laboratory environment. After validation of the basic technological elements as part of a coherent system in a realistic environment, *TRL 5* has been reached. At *TRL 6*, a representative model or prototype system was successfully tested in a relevant environment. When a system prototype of the technology demonstrated adequacy in the planned environment, *TRL 7* has been reached. After achieving *TRL 8*, the actual system was completed and qualified through test and demonstration in the operational environment. The highest maturity level of *TRL 9* is attained, when a technology has proven its usability through successful operation over a longer period (Mankins, 1995, pp. 2–5).

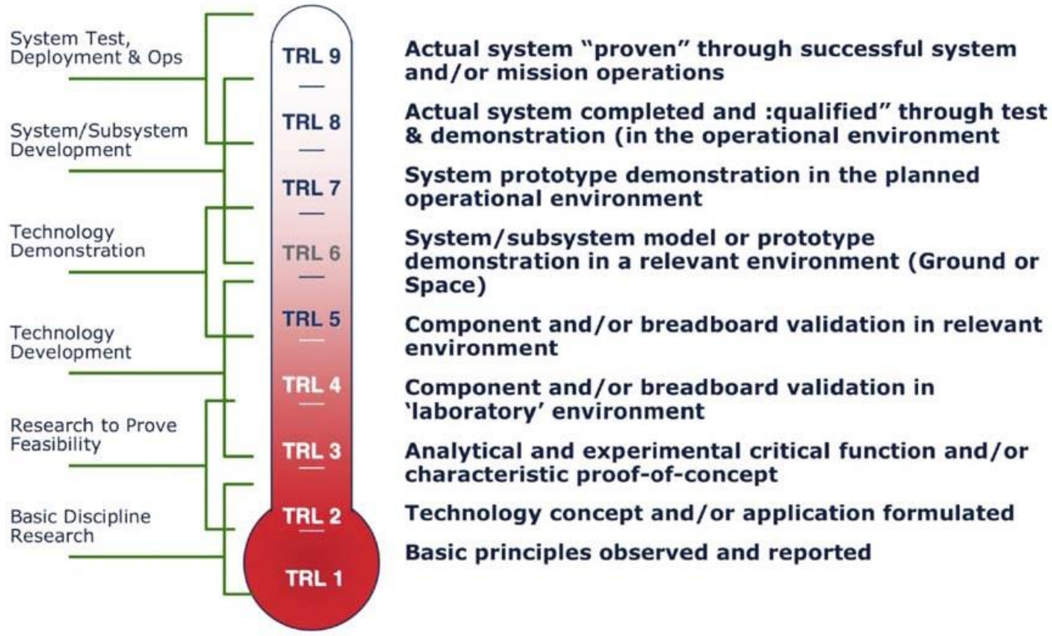


Figure 4: Overview of the TRL Scale (Mankins, 2009, p. 1218)

Competitive Impact

The management consulting firm Arthur D. Little has developed and manifested a widely accepted classification scheme for technologies according to their competitive impact. Thereby, the correlating potential of the focal technology is dependent on the concrete area of application and is thus, industry specific (Bullinger, 1994, p. 115).

The following four types of technologies are distinguished: (Bullinger, 1994, pp. 96–97)

- *Emerging technologies* are very new. Their competitive impact is promising but highly uncertain.
- *Pacing technologies* are expected to have great influence on the market development and competitive dynamics in the future. They are still in their development phase but it is already obvious, that they will have great potential in the specific industry.

- *Key technologies* have currently the highest competitive impact. They significantly influence the market situation and are already a fixed component of the technology spectrum in the industry. Nevertheless, they are still not accessible to all competitors.

- *Base technologies* are, due to their great prevalence rate and the common availability of knowledge in the industry, no instrument for differentiation. They shape the current form of the industry and the competence to control these base technologies is a prerequisite for serious competition in that industry.

Sustaining versus Disruptive Technologies

Christensen shaped a distinction principle by addressing the market impact of technologies: *sustaining* versus *disruptive technologies*. This concept is quite different from the incremental versus radical distinction (cf. chapter 2.2.2.3) (Christensen, 1997, p. xv).

Sustaining technologies improve the performance of established products, along the dimensions of performance that mainstream customers in major markets have historically valued. Some sustaining technologies can be radical in character while others may be more of an incremental nature. In contrast, *disruptive technologies* bring a very different value proposition to the market than what has previously been available (Christensen, 1997, p. xv). Moreover, this kind of technology can lead to the emergence of a completely new market. Generally, disruptive technologies underperform established technologies in mainstream markets in the near term, but they have other features that a few fringe customers value. Products based on mature disruptive technologies tend to be cheaper, simpler, smaller, and, frequently, more convenient to use (Christensen, 1997, p. xv).

2.1.2 Basics of Innovation

2.1.2.1 Concept of Innovation

The concept of the term *innovation* in the current usage has been shaped by the economist Joseph Alois Schumpeter (1883-1950). He used the term for the first time in his work *Business Cycles* in 1939, but he had already described the phenomenon in 1912 as the *implementation of new combinations* in his *Theorie der wirtschaftlichen Entwicklung* (Schumpeter and Röpke, 2006 reprint of 1912, p. 162). According to Schumpeter, innovation requires business action, the actual realization of the new combinations in the marketplace. The creation of the invention and the carrying out of the corresponding innovation are two entirely different things (Schumpeter, 2006 reprint of 1939, p. 81; Schumpeter and Röpke, 2006 reprint of 1912, p. 162). This concept manifested in the commonly known Schumpeter trilogy of innovation: *invention, innovation,* and *diffusion*. *Invention* refers to the generation of a new idea. *Innovation* is said to be accomplished when the idea from the invention is developed into a new product and is subsequently introduced to the market. *Diffusion* describes the process of broad market penetration of the corresponding innovation. Without diffusion, an innovation has no economic impact (Curlee and Goel, 1989, p. 5; OECD, 2005, p. 17).

Schumpeter defines innovations as the creation of a new product, the introduction of a new production method, the cultivation of a new market, the utilization of a new source for raw materials, or the attainment of a new market position such as a monopoly (Schumpeter, 1952, pp. 100–101). With this early concept of innovation, it becomes apparent that Schumpeter already distinguished different types of innovation. In the following, the most commonly used classifications of different types of innovation will be outlined as presented in the literature. These concepts are crucial for understanding the realization of radical technological innovations.

2.1.2.2 Classification of Innovations

Subject Area

In the *Oslo Manual* (guidelines for collecting and interpreting innovation data), the OECD has developed the Schumpeterian concept further and has created the following classification of innovation:

"An innovation is the implementation of a new or significantly improved product (good or service), or process, a new marketing method, or a new organisational method in business practices, workplace organisation or external relations." (OECD, 2005, p. 46)

Within this understanding of innovation, there are four basic types to be distinguished: *product, process, marketing,* and *organizational innovation* (OECD, 2005, p. 47)

- *"A product innovation is the introduction of a good or service that is new or significantly improved with respect to its characteristics or intended uses. This includes significant improvements in technical specifications, components and materials, incorporated software, user friendliness or other functional characteristics." (OECD, 2005, p. 48)*
- *"A process innovation is the implementation of a new or significantly improved production or delivery method. This includes significant changes in techniques, equipment and/or software." (OECD, 2005, p. 49)*
- *"A marketing innovation is the implementation of a new marketing method involving significant changes in product design or packaging, product placement, product promotion or pricing." (OECD, 2005, p. 49)*
- *"An organisational innovation is the implementation of a new organisational method in the firm's business practices, workplace organisation or external relations." (OECD, 2005, p. 50)*

In their definition of process innovations, the OECD only refers to production and delivery methods (OECD, 2005, p. 49). For the sake of completeness, this concept of innovation should be applied to every value-adding process within the firm, in which innovations could be created, such as sourcing and product development.

Furthermore, the concept of *architectural innovation* is missing within the OECD's classification of innovation. Product architecture describes the way how the specific product function is linked to its physical and logical components (Ulrich, 1995, p. 420). According to Henderson and Clark, *"[t]he essence of architectural innovation is the reconfiguration of an established system to link together existing components in a new way. (...) The important point is that the core design concept behind each component - and the associated scientific and engineering knowledge - remain the same."* (Henderson and Clark, 1990, pp. 12)

The described concepts of innovation include the commercial application of the underlying invention (Bullinger, 1994, pp. 34–35). Subsequently, to be implemented, a new or improved product, or an architecturally changed product, needs to be introduced to the market. New processes, marketing or organizational methods are implemented when they are brought into actual use in the firm's operations (OECD, 2005, p. 47).

Levels of Novelty

A basic requirement for an innovation is its novelty. In the Oslo-manual three concepts regarding the novelty of innovations are distinguished: *new to the firm, new to the market,* and *new to the world* (OECD, 2005, p. 57).

The minimum entry level is that the innovation is *new to the firm*. A product, process, marketing, or organizational method may already have been implemented by other firms, but it might still be an innovation for the contemplated firm if it is new or significantly improved in terms of products and processes (OECD, 2005, p. 57). If the firm is the first to introduce the innovation on its market, then the focal innovation is *new to the market*. The market is defined as the collective of the firm, its competitors, its customers, and its potential customers (OECD, 2005, p. 58).

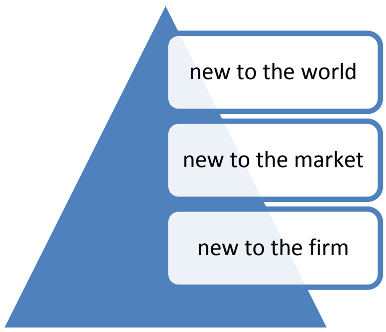


Figure 5: Levels of Novelty

It can refer to a geographic region or a product area and thus, is dependent on the firm's own conception of its operating market (OECD, 2005, p. 58). In order to be *new to the world*, the firm needs to be the first to introduce the innovation for all markets and industries, domestically and internationally. Thus, the concept of *new to the world* implies a qualitatively greater degree of novelty than just *new to the market* (OECD, 2005, p. 58).

Incremental versus Radical Innovations

One of the primary distinguishing characteristics of innovation is the extent of change. At this point, *radical* and *incremental innovations* are differentiated. Thereby, radicalness could be conceived as the combination of newness and the degree of differentness regarding the state of the art (Schilling, 2010, p. 50). *Incremental innovations* emerge on existing markets and already familiar fields of application. The level of risk is low and thus, incremental innovations are relatively easy to handle and to steer. Mostly, they are just advanced or improved innovations (Vahs and Brem, 2012, p. 67). In contrast, *radical innovations* have a high level of novelty. They cause deep and complex changes within the company. Hence, the level of risk is high, but correspondingly, the correlated market opportunities of radical innovations are better (Vahs and Brem, 2012, p. 67).

Market-Pull versus Technology-Push Innovations

The triggers for innovations can be diverse. Market induced innovations are called *market-pull* or *demand-pull*. They have been initiated by customer requirements and by concrete demands and needs of the market (Vahs and Brem, 2012, p. 63). These technical solutions emerge, as individuals, groups, or organizations formulate a perceived gap which desires satisfaction (Bullinger, 1994, p. 100). On the other hand, there are cases in which inventors search for market opportunities for a given technology. Thereby, potential markets and applications are initially unknown. These types of innovations are called *technology-push innovations*. The most obvious case of technology-push is that of a completely new technology originating from science searching for an opportunity for application. However, even the challenge of identifying further applications for existing technologies is an example of technology-push (Henkel and Jung, 2009, pp. 1–2). This approach emphasizes that innovations can, due to their technological potential, create new demands and open up new markets (Cross, 2008, p. 211). Thus, technology-push innovations have their origin in the application drive caused by a technical potential (Bullinger, 1994, p. 100).

2.1.3 Diffusion of Innovation

2.1.3.1 Diffusion Process

Diffusion describes the way in which innovations spread from their very first implementation to different consumers, countries, regions, sectors, markets, and firms (OECD, 2005, p. 17). Similar to the technology performance, the diffusion of innovations usually follows an s-curve, as shown in Figure 6 (Byers *et al.*, 2010, p. 269).

These curves are gained by plotting the cumulative number of adopters of an innovation against time. This yields and S-shaped curve as adoption is initially slow when an unfamiliar innovation is introduced to the market. It accelerates when the innovation becomes better understood and utilized by the mass market. Eventually, the market is saturated and thus, the rate of new adoptions declines (Schilling, 2008, p. 56).

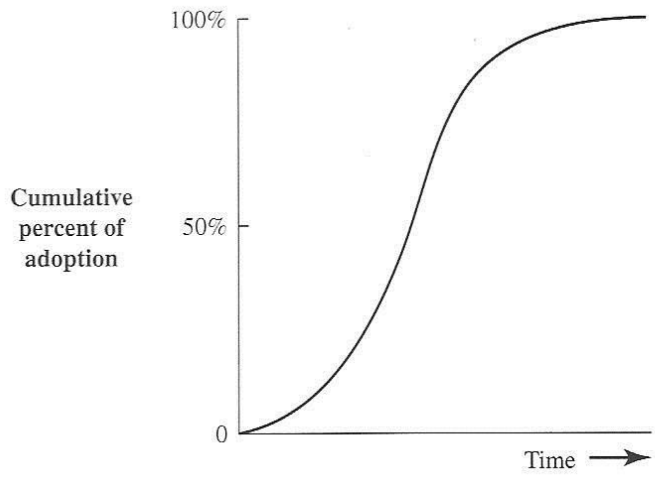


Figure 6: S-Curve of Adoption (Byers *et al.*, 2010, p. 269)

It is important to note that the s-curves of diffusion are in part a function of the s-curves of technology performance: if technologies are better developed, they correspondingly become more certain and useful to users, facilitating the adoption of the corresponding technological innovation. Moreover, as the learning-curve and scale advantages accrue to the technology, the price of finished goods often drops (Schilling, 2008, pp. 57–58).

2.1.3.2 Categorization of Adopters and Users

The diffusion of innovations describes the process of how innovations spread through a population of potential users. Based on their perception of its advantages and risks, customers will adopt an innovation. Correspondingly, potential users of an innovation are fundamentally different regarding their personal requirements and needs (Byers *et al.*, 2010, pp. 268–269; Rogers, 2003, pp. 280–285).

On this basis, Rogers established a categorization for different groups of adopters. His criterion for categorization was innovativeness and the degree to which an individual or another unit of adoption is relatively earlier in acquiring the innovation than other members of a social system. By means of statistics, he derived five categories: *innovators, early adopters, early majority, late majority,* and *laggards*. One difficulty with this method is incomplete adoption which occurs for innovations that have not reached 100% usage among customers. The five adopter categories are ideal types, based on abstractions from empirical investigations (Rogers, 2003, pp. 280–281).

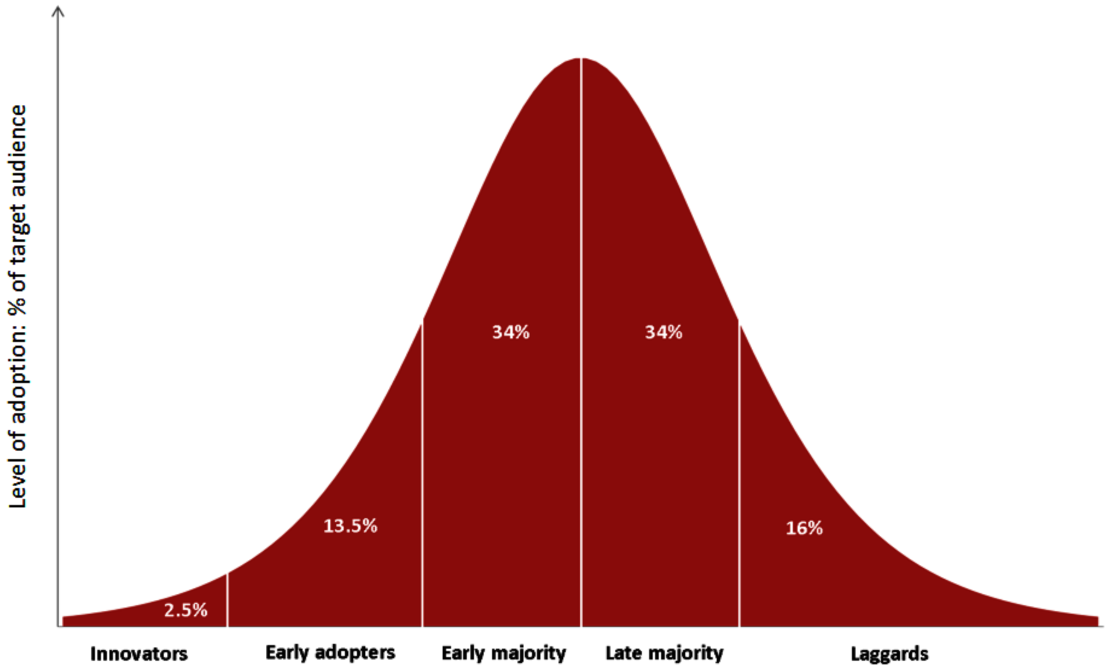


Figure 7: Adopter Categorization (Boretos, 2012, p. 35 derived from Rogers, 2003, p.281)

In the following, an overview of the main characteristics of the different adopter groups will be presented: (Rogers, 2003, pp. 282–284)

- *Innovators:* They have a great interest in new ideas and in connecting themselves with like-minded peer groups. Innovators are able to deal with complex technical knowledge and are willing to cope with a high degree of uncertainty regarding the innovation at the time of its adoption. They play an important role in the innovation diffusion process, as they provide the first industrial application of the young innovation.

- *Early Adopters:* This adopter category has the highest degree of opinion leadership since they are highly respected by their peers. Potential adopters look to early adopters for advice and information about an innovation. As the early adopters are not too far ahead of the average individual in innovativeness, they serve as a role model for the adoption of an innovation.

- *Early Majority:* The members of the early majority adopt new ideas just before the average member of a system does. They follow with a deliberate willingness in adopting innovations but they seldom lead. As they account for one third of all members of a system, their role in the full establishment of an innovation is decisive.

- *Late Majority:* The members of the late majority adopt new ideas just after the average member of a system does. Like the ones of the early majority, they account for one third of the members of a system. For them, adoption may be both an economic necessity and the result of increasing peer pressures. Their relatively scarce resources mean that most of the uncertainties about a new idea must be removed before they feel safe to adopt an innovation.

- *Laggards:* Laggards are the last group in a social system to adopt an innovation. As they are traditionally minded, they tend to be suspicious of innovations and change. Their resistance to innovations may be due to their limited resources and thus, the need to be certain that a new idea will not fail before they can adopt it.

Besides the adopter categorization of Rogers, there is another user concept established by Eric von Hippel. He introduced the so-called *Lead User* concept. Lead users face needs that will be general in a marketplace, but face them a long time before the mainstream users will do. Furthermore, lead users would benefit significantly by obtaining a solution to those needs (Hippel, 1986, p. 796). Especially, for market research or the development of new product concepts the involvement of lead users could be very helpful (Herstatt and Hippel, 1992, p. 213). Lead users often have ideas for new products and features or may even innovate themselves. In any case, they are far more likely to express their opinion regarding product concepts than average users will do (Henkel and Jung, 2009, p. 4). Thus, lead users are primarily perceived to be innovators or early adopters (Seitz, 2015, p. 26).

2.2 Previous Studies and Conceptual Frameworks

The topic of radical technological innovation, in general, and the search for factors fostering innovation success, in particular, have been previously analyzed in several practical and scientific studies from diverse perspectives, with various focus areas, and with different methodological approaches. In the following section, a brief overview of selected past and contemporary innovation research is presented to point out the main findings, perceptions, and open questions. This analysis formed the starting base for the conducted research outlined in this thesis.

2.2.1 Practical Studies and Best Practices

2.2.1.1 McKinsey and VDMA-Study of the German Mechanical Engineering Industry

In 2014, the German Engineering Federation (Verband deutscher Maschinen und Anlagenbauer – VDMA) and McKinsey & Company conducted a cooperative study regarding success patterns and trends within the German power transmission industry. In this study, 333 companies participated from all sectors of the mechanical engineering industry with different sizes, ownership, and management structures. Thus, this sample ensured the involvement of a broad cross-section of the industry. Furthermore, in-depth interviews with more than 50 executives were conducted and external data was considered (VDMA and McKinsey, 2014b, p. 13).

The findings of the study indicate that there is no single formula for high profitability and growth in the German mechanical engineering industry. Accordingly, companies find success in very different ways. Overall, ten distinct success patterns were detected. For one company, success comes from size, innovative strength, and internationalization, but also from focusing on core business and operational excellence. Other companies benefit from their industry affiliation or management structure, the specific benefits of their solution or component business, a successful after-sales program and service business, or a premium position (VDMA and McKinsey, 2014b, p. 18, 2014b, p. 16).

In general, the whole German mechanical engineering industry was in a good position. However, the market circumstances were changing. Correspondingly, five core industry trends could be derived from the study: The demand for customized systems and integration solutions increased. The general demand for products and services shifted to countries outside Europe. After-sales and service achieved increasing relevance. The competition was rising due to new market participants. The competitiveness of Germany as a location was growing in importance (VDMA and McKinsey, 2014b, pp. 41–45, 2014b, p. 38).

With respect to these trends, most of the companies within the industry saw themselves in a good position. However, to be successful in the long-term, six fields of action were developed that consist of an adequate combination of current success patterns and emerging industry trends (cf. Figure 8): targeted and granular internationalization and growth strategy; expansion of after-sales/service segment through integrated innovative solutions; standardization and modularization, while also providing customer specific offers and new business models; continuous optimization of the product/portfolio value, especially by innovations; excellence, in particular in domestic operations; stringent, risk-differentiated project management, particularly in the solutions business (VDMA and McKinsey, 2014b, pp. 51–70). Nevertheless, not all action plans are equally relevant to all companies. Depending on the context and the respective company strategy, some fields of action are more or less important (VDMA and McKinsey, 2014b, p. 74).

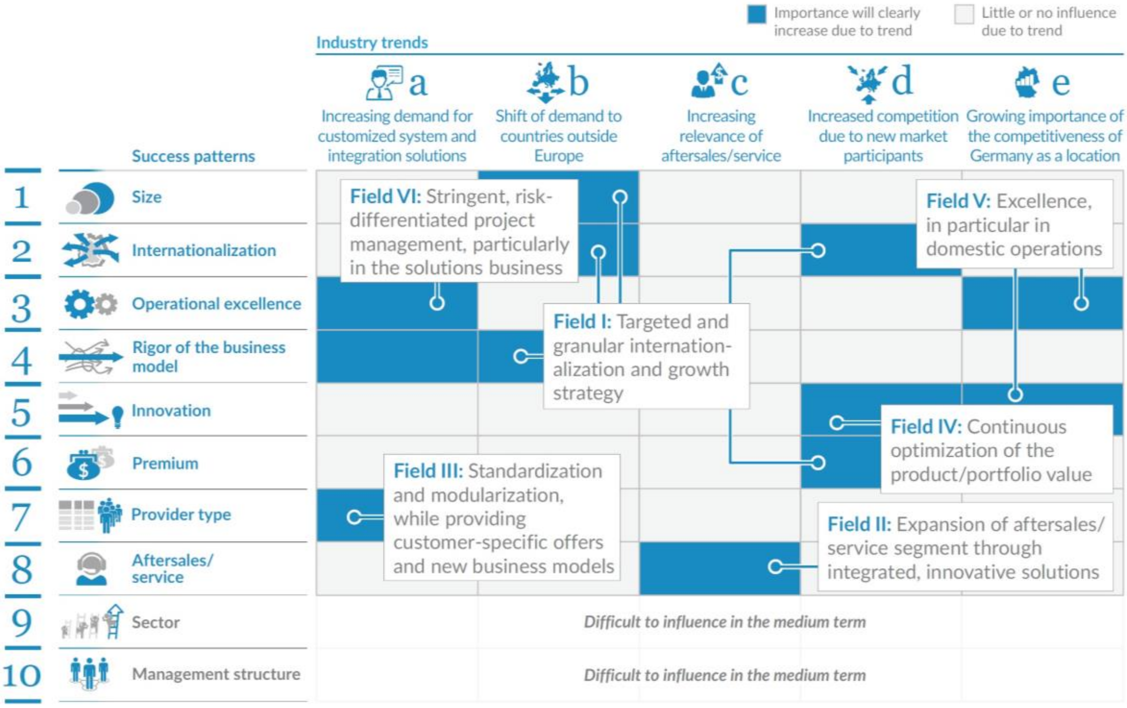


Figure 8: Fields of Action for the German Mechanical Engineering Industry (VDMA and McKinsey, 2014b, p. 50)

2.2.1.2 PwC's Global Innovation Survey

PwC conducted, in 2013, a global innovation survey among 1,757 executives to study innovation, growth, and business strategy (Shelton and Percival, 2013, p. 41). The interviewed executives perceived innovation as a driver for rapid and profitable revenue growth and as being integral to sustaining the long-term future of their business. Ninety-three percent of the survey participants expressed the view that organic growth through innovation will drive the greater proportion of their revenue growth. Therefore, leading innovators can expect significant rewards both financially, and in terms of competitive positioning (Shelton and Percival, 2013, pp. 4–5).

Furthermore, PwC deliberately considered the top and the bottom 20% of innovators to compare and contrast their relative characteristics and innovation approaches (Shelton and Percival, 2013, p. 41). Regarding the different innovation strategies, they found that leading innovators have a deliberate innovation strategy and are taking a more sophisticated approach to innovation. They are targeting a higher proportion of breakthrough and radical innovations, particularly around products, services, technology, and business models. In some areas, the proportion is around twice that of the less innovative companies. Furthermore, they are collaborating much more than the bottom 20% and generate a greater proportion of revenue from new products and services. (Shelton and Percival, 2013, p. 13; p. 5).

Another result of this survey was that there is no single roadmap for success in innovation. However, PwC developed the so-called *Innovation Blueprint* depicted in Figure 9 to support managers thinking through the appropriate approach for growth via innovation, from strategy to execution (Shelton and Percival, 2013, p. 18).

According to PwC, this blueprint contains lessons that can be tailored and made to work for any business. Elements 1 and 2 address the alignment of innovation strategy with the respective business strategy. Elements 3 to 7 focus on maximizing the company's ability to come up with new innovative ideas. Elements 8 to 12 target the operational efforts, including new ways of working that are necessary to bring these new ideas to market. As a result, an innovation capability will be generated that drives new products, services, technologies, and business models (Shelton and Percival, 2013, p. 22).

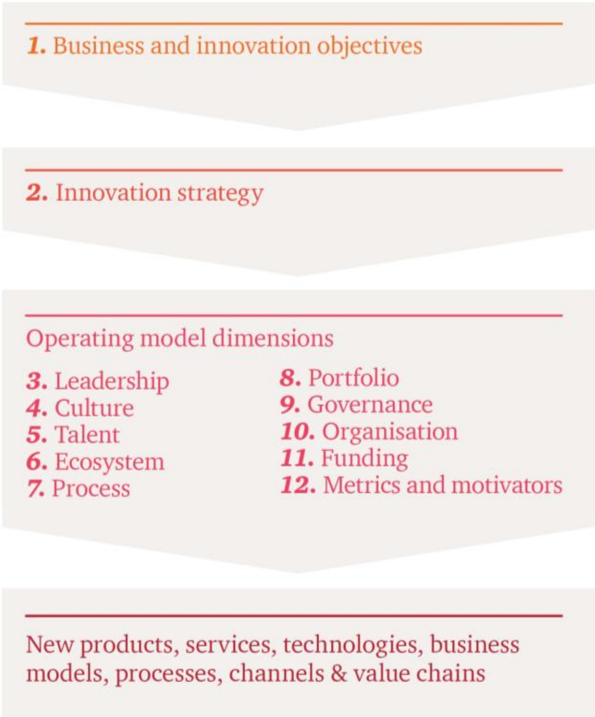


Figure 9: PwC's Innovation Blueprint (Shelton and Percival, 2013, p. 22)

2.2.1.3 Kienbaum-Survey: The Return of Innovation

Over a period of seven years, a Kienbaum team led by Berth conducted a longitudinal study within 116 small, medium-sized, and big enterprises in Germany to analyze the origin and success rate of innovations. In sum, 1,919 ideas were considered. The study was called "*The Return of Innovation*" and was finally published in 1993. In this study, neither a distinction was made with respect to the industrial origin, nor regarding incremental and radical ideas. However, besides these differences, Berth articulates that the study served empirical evidence for an exceptional similarity regarding the success rates of the analyzed ideas. Therefore, the sample was entirely considered without differentiation of distinct types of innovations (Berth, 1993, 1995, p. 277; Fischer and Risch, 1993, p. 212).

The result of this study was quite disillusioning (cf. Figure 10). Out of 1,919 first ideas, just 524 preliminary studies were initiated. Based on these, 369 projects were started and finally 176 products were introduced to the market. Five years after market launch, 124 products totally flopped and were withdrawn from the market. Out of the remaining products that were still on the market, 24 products were loss makers and 17 products achieved a mediocre success level however with a lower return on investment rate than the average rate of products within the respective business unit. Just 11 products were actually successful which accounts for a total success rate of 0.57% (Berth, 1993, 1995, pp. 278–279).

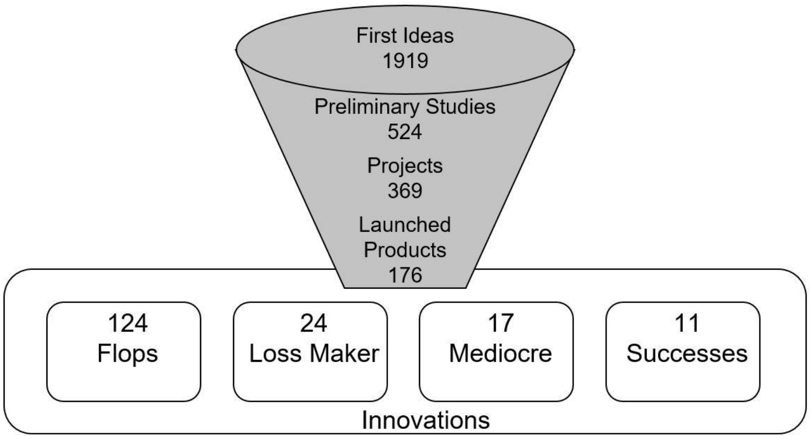


Figure 10: Success Rate of Innovations (Berth, 1995, p. 279)

2.2.1 Scientific Studies

In the SAPPHO-project, Rothwell et al. conducted a comparative analysis of 72 successful and unsuccessful technological innovations. To systematically discover differences, a successful innovation was paired with an unsuccessful one. The criterion for the formation of a pair was the precondition that the two innovations competed for the same market. Subsequently, five main areas of difference emerged: understanding of user needs, efficiency of development, characteristics of managers, efficiency of communications, and marketing and sales efforts (Rothwell *et al.*, 1974, p. 258).

A study by the OECD regarding the conditions for success in technological innovation highlights that success requires the existence of three factors: science and technological capability, market demand, and an agent which transforms this capability into goods and services which satisfy the demand. According to the study, the characteristics of uncertainty and long-time horizons that are both commonly linked to technological innovations pose specific challenges to the management. Communication across disciplinary and functional boundaries, a flexible organization to respond to market circumstances, and a risk-taking attitude are decisive to raise the chances for success (OECD, 1971, pp. 11–13).

Abetti analyzed five cases of technological innovations along their successive evolutionary stages to identify success factors for radical technological innovation. He emphasized that from the list of factors technology is not the principal criterion as the market, financial, organizational, and strategic issues are predominant (Abetti, 2000, p. 220).

In his study of fifteen successful highly varied and diverse technological innovations, Souder derived several success factors for the technology-push process. Initially targeting minor markets, constantly interacting with users, interdisciplinary teams, and an iterative try-and-modify approach are decisive to the success of technology commercialization (Souder, 1989, pp. 19–20).

Within their case study of the MCC (Microelectronics and Computer Technology Corporation), a US-based R&D consortium, Gibson and Smilor detected four variables which are central to accelerating inter-organizational technology transfer and therewith, for the success of technological innovation: communication interactivity, cultural and geographic distance, technological equivocality, and personal motivation (Gibson and Smilor, 1991, p. 287).

Chiesa and Frattini analyzed eight technological innovations launched on consumer high-tech markets, regarding the impact of positioning and market introduction decisions on the overall success of the focal products (Chiesa and Frattini, 2011, p. 437). The authors found that predominantly, the support and attitude of early adopters towards an innovation predetermines the successive success and failure (Chiesa and Frattini, 2011, p. 452).

Henderson studied the results of innovation investments made by incumbent firms, in contrast to entrants, using data derived from a detailed field study of the photolithographic alignment equipment industry. She found that established firms invested more than entrants in incremental innovation, but the research efforts of incumbents seeking to exploit radical innovation were significantly less productive than those of entrants (Henderson, 1993).

With a quantitative survey of three high-tech industries (computer hardware, photonics, and telecommunication), Chandy and Tellis tried to answer the question why some firms are more successful at introducing radical product innovations than others. The researchers focused their studies on organizational factors driving innovation success. Beforehand, many researchers suggested that firm size is the key organizational predictor of radical product innovation. In contrast, Chandy and Tellis found evidence for their hypothesis that one main variable that differentiates firms with strong radical product innovation records from others is the firms' willingness to cannibalize their own investments (Chandy and Tellis, 1998).

McDermott and O'Conner conducted a longitudinal, multidisciplinary, multiple case study of twelve radical innovation projects in ten large, established North American firms. The purpose of their study was to explore the process of radical new product development from a strategic perspective and to outline key observations and challenges that managers face as they move these projects to market. As a result, they found that project teams engaging in radical innovation encounter a much different set of challenges than those typically faced by NPD teams engaged in incremental innovation. These challenges address the unfamiliarity of new markets and territories, particular requirements to people and team competences, the willingness to product cannibalization, and organizational issues, as well as the search for a divisional home (McDermott and O'Connor, 2002).

2.2.2 Conceptual Frameworks

2.2.2.1 Conceptual Model of New Product Outcome

The goal of an early study of Cooper was to identify the determinants of commercial success in industrial product innovation. Therefore, 102 successes and 93 failures were studied and statistically analyzed based on a conceptual model. This model of new product outcomes (cf. Figure 11) distinguished two categories of variables that have a potential impact on new product success. These were controllable and environmental variables. The controllable variables were those that described the new product process and its output. The environmental variables described the setting in which a new product was developed. In sum, three environments were differentiated: the marketplace, the firm (resource base), and the nature of the venture e.g. its source (Cooper, 1979, pp. 125–126).

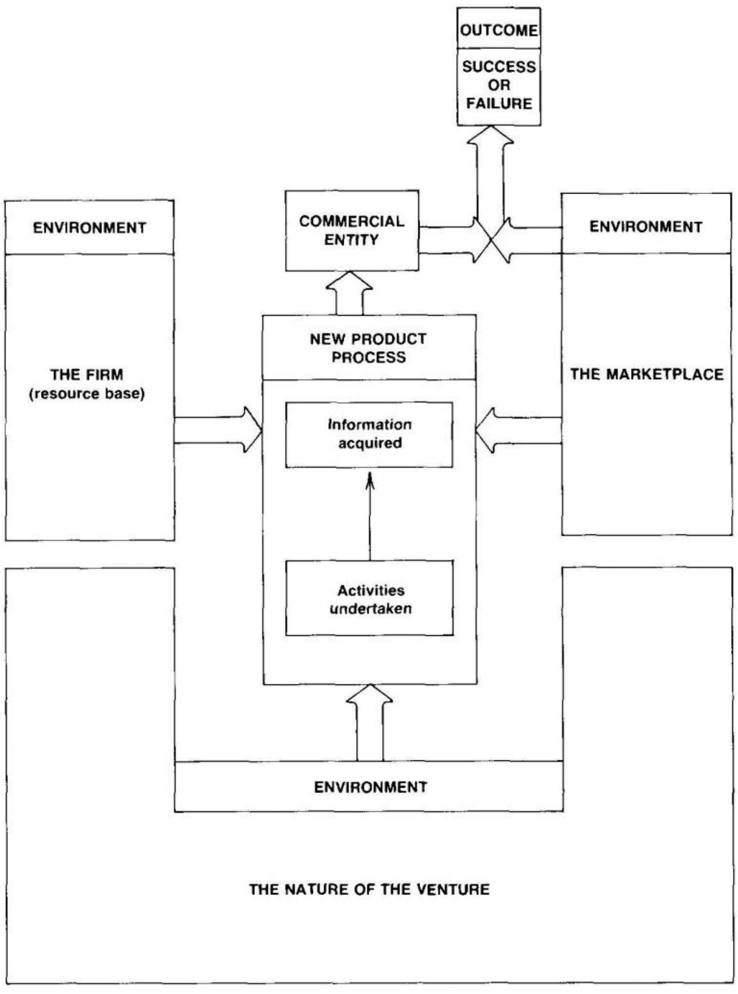


Figure 11: Conceptual Model of New Product Outcome (Cooper, 1979, p. 125)

The study indicates that the outcome of new products tends to be more dependent on variables over which the firm has control during the innovation process than on situational or environmental variables (Cooper, 1979, p. 130).

2.2.2.2 Advanced Conceptual Model of New Product Outcome

Within a follow-up study of Cooper and Kleinschmidt, Cooper's initial conceptual model of new product outcome was modified and extended. The new model (cf. Figure 12) postulated that new product outcomes are determined by the interaction of the market environment and the new product strategy and execution. The new product strategy and execution are the results of the new product process, a series of activities that move the product from idea to launch. This process takes place within a corporate environment consisting of resources, experience, and skills in marketing, production, and technology (Cooper and Kleinschmidt, 1987, p. 172).

To test this conceptual framework, a quantitative survey was conducted. Ultimately, 123 successful new products and 80 failures were studied and statistically analyzed. Besides the role of market competitiveness, all hypotheses outlined in the conceptual model could significantly be retained (Cooper and Kleinschmidt, 1987, p. 181, 1987, p. 174).

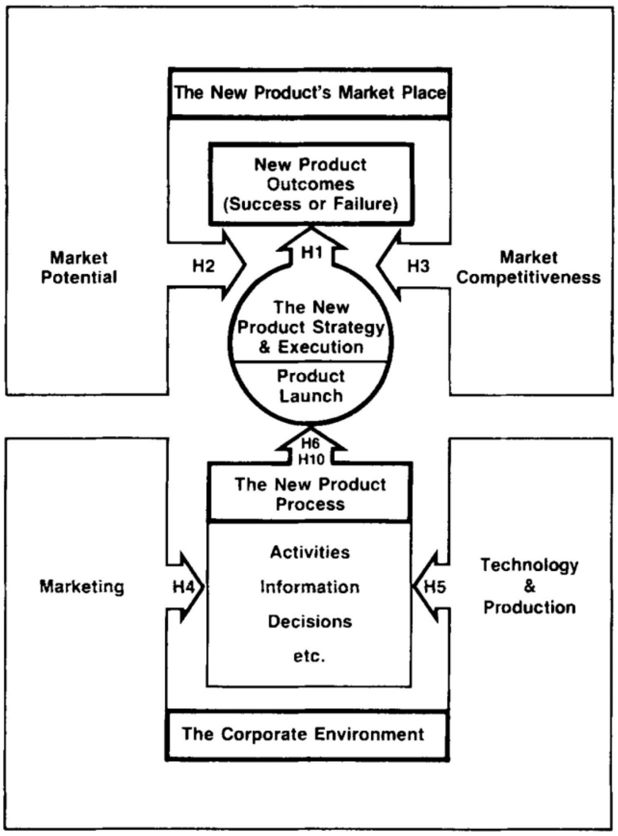


Figure 12: Advanced Conceptual Model of New Product Outcome (Cooper and Kleinschmidt, 1987, p. 172)

2.2.2.3 Integrated Framework of New Technology Ventures' Performance

Song et al. studied the factors that lead to the success or failure of new technology ventures. In doing so, they conducted a meta-analysis by scanning academic literature and collecting data from existing empirical studies (Song *et al.*, 2008, p. 7).

Based on the study's results and contemporary literature, they derived the theoretical framework shown in Figure 13. The entrepreneurial team was defined as the management team of the new venture. Entrepreneurial opportunities represent beneficial business situations in which innovations may be implemented while the entrepreneurial resources include all tangible and intangible assets that a firm may possess and control. The *strategic and organizational fit* is perceived as the congruence between strategy and organization of the new technology venture and the driving forces *entrepreneurial team, entrepreneurial opportunity,* and *entrepreneurial resource*. The framework suggests that the better the strategic and organizational fit, the better the ultimate performance (Song *et al.*, 2008, pp. 17–19).

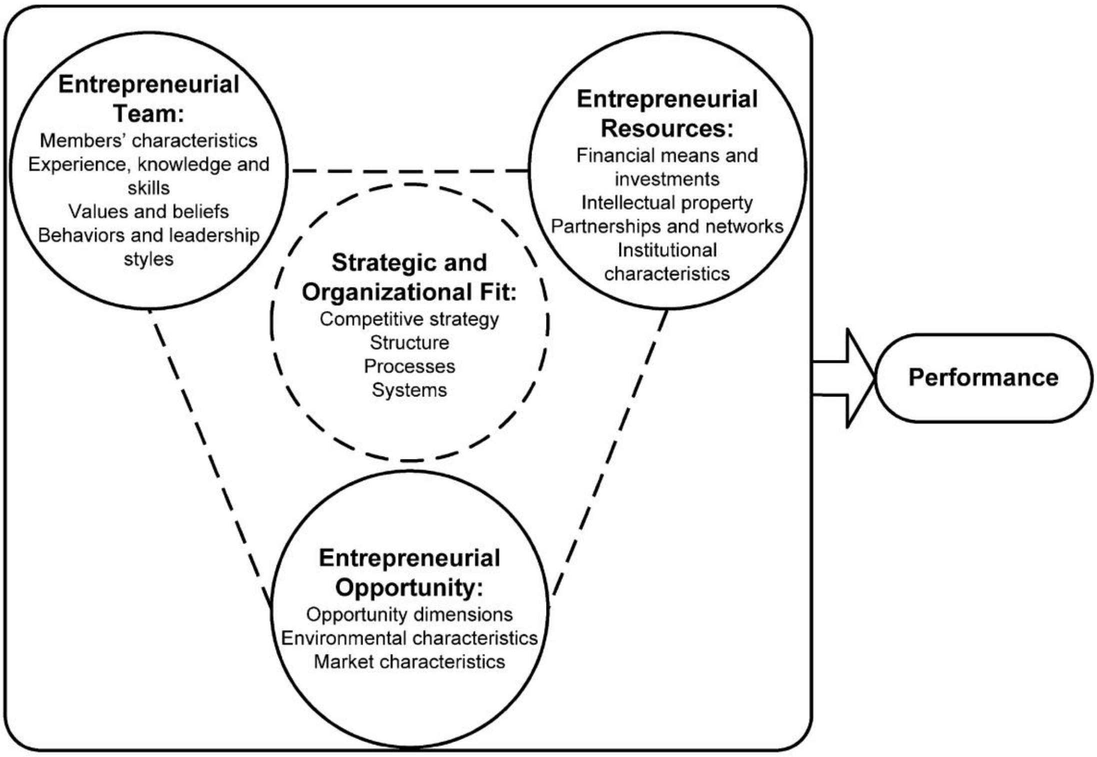


Figure 13: Integrated Framework of New Technology Ventures' Performance (Song *et al.*, 2008, p. 18)

2.2.2.4 TOE-Framework

A central model by Tornatzky and Fleischer addresses the influencing factors of adopter behavior. This model highlights the three main elements of a firm's context affecting the process by which it adopts and implements technological innovation: *technology, organization,* and *external task envi-*

ronment. Thus, it is called TOE-framework (Tornatzky and Fleischer, 1990, p. 152). Further research has demonstrated that the framework has broad applicability across a number of technological, industrial, and cultural contexts (Baker, 2012, p. 235).

The characteristics of the organization are typically perceived in descriptive terms: firm size; centralization, formalization, and complexity of the managerial structure; quality of human resources; amount of slack resources available internally; and communication processes. The environmental context is the area, in which a company conducts its business: its industry, competitors, access to resources, and dealing with the government. These environmental impacts may be critical to the capacity of a company to make innovation adoption and implementation decisions. Separately, from the rest of the environment, Tornatzky and Fleischer focused their attention on how features of the technologies can influence both the adoption process and implementation. Therefore, the availability of a particular new technology and its characteristics is decisive (Tornatzky and Fleischer, 1990, pp. 153–154).

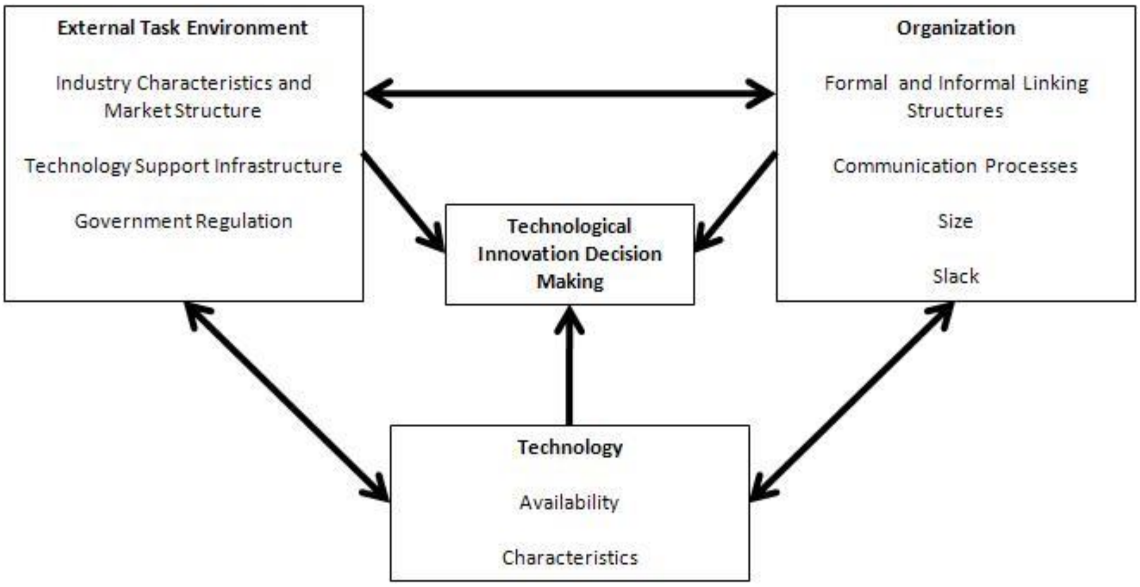


Figure 14: TOE-Framework (Tornatzky and Fleischer, 1990, p. 153)

2.2.3 Critical Review and Open Questions

The recent VDMA and McKinsey study clearly points out that there is no single formula for high profitability and growth in the German mechanical engineering industry. However, innovation is one of the ten distinct success patterns. Especially for dealing with the increased competition due to new market participants, a continuous optimization of the product portfolio is crucial (VDMA and McKinsey, 2014b). Similarly, the interviewed executives of the PwC survey perceived innovation as a driver for rapid and profitable revenue growth and as being crucial for the long-term future of their business. It becomes obvious that the claim for innovation is not just specific to the German mechanical engineering industry, but is of global relevance. Furthermore, the PwC study emphasizes that leading innovators are particularly focusing on breakthrough and radical innovations (Shelton and Percival, 2013). According to these studies, the topic of radical technological innovations within the mechanical engineering industry is highly relevant. Nevertheless, the Kienbaum study highlights the low success rate of innovative ideas. Despite the great importance of innovations, the risk of failure is high (Berth, 1993). Therefore, the question arises, what factors influence innovation success. PwC's innovation blueprint lists on an abstract level several elements influencing innovation output. These elements represent a list of best practices, rather than a description of scientifically validated success factors.

However, success factors of technological innovation have been previously analyzed in the listed scientific studies from diverse perspectives, with various focus areas, and with different research approaches. Some studies focus on concrete innovation projects and their correlated success. Thereby the studies of Abetti, Gibson and Smilor, and Souder address successful innovations to extract the key parameters of success while Cooper, Cooper and Kleinschmidt, Rothwell et al., Chiesa and Frattini, and McDermott and O'Conner address successes and failures within one study to identify the respective reasons. In contrast, Henderson, the OECD, Chandy and Tellis, and Gibson and Smilor analyzed the overall innovation portfolio of firms and sought to find out which circumstances are advantageous for the realization and subsequent success of technological innovations. However, Souder, McDermott and O'Conner, Chiesa and Frattini, and Chandy and Tellis mainly focused on the innovation process to condense the factors that are decisive at the actual implementation of innovation projects. Rothwell et al., Cooper, and Cooper and Kleinschmidt analyzed success factors of the contextual circumstances and the innovation process within one study. The research approaches used were quantitative surveys (Chandy and Tellis, Rothwell et al., OECD), case study research (Abetti, Chiesa and Frattini, Gibson and Smilor, Souder, McDermott and O'Conner), field study research (Henderson), and meta-analysis (Song).

With the outlined conceptual frameworks, the respective researchers tried to organize the success parameters for further statistical testing. In his two conceptual models, Cooper tried to distinguish success parameters that are shaped by the contextual circumstances and parameters shaped by the innovation process. Both dimensions ultimately determine success or failure. Song addressed solely the contextual circumstances for new technology ventures and their impact on the subsequent performance. The TOE-Framework of Tornatzky and Fleischer highlights the impacts of the contextual preconditions on the technological innovation decision making from the adopter perspective. The adoption by the final user of the technological innovation represents a direct precondition for the ultimate innovation success.

The analysis of these studies and conceptual frameworks showed that there are plenty of factors influencing the success of technological innovations. Some of them are controllable from within the organization (internal factors), but others are external and uncontrollable (external factors). Furthermore, the studies are non-uniform, and in some cases, they are even contradictory. Varying contexts could be the reason for the contradictory nature of some of the factors. The contexts for each individual innovation project determine the appearance or nonappearance of some factors. Correspondingly, the situational preconditions regarding the internal and external context for each individual innovation project have to be considered. Furthermore, several studies do not differentiate radical and incremental innovations. Accordingly, the meaningfulness and generalizability of these studies for the topic of radical technological innovations within the mechanical engineering industry have to be questioned (Balachandra and Friar, 1997, pp. 276–277; Vahs and Brem, 2012, p. 70).

Thus, the following questions remain open:

1. Which factors determine the innovation success of radical technological innovations within the mechanical engineering industry?
2. Which of these factors are controllable and which are not controllable by the innovation manager?
3. How do the contextual circumstances influence innovation realization?
4. Are there any patterns that can be distinguished regarding the innovation context?
5. Which recommendations for action could be derived for forthcoming innovation projects that are based on the specific contextual circumstances?

2.3 Problem Statement and Research Questions

The central research problem of this thesis is the challenge of realizing radical technological innovations within the mechanical engineering industry. Therefore, the goal is to determine, what influences the success of these innovations. The thesis creates knowledge that offers guidance for innovation managers how to best execute early stage radical technological innovations within the mechanical engineering industry. As highlighted in the state of the art review, this research problem is highly relevant and there is currently a lack of knowledge and understanding on how to deal with these innovations in a successful way.

The central research problem is divided into three sub-problems: (i) detection of critical success factors for the realization of radical technological innovations within the mechanical engineering industry, (ii) identification of innovation archetypes, and (iii) generation of an operational framework with concrete recommendations for action regarding forthcoming innovation projects. These sub-problems provide answers to the open questions outlined in chapter 2.2.3 and contribute to closing the corresponding research gap. The three sub-problems are complementary and add up to the central research problem. Accordingly, they represent a way to achieve the ultimate thesis goal in a manageable and systematic manner (Leedy and Ormrod, 2009, pp. 54–56). In the following section, the three sub-problems and corresponding research questions are outlined in detail.

2.3.1 Sub-Problem 1: Critical Success Factors

The concept of *Critical Success Factors* (CSFs) goes back to ideas of long-time McKinsey & Company managing director Ronald Daniel. He introduced the term "*Success Factors*" as those parameters that determine company success. These factors will vary depending on the nature of the industry, the size and operating territory of the company, and the acceptance by management of planning as an essential function. Nevertheless, in every case it is important for management to both formalize and regulate the collection, transmission, processing, and presentation of planning information (Boynton and Zmud, 1984, p. 17, Daniel, 1961, p. 116, 1961, p. 117; Hilgers, 2015, p. 15).

The success factor concept was further examined and refined at the MIT Sloan School of Management in the 1970s. CSFs were established as those factors that determine the key information needs for successful strategic management (Butler and Fitzgerald, 1999, p. 352). According to Rockart (Rockart, 1979, p. 85):

"Critical success factors thus are, for any business, the limited number of areas in which results, if they are satisfactory, will ensure successful competitive performance for the organization. They are the few key areas where 'things must go right' for the business to flourish. […] As a result, the critical success factors are areas of activity that should receive constant and careful attention from management."

However, CSFs should not be confused with the concept of *Key Performance Indicators* (KPIs). While CSFs form the underlying cause for success or failure, KPIs indicate the achieved success by measuring performance (BSC Designer, 2015). The latter managerial task concentrates on collecting adequate performance indicators and consolidates them into KPIs (Samsonowa, 2012, p. 41).

Especially, the realization of a radical technological innovation represents a specific challenge. Subsequently, knowing the relevant CSFs is a precondition for designing the innovation process in a successful way. Therefore, the first central research question (RQ) is:

> ***RQ 1:*** *What are the Critical Success Factors for the realization of a radical technological innovation within the mechanical engineering industry?*

Within this study, radical technological innovations are clearly targeted. Therefore, incremental innovations are not of focus. At the analysis of the CSFs, the definition of Rockart is followed. Furthermore, controllable and uncontrollable factors are distinguished, while the internal and external contextual circumstances of the respective innovations are considered. Correspondingly, the open questions 1, 2, and 3 outlined in chapter 2.2.3 are addressed by answering RQ 1.

2.3.2 Sub-Problem 2: Innovation Archetypes

In general, CSFs are rather a lens for analysis and managerial attention than concrete recommendations for action (Leidecker and Bruno, 1984, p. 23). Knowing the CSFs does not indicate how the challenge of developing and commercializing a radical technological innovation could be realized in a specific situation. Moreover, radical innovations are, in principle, unique. Therefore, the factors leading to success cannot be totally explained by one universal set of equally important factors for all situations. Depending on the contextual nature of the respective innovation projects, the relative importance of the CSFs would be different. In some situations, the innovation manager may not even have to consider several factors in detail, while other factors have to be very carefully evaluated because of their high relevance for a given combination of contextual factors (Abetti, 2000, p. 208; Balachandra and Friar, 1997, pp. 284–285). Based on the assessment of the contextual circumstances, the specific realization strategy for the respective innovation has to be formulated. In this context, the second central research question arises:

> ***RQ 2:*** *Is it possible to distinguish distinct innovation archetypes and corresponding strategies for the realization of radical technological innovations within the mechanical engineering industry that depend on the project-specific contextual circumstances?*

The term *innovation archetypes* characterizes recurring patterns that depend on the innovation-specific internal and external context and suggest a distinct realization strategy for the implementation process of radical technological innovations. Accordingly, the search for innovation archetypes has to be based on the set of context specific CSFs detected by answering RQ 1. Moreover, the concrete combination and peculiarity of these CSFs need to be analyzed. With RQ 2, the open question 4 detailed in chapter 2.2.3 is addressed.

2.3.3 Sub-Problem 3: Operational Framework

The process of realizing a radical technological innovation within the mechanical engineering industry is highly complex. In general, firms face not one, but a rich multiplicity of, possible strategies for dealing with this challenge (Utterback, 1971, p. 85). According to Bullinger, strategies express how a company utilizes its strengths to deal with an existing environment for achieving its business goals (Bullinger, 1994, p. 130). Correspondingly, it seems reasonable to base the process strategies on the specific contextual circumstances of a distinct innovation project. Therefore, it is aimed to support innovation managers with the establishment of concrete recommendations for action regarding the innovation realization strategy. This issue is addressed by the third central research question:

> ***RQ 3:*** *How can an operational framework be designed for the realization of radical technological innovations within the mechanical engineering industry which is based on the project-specific contextual circumstances and contains concrete recommendations for action?*

With the term *operational framework*, the author refers to a strategy model that supports innovation managers of forthcoming projects with the generation of an overall plan to realize their respective innovations. This operational framework should contain concrete recommendations for action that are based on the innovation archetypes derived by answering RQ 2. The RQ 3 focuses on the open question 5 outlined in chapter 2.2.3.

3 Research Approach

3.1 Methodology of Design Science

For addressing the main research problem and answering the three central research questions, the design science approach was followed as the overarching methodology. This research approach was shaped by Hevner et al. for the information systems discipline (Hevner *et al.*, 2004). However, this method proved to be highly relevant in the field of management science as well (van Aken, 2005, p. 22). The design science approach describes a problem-solving paradigm and aims to create new and innovative artifacts. According to Hever et al., design is both a process (set of activities) and a product (artifact) – a verb and a noun. Four potential artifacts are differentiated: *constructs* (vocabulary and symbols), *models* (abstractions and representations), *methods* (algorithms and practices), and *instantiations* (implemented and prototype systems). The design process is a sequence of activities to build and evaluate the artifact. With the evaluation of the artifact, feedback and a better understanding of the problem is provided in order to improve both the quality of the product and the design process. This build-and-evaluate loop is typically iterated a number of times before the final design artifact is achieved (Hevner *et al.*, 2004, pp. 75–78).

The underlying principle of design-science is that knowledge and understanding of a design problem and its solution are acquired in the building and application of the respective artifact. Therefore, Hevner et al. derived seven guidelines for the implementation of this research approach which are outlined in Figure 15.

According to Hevner et al., the design-science approach requires the creation of an innovative, purposeful artifact (guideline 1) for a concrete business problem (guideline 2). The artifact has to yield utility for the specified problem and thorough evaluation of the artifact is crucial (guideline 3). Novelty is similarly decisive as the artifact may extend the knowledge base or apply existing knowledge in new and innovative ways (guideline 4). In this context, design-science research is differentiated from the practice of design, because rigorous research methods have to be implemented for the construction and evaluation of the respective artifact (guideline 5). Design is essentially an iterative search process to discover an effective solution to the addressed business problem (guideline 6). Finally, the results of the design-science research have to be communicated effectively (guideline 7) both to a technical and a managerial audience (Hevner *et al.*, 2004, pp. 82–90).

Guideline	Description
Guideline 1: Design as an Artifact	Design-science research must produce a viable artifact in the form of a construct, a model, a method, or an instantiation.
Guideline 2: Problem Relevance	The objective of design-science research is to develop technology-based solutions to important and relevant business problems.
Guideline 3: Design Evaluation	The utility, quality, and efficacy of a design artifact must be rigorously demonstrated via well-executed evaluation methods.
Guideline 4: Research Contributions	Effective design-science research must provide clear and verifiable contributions in the areas of the design artifact, design foundations, and/or design methodologies.
Guideline 5: Research Rigor	Design-science research relies upon the application of rigorous methods in both the construction and evaluation of the design artifact.
Guideline 6: Design as a Search Process	The search for an effective artifact requires utilizing available means to reach desired ends while satisfying laws in the problem environment.
Guideline 7: Communication of Research	Design-science research must be presented effectively both to technology-oriented as well as management-oriented audiences.

Figure 15: Design-Science Research Guidelines (Hevner *et al.*, 2004, p. 83)

3.2 Application of the Design Science Research Guidelines

Figure 16 gives an overview of the conducted research approach which was composed of a mixture of qualitative and quantitative methodologies. As heuristic of this study, a secondary case study analysis was conducted to create the initial model of CSFs for radical technological innovations within the mechanical engineering industry. This CSF framework was qualitatively validated. Therefore, the framework was compared to existing literature, evaluated and adapted based on expert interviews, and validated by conducting primary case studies. The following three cases of radical technological innovations within the mechanical engineering industry were studied: P1.18 bicycle transmission by Pinion, Friction Disc by SKF, and cryogenic machining by 5ME. Afterward, the CSF framework was quantitatively validated and modified. Correspondingly, a quantitative survey was conducted and the results were statistically analyzed. Based on the survey results, distinct innovation archetypes were detected. These innovation archetypes formed the underlying basis for the extraction of the operational framework. For forthcoming innovation projects, the operational framework represents a method to derive concrete recommendations for action which are based on the project-specific contextual circumstances. Finally, the operational framework was qualitatively validated by applying it to the three conducted primary case studies.

Figure 16: Overview Research Approach (Icons designed by Freepik, 2015)

Guideline 1: Design as an Artifact

In this thesis, two fundamental artifacts were designed. These are the *CSF framework* derived by answering the first research question and the *operational framework* generated by answering the third research question. The *innovation archetypes* as an answer to the second research question do not represent an artifact, but formed the underlying basis for the establishment of the operational framework. The CSF framework represents a model while the operational framework constitutes a method.

Guideline 2: Problem Relevance

Within the mechanical engineering industry, radical technological innovations enable companies to reach strong market positions and to stand out from its rivals. The identification of CSFs for these innovations is sensible as their realization is risky, costly, and time-consuming. Therefore, the knowledge of these factors helps to reduce complexity and to focus on the main aspects of the planning, development, and implementation. Furthermore, the establishment of an operational framework for the project specific realization of forthcoming innovation projects supports companies in the successful implementation of the respective innovations (Bullinger, 1994, p. 34; Vahs and Brem, 2012, p. 68). Correspondingly, the underlying business problems of both artifacts are highly relevant.

Guideline 3: Design Evaluation

As previously outlined, the CSF framework was qualitatively and quantitatively evaluated. Accordingly, a thorough literature review, expert interviews, primary case studies, and a quantitative survey were conducted. On this basis, the CSF framework was evaluated and subsequently modified. Similarly, the established operational framework was applied to the three primary case studies and evaluated regarding its applicability.

Guideline 4: Research Contribution

By analyzing the state of the art, open questions and the corresponding research gap were derived and outlined in chapter 2.2.3. The research contribution of this thesis and similarly the two artifacts directly address this gap. Therefore, the artifacts provide a solution approach for the unsolved business problem of how to realize radical technological innovations within the mechanical engineering industry successfully and thus, extend the knowledge base in this research domain. Correspondingly, the main contribution of this thesis lies in the elaborate artifacts.

Guideline 5: Research Rigor

For the generation and evaluation of the two central artifacts, rigorous research methods were utilized. In the following chapters, the respective methods and their implementation within the study of this thesis are outlined in detail. Furthermore, the results and limitations of each research step are discussed by the end of each methodological section.

Guideline 6: Design as a Search Process

As recommended by Hevner et al., the design of the two artifacts was realized as an iterative search process. Starting with a secondary case study analysis, a first draft of the CSF framework was generated. This was iteratively reviewed, evaluated, and modified within several qualitative and quantitative research steps. The operational framework was based on the results of the quantitative and qualitative analyses. Subsequently, the operational framework was qualitatively validated by applying it to the three primary case studies.

Guideline 7: Communication of Research

The intermediate and final results of this study were documented in the form of research papers and were presented at several scientific and practitioner conferences. Furthermore, the results were presented to several management representatives of the mechanical engineering industry. On these occasions, the two artifacts were discussed and subsequently, feedback was gained. The feedback was directly integrated at the generation of the final versions of both artifacts. Chapter 1.3 provides an overview of the prepared papers.

4 Heuristics and Model Building for Critical Success Factors

In order to answer the first research question, a secondary case study analysis was initially conducted. This inductive research approach reflects the heuristics of the study at hand and forms the first step of model building for CSFs of radical technological innovations within the mechanical engineering industry. The advantage of this methodology is the ability to gain access to condensed data of projects that address the concrete realization of such innovations. Through a cross-case analysis of multiple case studies, best practices in solving problems of this particular type were extracted and thus, patterns of success for this kind of projects could be derived (van Aken, 2005, p. 25).

4.1 Methodology of Secondary Case Study Analysis

Case studies are documented in the form of written texts - completed linguistic material. Therefore, the method of qualitative content analysis was chosen as the approach follows content analytical rules and step by step models for empirical, methodologically controlled analysis of texts. This method consists of two main steps: investigation of the raw material and actual text analysis (Mayring, 2000, p. 2).

At first, it was decisive to exactly investigate the raw material. In general, three steps are basic: choosing the material to be analyzed, examining the situation-related context, and studying the formal characteristics of the material (Mayring, 1997, pp. 46–47).

4.1.1 Case Study Sample

Table 1 contains a brief summary of the selected 23 secondary case studies – the sample for analysis. The table includes the companies' names, time of analysis, region, industry, product area, and reference source. Besides of three (Lichtenstein, UK, Japan), all studies deal with cases of US-companies. This is due to the fact that the pool for cases is far bigger in the US, as case studies are systematically produced as teaching cases for US-based Business Schools. All cases are written in English and contain approximately 15 to 20 pages.

The main criteria for selecting case studies were their relevance for the focal topic: the realization of radical technological innovations. Therefore, cases were deductively chosen that deal with the development and commercialization of mainly radical technology-push innovations with a high level of novelty (e.g. 3 D-chip Design for Semiconductors, 1.3-inch Hard Disk Drive). The contemplated technologies were largely in an early stage of development but have reached, or were about to reach, application maturity (e.g. Digital Printing, Digital Imaging). Primary product innovations were focused, in particular goods, not services (e.g. Walkman, Surgical Drapes). In general, cases were suitable that went through all phases of the innovation process. Furthermore, companies with an affinity for hardware and production (e.g. 3M, IBM) were preferred.

Table 1: Summary of the Analyzed Secondary Case Studies

Company	Time	Region	Industry	Product Area	Source
Apple Computer	1975-1981	USA	Information Technologies	Personal Computers	(Gable *et al.*, 1988)
Biodel	1970-1979	USA	Biotechnology	Contract Research, Research Products	(Crowe and Maidique, 1988)
CDC	1957-1983	USA	Information Technologies	Mainframe Computers, Services	(Poel, M. van den and Burgelman, 1988)
Data Net	1984-1985	USA	Mechanical Engineering	Data Collection Terminals	(Frevola and Maidique, 1988)
IBM	1960-1975	USA	Information Technologies	Hard- & Software	(Cohen *et al.*, 1988)
PC&D	1965-1976	USA	Mechanical Engineering	Industrial Machinery	(Christiansen *et al.*, 1988)
TI	1975-1980	USA	Consumer Electronics	Hand-Held Learning Device	(Jakimo and Bupp, 1988)
Hilti	early 1990s	Lichten-stein	Mechanical Engineering	Pipe Hanger System	(Herstatt and Hippel, 1992)
Sony	1978-1991	Japan	Consumer Electronics	Walkman	(Sanderson and Uzume-ri, 1995)
HP	1991-1994	USA	Information Technologies	Hard Disk Drive	(Christensen and Rogers, 1997)
3M	mid-1990s	USA	Health Care	Surgical Drapes	(Hippel *et al.*, 1999)
3M	2000	USA	Manufacturing, Health Care, etc.	Adhesives, Materials, etc.	(Figueroa and Con-ceição, 2000)
ARM	1990-2002	UK	Semiconductor Industry	Chip Design for RISC Processors	(O'Keeffe, 2002)
3M	1997-2002	USA	Electronics	Adhesives, Chemicals, etc.	(Conceição *et al.*, 2002)
TechCo[1]	1995-1999	USA	Electronics, Telecommunication	Network Service Platform	(Pavia and Dodson, 2008)
Donnelley	1993-1995	USA	Printers	Digital Printing	(March, 2009)
Elio	1998-1999	USA	Automotive Industry	Light Weight ABTS-Seat Concept	(Sankara and Wink-mann, 2009)
Intel	2000-2006	USA	Information Technologies	Centrino Platform	(Burgelman *et al.*, 2009)
Matrix	1997-1999	USA	Semiconductor Industry	3 D-Chip Design	(Denend *et al.*, 2009)
Pixim	1999-2001	USA	Semiconductor Industry	Semiconductor-Design Based on DPS	(McVie *et al.*, 2009)
Pitney Bowes	2006	USA	Mechanical Engineering	Stamp Expressions: Amita	(Christensen and Yu, 2009)
SMaL	1999-2003	USA	Cameras	Kits for Small Consumer Cameras	(Christensen and Anthony, 2009)
Vitreon	2004-2005	USA	Automotive Industry	Hyalite: Very Strong Glass	(Shapiro, 2009)

In this first empirical phase, the mechanical engineering industry was not exclusively studied. Instead, cases of further industries and branches (e.g. Information Technology Industry, Consumer

[1] TechCo's true identity was disguised

Electronics Industry) were included. This broad approach was deliberately chosen to initially integrate impulses from other industries as well. Consequently, the analyzed cases covered various fields and industries (e.g. Health Care, Mechanical Engineering), and addressed B2B-markets (e.g. Semiconductor Industry, Automotive Industry) as well as B2C-markets (e.g. Consumer Electronics, PCs). Among the companies were small technology start-ups with less than 10 employees (e.g. Elio, Matrix), middle-size companies between 10 and 500 employees (e.g. SMal, Pixim), and major corporations with more than 10,000 employees (e.g. IBM, HP). The time slots of analyses ranged from the late-1950s until the mid-2000s. However, the companies were all technology driven so that their cases were relevant for the present research endeavor. The criteria, if the projects were perceived to be successful, have been qualitative as well: If the project has been canceled, then the case was emphasized as a failure. The first stage of success was the actual market introduction of a technological innovation; the second stage was its sustainable commercial success.

4.1.2 Data Analysis

Within the next step, the distinct analysis method had to be selected. For the detection of CSFs for radical technological innovations, the step model of inductive category development seemed to be adequate (cf. Figure 17). The developed categories corresponded to the CSFs. The central questions for analyzing the 23 selected case studies were what companies have done correctly and what they have done wrong at the realization of their innovation. Thus, the aim was to understand why companies either succeeded or failed so that the reasons for success could be generated and eventually CSFs could be derived. Hence, the criteria for the category development and the corresponding abstraction levels were determined by the definition of CSFs for radical technological innovation.

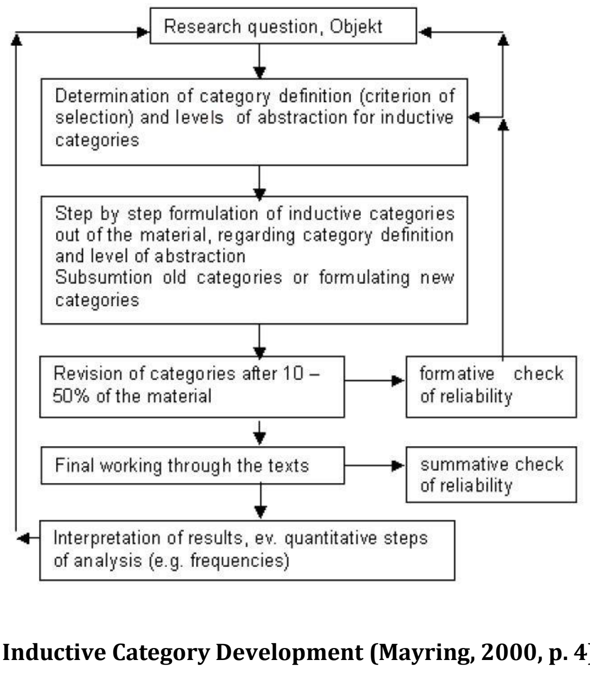


Figure 17: Step Model of Inductive Category Development (Mayring, 2000, p. 4)

Following these criteria, CSFs were tentatively identified and then further scrutinized as each case was reviewed and evaluated. The TOE-framework by Tornatzky and Fleischer (cf. chapter 2.2.2.4, Figure 14) and the conceptual models of new product outcome by Cooper and Kleinschmidt (cf. chapter 2.2.2.1 and 2.2.2.2, Figure 11 and Figure 12) were combined and used as research roadmap for the categorization of the derived CSFs. As outlined in the state of the art review, Cooper and Kleinschmidt distinguished two categories of variables influencing new product success: controllable and environmental variables. The controllable variables address the new product process and its output while the environmental variables address the contextual circumstances for the process (Cooper, 1979, pp. 125–126, 1987, p. 172). This general differentiation has been followed while analyzing the case studies. Moreover, regarding a more detailed perspective on the contextual variables, Tornatzky and Fleischer's framework was utilized and slightly modified.

Consequently, the following four perspectives were applied for the categorization of the CSFs: *technology, organization, target market, and innovation process*. The categories technology, organization, and target market reflect the environmental and the innovation process the controllable variables.

After five case studies had been analyzed, the so far derived CSFs were revised and checked with respect to their reliability. Afterward, the remaining case studies were worked through. Six iterative feedback loops were conducted to finally revise those factors, eventually, reduce them to main factors, and check their reliability (Mayring, 2000, p. 4).

4.2 Findings: The TOMP-Framework

Figure 18 gives an overview of the 25 CSFs that have been derived from the secondary case studies. As written above, these factors were matched to the four main categories: *technology, organization, target market,* and *innovation process*. Correspondingly, the framework was named Technology-Organization-Market-Process (TOMP) framework.

Compared to the Schumpeter trilogy of innovation (invention, innovation, and diffusion), the innovation process in the TOMP framework was composed of three different stages, namely *product development, market introduction,* and *diffusion*. This is due to the indications found in the case studies. Therefore, the innovation phase has been split into its two elements: product development and market introduction. Additionally, the invention phase was incorporated into the product development phase, as they are thematically closely related and difficult to separate.

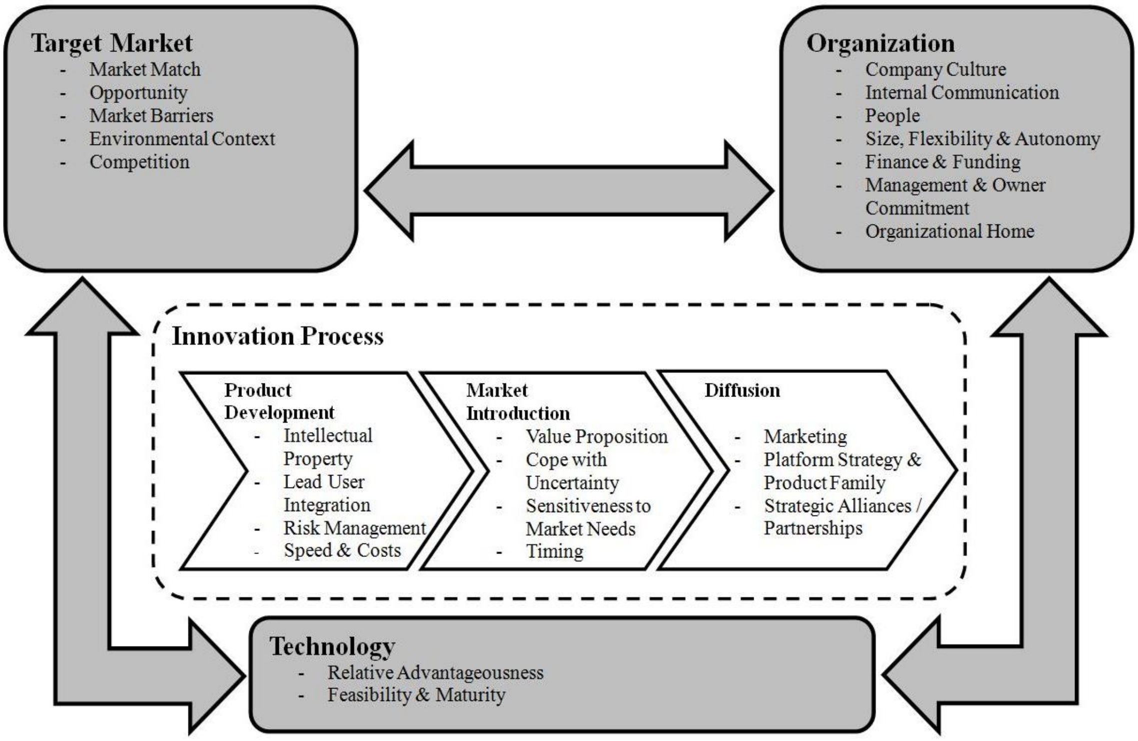


Figure 18: TOMP Framework

The universality of the induced factors cannot be totally verified due to the sample of 23 analyzed cases. However, in analyzing case studies, it is essential to show that distinct patterns repeatedly emerge in a similar form. Thus, quantitative means can potentially underpin the relevance of certain CSFs. Therefore, Table 2 delivers an overview of the concrete indications with page numbers and thus, the frequencies of the CSFs that were found in the case studies. As the indications may be difficult to read, the table has been split and reprinted in Appendix I in a larger font size.

In the following, each category and the associated CSFs will be explained. Furthermore, a concrete example from the analyzed case studies will be given that underpins the essence of the respective CSFs.

4.2.1.1 Technology

The first contextual element that determines success or failure of the innovation process is the value of the focal technology. The value a new technology offers depends on the attractiveness of a technological opportunity and the degree of difficulty a producer will encounter in exploiting it (Christensen, 1997, pp. 38–39). More precisely, the ratio of benefits to costs of obtaining the technology determines a technology's value (Schilling, 2010, p. 77). The following two CSFs addressing the technology have been derived: *Relative Advantageousness* and *Feasibility & Maturity*.

Table 2: List of Indications for CSFs Derived from Case Studies with Page Numbers

Critical Success Factors	Technology		Target Market					Organization						
	Relative Advantageousness	*Feasibility & Maturity*	*Market Match*	*Opportunity*	*Market Barriers*	*Environmental Context*	*Competition*	*Company Culture*	*Internal Communication*	*People*	*Size, Flexibility & Autonomy*	*Finance & Funding*	*Management & Owner Commitment*	*Organizational Home*
Apple - Gable et al. (1988)	267		267	260			260	262-265						
Biodel - Crowe and Maidique (1988)	174	174		181				178		177-178		173-181	178	
CDC - Poel and Burgelman (1988)			588	588	588			581		591		591-592	581	592
Data Net - Frevola and Maidique (1988)	389-404			397	407		397					389-414		
IBM - Cohen et al. (1988)	461	461-462					462-464		459	462-463	459		465	461-462
PC&D - Christiansen et al. (1988)							536-537			526-537	525-530	526-528	526-527	
TI - Jakimo and Bupp (1988)	123				116-118						120-121	120-121	122	120-121
Hilti - Herstatt and Hippel (1992)		219												
Sony - Sanderson and Uzumeri (1995)	769			761	780		778		775		770-780			770-780
HP - Christensen and Rogers (1997)	1		6-8	5-6			2-3; 7			4-18	2-4	4	2	
3 M - Hippel et al. (1999)				51-54										
3M - Figueroa and Conceição (2000)						99		101	94-102		94-103			
ARM - O'Keeffe (2002)	9; 17	5		6-7; 17	11		4	15	15					
3M - Conceição et al. (2002)				34-37		29		31-33	33	33	27-29		30-31	
TechCo - Pavia and Dodson (2008)	152		128-151				152			127-128	131-137	128	151	
Donnelley - March (2009)			912	904-906							910			
Elio - Sankara and Winkmann (2009)	14-16	14; 30	18	15	28-29		19-28							
Intel - Burgelman et al. (2009)	1140-1141				1155	1155				1148			1156-1157	
Matrix - Denend et al. (2009)	108	108	108-119	114-119							120			
Pixim - McVie et al. (2009)	78-81		86-90											
Pitney Bowes - Christensen and Yu (2009)	878		882; 887	884		878-885	887			883				883
SMal - Christensen and Anthony (2009)	351; 359		352		352		359							
Vitreon - Shapiro (2009)	1017-1018	1018		1014	1018		1018	1013		1020-1021				1014
SUM of Indications	16	7	10	14	9	4	12	7	5	10	10	7	9	6

Critical Success Factors	Innovation Process: Product Development				Market Introduction				Diffusion		
	Intellectual Property	*Lead User Integration*	*Risk Management*	*Speed & Costs*	*Value Proposition*	*Cope with Uncertainty*	*Sensitiveness to Market Needs*	*Timing*	*Marketing*	*Platform Strategy & Product Family*	*Partnerships / Strategic Alliances*
Apple - Gable et al. (1988)		260			257-259				266-267	267	261
Biodel - Crowe and Maidique (1988)	179-180		184		175-176	184					
CDC - Poel and Burgelman (1988)											585-588
Data Net - Frevola and Maidique (1988)				404-408	404		397-407	404	408-409		
IBM - Cohen et al. (1988)				461				464	459		
PC&D - Christiansen et al. (1988)											
TI - Jakimo and Bupp (1988)				122; 127	114; 123				122-123		
Hilti - Herstatt and Hippel (1992)	218	213-215		213; 220			218-219				
Sony - Sanderson and Uzumeri (1995)			780	762; 777	762-763		775-777	762	772-773	769-771	
HP - Christensen and Rogers (1997)			8-10	4	1	1-8	7	8	8		
3 M - Hippel et al. (1999)		48-49					51-54				
3M - Figueroa and Conceição (2000)											
ARM - O'Keeffe (2002)	4-5		4-6		1				1-4	13	5-10
3M - Conceição et al. (2002)	31	32					32				
TechCo - Pavia and Dodson (2008)					134-135	148	136		127-128	136-139	
Donnelley - March (2009)				903-905	905-910		906		910		
Elio - Sankara and Winkmann (2009)	16		29-30	30	14-18						29
Intel - Burgelman et al. (2009)				1156-1157	1153		1140; 1156	1155-1157	1155-1157		1155
Matrix - Denend et al. (2009)	111; 119-120				119	114			119		120
Pixim - McVie et al. (2009)			86		86	86					85
Pitney Bowes - Christensen and Yu (2009)		883-884			886	884	883-884		883		
SMal - Christensen and Anthony (2009)				357	350-360				357		357
Vitreon - Shapiro (2009)					1017-1018						
SUM of Indications	5	5	6	10	16	6	10	5	13	4	8

Relative Advantageousness – Relative advantage is the degree to which a new technology is perceived to be better than the incumbent technology it would replace (Rogers, 2003, p. 15). This advantage could contain economic benefits to the adopter or better performance (Byers *et al.*, 2010, p. 268). Successful technology commercialization depends on the advantageousness of the central technology. Only if the adopters gain a significant advantage they would be willing to adopt it.

In their case study of Matrix, Denend et al. highlighted the relative advantage of the 3D-chip technology for semiconductors. Traditionally, chips were developed in two dimensions. To improve the performance, engineers expanded the area of each chip. In the case of 3D-chips, functional transistors were placed on multiple layers of a single chip and thus, dramatically increased the density of circuits on the chip. Since the price of silicon was roughly proportional to the area (not the volume) consumed per chip, this has a significant impact on the semiconductor cost model (Denend *et al.*, 2009, p. 108).

Feasibility & Maturity – The degree of difficulty a producer will encounter in exploiting its technology will be a CSF for technological innovation (Christensen, 1997, pp. 38–39). This depends on the feasibility & maturity of the technology. As technologies are better developed, learning-curves and scale advantages accrue, and the technologies become more certain and useful to users, facilitating their adoption (Schilling, 2008, pp. 57–58). In general, the technology in question must have a higher benefit-cost-ratio than the technology to be replaced (Keinz and Prügl, 2010, p. 274).

Shapiro described in his case study of the Vitreon Corporation the Hyalite technology. By using an innovative glass-forming and coating process, Vitreon produced a specialized automotive glass and attained a strong market position. The process itself was very complex, hard to control, and subsequently quite difficult. Thus, the technology was mature, but its feasibility was closely linked to the involved personnel. When several process experts left the company, Vitreon faced tough problems that resulted in a significant sales decline (Shapiro, 2009, pp. 1014–1021).

4.2.1.2 Target Market

The first element shaping the context for the innovation process is the target market. According to Utterback, market factors appear to be the primary influence on technological innovation (Utterback, 1974, p. 621). The decisive question in technology commercialization is to find a target market that values the characteristics of the focal technology. Hence, this is a marketing challenge, not a technological one (Christensen, 1997, pp. 208–209). The following market-related CSFs were identified to be crucial for the success of radical technological innovations: *Market Match, Opportunity, Market Barriers, Environmental Context,* and *Competition*.

Market Match – The experience of technology driven companies shows that an extraordinary technical idea or solution will not coercively lead to commercial success (Bullinger, 1994, p. 85).

For utilizing a new technology an adequate market has to be identified at first. Therefore, the results of technology development have to be matched to a market need or a new market has to be developed for them (Ullman, 2003, p. 69). The ability to identify and exploit opportunities is seen as a major driver of the potential market success (Henkel and Jung, 2009, p. 1).

With the case study of SMaL Camera Technologies, Christensen and Anthony pointed out that a strategic selection of the target market is essential for success. The company, building kits for ultra-small cameras, decided to serve the market for consumer cameras first. It then planned to address the security and surveillance market with the long-term vision of selling to the automotive industry. The automotive opportunity seemed to be the largest, but due to long lead times within this industry, the chances of overall success for SMaL were supposed to be higher when firstly taking the other two options (Christensen and Anthony, 2009, p. 352).

Opportunity – An opportunity is a timely and favorable juncture of circumstances providing a good chance for market success (Byers *et al.*, 2010, p. 26). As developing innovations usually require an extensive amount of capital investment, identifying an adequate market opportunity is essential to recover these costs and to become profitable (Ullman, 2003, p. 69). Choosing the right opportunity depends on the question where the best chances for success are available within the context of the marketplace (Byers *et al.*, 2010, p. 36).

O`Keeffe reported in her case study of a great market opportunity for ARM that determined the company's global success. Nokia did not emphasize the microprocessor as a key differentiator for their products. Thus, ARM had the chance to become the defacto global standard for microprocessor designs as Nokia did not care that its competitors were using the same design. ARM was able to license its design to a huge range of customers from different markets and industries (O'Keeffe, 2002, p. 17).

Market Barriers – The access to markets can be hampered by existent market barriers. Dependent on the industry, the obstacles can differ. Some of these barriers are spontaneous or sudden while others are purposefully designed by established companies to prevent others from stepping in. According to Kotler, the main market barriers are economies of scale, high capital demand, patent situation, image requirements, and lack of appropriate locations, resources or suppliers (Kotler *et al.*, 2007, p. 1092).

The case study of Elio Engineering Inc. by Sankara and Winkmann serves as a good example of how market barriers could affect the opportunities of technology driven companies. Elio developed a seat design which was easier to use, had a higher comfort level, and was potentially safer (Sankara and Winkmann, 2009, p. 16). OEMs within the automotive industry emphasized reliability and standardized processes combined with certification norms and thus, prefered to deal with only a very limited number of suppliers. Hence, it was extremely difficult for a new entrant like Elio to compete with the incumbent companies (Sankara and Winkmann, 2009, pp. 28–29).

Environmental Context – As companies are acting in an environment which is influenced by parameters that are not controllable by the firm itself, they have to be very sensitive to these impacts at the point of strategic decision making (Kerth *et al.*, 2007, p. 117). At analyzing the environmental context, six components are essential: political, economic, social, technological, legal, and environmental influences (Kotler *et al.*, 2007, p. 237).

Christensen and Yu reported on Pitney Bowes, a company that developed a postage printer called "Stamp Expressions". The printer was supposed to be owned by individuals as a more convenient alternative to postal stamps and allowed customers to print-on-demand postage in their homes or offices that featured their own corporate logos or photographs (Christensen and Yu, 2009, p. 878). Historically, U.S. regulations have prohibited individuals from owning a postal value storage device. Therefore, the company had to negotiate with the U.S. Postal Service as it was dependent on their permission (Christensen and Yu, 2009, p. 885).

Competition – To be the main party to reap the benefits of a technology the innovating company has to be carefully aware of existent and emerging competition in the target market. If the technology proves to be valuable, it is just a question of time until competitors will enter the market (Schilling, 1998, p. 277). Being aware of competition could help to increase warning times before competitors would introduce competing innovations (Brockhoff, 1991, p. 91).

With the case study of SMal, Christensen and Anthony gave a vivid example of how competitors could affect a company's business. The MIT spin-off proved with its credit card-sized camera that a market existed for very small cameras. Soon after the first successes, competitors entered the field and forced SMal to change their strategic direction (Christensen and Anthony, 2009, p. 359).

4.2.1.3 Organization

The organization itself can facilitate or hamper the innovation process due to several internal characteristics, including its resources, personnel, and patterns of communication and decision making (Utterback, 1974, p. 621). Some of these characteristics are formal and represent the way an organization divides its labor into distinct tasks while others are informal through their naturally occurring behavioral patterns (Tornatzky and Fleischer, 1990, pp. 154–155). As radical technological innovations pose particular challenges to an organization, the following CSFs have been derived that address the organizational context: *Company Culture, Internal Communication, People, Size, Flexibility & Autonomy, Finance & Funding, Management & Owner Commitment,* and *Organizational Home.*

Company Culture – Company Culture is the sum of values, beliefs, codes of conduct, and mindsets within the company (Vahs and Brem, 2012, p. 191). It represents the collective personality of a company and predetermines its basic attitude towards innovation (Birkenmeier and Brodbeck, 2010, p. 27). Consequently, an innovation-friendly company culture is fundamental for the successful realization of technological innovations. Therefore, an open atmosphere, areas of freedom for the innovators, and a climate of risk tolerance has to be created (Vahs and Brem, 2012, p. 190).

Around the globe, 3M is recognized as one of the world's most innovative companies. The reasons are closely linked to the company's innovation-friendly culture. To promote the innovative spirit, the 3M management cultivates a climate of informality, failure tolerance as part of the innovation process, entrepreneurship and intrapreneurship, and technology exchange within the company. This is formally manifested by the 30% and the 15% rule. 30% of 3M's sales must result from products introduced in the last four years and technical people are allowed to spend 15% of their time on their own projects (Conceição *et al.*, 2002, pp. 30–32).

Internal Communication – The innovation process is a highly uncertain endeavor. Hence, there is a need for an intensive information exchange across disciplinary and functional boundaries to evaluate and respond to new and often unforeseen technical and market circumstances (OECD, 1971, p. 13). Especially at product development, a lack of internal communication can be extremely unfavorable and can subsequently lead to a poor fit between product attributes and customer requirements (Schilling, 2010, p. 266).

Correspondingly, O'Keeffe reported of ARM's perception that oiling the wheels of internal communication is one of the keys to successful innovation (O'Keeffe, 2002, p. 15).

People – The employment of a technological innovation is strongly dependent on the involved people. Firstly, technological knowledge is mainly person-embodied. Secondly, in the meanwhile successful innovations are not due to genius inventions of individuals (OECD, 1971, p. 16), but due to the cooperation of integrative development teams (Vahs and Brem, 2012, p. 204). Hence, the appropriate composition of team members depends on specialist knowledge on the one hand, and on the personalities of the individuals on the other hand (Schilling, 2010, pp. 267–268).

In the case study of HP's attempt to commercialize the 1.3-inch hard disk drive, the team was composed of risk takers with a strong can-do attitude. Though the project failed, none of the team members was laid off, as the company attested that they performed well (Christensen and Rogers, 1997, p. 18).

Size, Flexibility & Autonomy – As uncertainty is high in the case of radical technological innovations, the ability to respond to market needs in a flexible manner is decisive. Flexibility within product development is closely linked to company size (Schilling, 2008, p. 91). In the case of large organizations the danger of too much bureaucracy which hampers flexibility and the ability to respond rapidly to market needs, is factual (Vahs and Brem, 2012, p. 82). Christensen stated that the only instances in which mainstream firms have successfully established a timely position in a radical, disruptive technology were those in which the firms' managers set up an autonomous organization in charge of building a new and independent business for the disruptive technology (Christensen, 1997, p. xix). Large organizations strive for efficiency and well-defined processes. However, true innovations, as a rule, and supported by research in the field, do not evolve within tight structures and hierarchies. Thus, for commercializing technologies either the technology needs to be spun out or a fully autonomous organization within the parent company has to be established (Holzschuher and Pechlaner, 2007, p. 45).

Christiansen et al. underlined in their Case Study of PC&D Inc. that employing a distinct business idea or technology affords flexibility at research and development efforts. To reach this aim, PC&D Inc. followed a strategy of setting up small, independent subsidiaries to leverage technology commercialization. Especially regarding decision making, this has been an effective approach (Christiansen *et al.*, 1988, pp. 528–529).

Finance & Funding – One fundamental issue to the overall innovation process is finance & funding as financial capital is one of the elementary resources enterprises need to operate (Cassar, 2004, p. 261). If the technology remains within the company, funding is generally realized by the parent company. However, involving the executing staff in funding could increase the entrepreneurial spirit of these people and raise their motivation to bring the project to success. In the case of spin-offs or start-ups, these companies need to acquire investors or take on debt or equity. This should be considered carefully due to the fact that capital decisions and the use of debt and equity during the ramp-up phase have important implications for business operations, firm performance, the risk of failure, and the potential of business expansion (Cassar, 2004, p. 263).

Poel and Burgelman described with their case study of the computer company CDC how CDC tried to handle the funding of their corporate spin-offs. The company facilitated a number of spin-offs in high-technology fields to stimulate new businesses. Therefore, CDC wanted to retain some interest within the spin-offs but help the entrepreneurs by providing them significant freedom (Poel, M. van den and Burgelman, 1988, p. 581). Consequently, those spin-offs were funded by a CDC minority participation and a venture capital group created for that purpose (Poel, M. van den and Burgelman, 1988, p. 591).

Management & Owner Commitment – Management commitment or in the case of a spin-off or start-up investor commitment is important for the success of any strategy. For the innovation process this appears to be even more relevant (Saleh and Wang, 1993, p. 15). In the face of high uncertainties and long-time horizons, technological innovations open up specific challenges. Therefore, top management's commitment, especially regarding risk taking, is needed (OECD, 1971, p. 13). By investing into a new technology the managers or investors show initial commitment, but beyond that deep support, cautiousness, and goodwill are required to reach market maturity and commercial success (Meier, 2007, p. 282).

Before the very successful Centrino-launch, Intel's platform addressing the mobile computer market, Centrino managers wanted to create a buffer in case demand exceeded expectation. As the production of Pentium 4 had to be reduced it was a question of manufacturing capacity. Intel's top management supported the Centrino project. This was a real proof of confidence because the product was new and the demand could not be accurately predicted (Burgelman *et al.*, 2009, pp. 1156–1157).

Organizational Home – For technologies that are not totally spun out, but stay e.g. as an autonomous division within the parent company, there eventually comes a time to decide where in the organization they should be integrated. To fully reap the benefits of a technology, an adequate organizational home must be found. Thereby, the difficulty is that potentially game-changing technologies are not underresourced if they do not fit the company's current infrastructure (O`Connor and DeMartino, 2006, p. 487).

Christensen reported on an 'orphaned' technological innovation within the postage meter company Pitney Bowes. The company developed a document management solution for hospitals that significantly increased hospital profitability, but as no adequate organizational home was found, the project was abandoned (Christensen and Yu, 2009, p. 883).

4.2.1.4 Innovation Process

Besides the context for radical technological innovations, the innovation process itself has naturally a great impact on success or failure. While less successful organizations treat the innovation process as a series of separate steps that cannot be tightly managed, the leading organizations view the process as a set of action demanding high discipline (Nevens, 1990, p. 21). Due to the fact that the process is not unidirectional, different sets of functions, activities, and networks must occur simultaneously to overcome obstacles and barriers (Gibson and Smilor, 1991, p. 292). As written above, the innovation process contains the stages *product development, market introduction,* and *diffusion*.

Product Development

Within the product development stage, the following CSFs for radical technological innovations have been identified: *Intellectual Property, Lead User Integration, Risk Management, and Speed & Costs*.

Intellectual Property – A crucial element is the question whether, and to what extent, a firm should protect its intellectual property. To be the first to benefit from a technological innovation's rewards, a company has to plan carefully its protection strategy. If a firm neglects the protection of its innovation, competitors could easily imitate and benefit from it. On the other hand, not to vigorously protect an innovation can help to increase its diffusion and support the establishment of a dominant design position (Schilling, 2008, p. 182).

Denend et al. described in their case study the intellectual property strategy of Matrix, a company that developed 3-D semiconductor chips. Matrix aggressively filed for a broad patent protection across the 3-D semiconductor space and therewith protected multiple generations of its products. Thus, the company could license its technology to other companies and gain royalties if it would decide not to actively address all of the areas it has ultimately protected (Denend *et al.*, 2009, p. 111).

Lead User Integration – In the case of radical technological innovations conventional market research methods face limitations (Herstatt and Hippel, 1992, p. 213). To overcome these obstacles, Eric von Hippel created a method to integrate lead users in the product development process. In his definition, lead users display two significant characteristics: They face needs earlier than other users and they benefit significantly by obtaining a solution to those needs (Hippel, 1986, p. 796). By integrating them into the product development process, the probability of success will be higher.

Christensen reported that Pitney Bowes a U.S. postage meter company made very positive experience with their customer-centered approach which was heavily influenced by Eric von Hippel's method for finding new growth opportunities. Their approach focused on understanding emergent and unspoken customer needs and values by using prototypes (Christensen and Yu, 2009, pp. 883–884).

Risk Management – Risk is the chance or possibility of loss with regard to financial, physical, or reputational issues (Byers *et al.*, 2010, p. 138). Introducing a radical technological innovation into the market means to be in a high-risk, low-data state (Moore, 2005, p. 90). Correspondingly, the risk of failure is high and thus, the need for strategic risk management is obvious. By constantly asking about potential challenges to the product, the brand, and its business model, a company can effectively manage risks (Byers *et al.*, 2010, p. 156).

O'Keeffe described how ARM managed their biggest risk in their business. By licensing its chip designs to semiconductor companies, the fate of ARM was in the hands of its customers (O'Keeffe, 2002, p. 5). The company knew that it needed partnerships to get the ARM chip design embedded into end products. Thus, ARM strategically chose its partners and similarly cooperated closely with market-leading OEMs (O'Keeffe, 2002, p. 8).

Speed & Costs – The main impacts on the efficiency of the product development process are speed and costs. Time-to-market becomes increasingly an important parameter for the commercial success of innovations, as the length of product life cycles generally decreases. Hence, the period in which investments can be earned back diminishes. Furthermore, within product development, a great portion of the costs will be determined by the product design and consumed by the development process itself. Therefore, product development is from a cost-perspective a very important phase (Bullinger, 1994, p. 118), (Verburg *et al.*, 2005, p. 8).

The Sony Walkman case study by Sanderson and Uzumeri can serve as a good example for efficient product development. By their platform strategy, Sony managed to realize design changes at a very low-cost level, that Sony only needs to sell 30,000 units worldwide to break even on a new model (Sanderson and Uzumeri, 1995, p. 777). Additionally, Sony was consistently faster than its competitors in getting new models to market. This capability enabled Sony to occupy a leading position over decades (Sanderson and Uzumeri, 1995, p. 761).

Market Introduction

The market introduction stage is shaped by these CSFs: *Value Proposition, Cope with Uncertainty, Sensitiveness to Market Needs,* and *Timing*.

Value Proposition – The central element of a company's market offer is its value proposition (Osterwalder *et al.*, 2010, p. 22). Wouters defines value in business markets as the worth in monetary terms of the technical, economic, service, and social benefits a customer company receives in exchange for the price it pays for a market offering. The best way to understand customer value is to compare it to the next-best alternative (Wouters, 2009, p. 1028).

With the establishment of the digital division, Donnelley & Sons, one of the world leading companies in the commercial printing business, offered their customers a totally new value proposition. Traditionally, a printing order was linked to high fix costs which could be abolished through digital printing. Donnelley became much more flexible especially for short runs and was able to get significantly higher margins therewith (March, 2009, pp. 905–910).

Cope with Uncertainty – Especially in the early stages of the innovation process, uncertainty is high. Both emerging and pacing technologies are characterized by vague competitive impact and their final application areas may not be apparent (Schilling, 2008, p. 54), (Bullinger, 1994, p. 96). Traditional management methods relying on a stable business environment are inadequate. Just to trust on planning and forecasting without any customer feedback during the commercialization phase may be fatal and lead to failure (Ries, 2011, p. 9).

The case of HP, as reported by Christensen and Rogers, represents an impressive example of how a company failed to deal with uncertainty. HP formed a team to develop a revolutionary 1.3-inch 20MB drive which was code-named Kittyhawk. The team focused on the PDA market and thus, followed a thoroughly derived requirements list. The Kittyhawk-drive was developed on time and introduced in the schedule, but the PDA market never emerged as expected (Christensen and Rogers, 1997, pp. 1–8). In retrospect, the HP project managers view their faith on the initial market forecasts as their biggest mistake. Given a second chance, they would choose a more exploratory, flexible approach toward product design (Christensen, 1997, p. 153).

Sensitiveness to Market Needs – Numerous companies offered technologically advanced products but have failed to match customer requirements and were subsequently rejected by the market (Schilling, 2010, p. 240). Thus, sensitiveness to market needs is a decisive success parameter for technological innovations especially as uncertainty is high.

Conceição et al. described in their case study 3M's strong commitment to developing products driven by the marketplace and the company's emphasizing on sensing market needs. In order to create products that really satisfy the customer needs, both sales representatives and technical people had to be in frequent contact with the customer where the products being used (Conceição *et al.*, 2002, p. 32).

Timing – To profit fully from technological innovations requires finding the appropriate time to launch (Jolly, 1997, p. 320). The optimal timing of entry is a function of several factors, including the degree of advantage, the state of enabling technologies, the customer expectations, the competitor's position, and a firm's resources (Schilling, 2010, p. 104).

Burgelman et al.'s case study of the Intel Centrino launch contributes to the CSF of timing. The company feared losses upwards of hundreds of millions of dollars as the Centrino's launch had to be delayed from January to March 2003 due to the fact that the wireless component was not shippable. As the wireless component was one of the key components of their Centrino platform, Intel decided to postpone the launch. Subsequently, the platform was very successful (Burgelman *et al.*, 2009, pp. 1155–1157).

Diffusion

For the diffusion stage, the subsequent set of CSFs were defined: *Marketing, Platform Strategy & Product Family, and Strategic Alliances / Partnerships*.

Marketing – Good technological innovations do not usually sell themselves (Gibson and Smilor, 1991, p. 291). Thus, appropriate marketing is essential to recover the efforts made for product development and to become profitable. In general, marketing means taking actions to create, grow, maintain, or defend markets (Moore, 2005, p. 28). When designing the marketing plan, the firm must take into account both the characteristics of the innovation and the characteristics of the market (Schilling, 2008, pp. 293–294).

In their case study of the Data Net Corporation, Frevola and Maidique described how the company marketed its product – a Factory Data Collection Terminal (Frevola and Maidique, 1988, p. 389). The company sold the first systems with a 100% money-back guarantee if the system did not work to gain trust in the conservative manufacturing market. Data Net chose a direct sales strategy and promoted their product through trade shows, targeted advertising and a direct-mail campaign that finally led to huge commercial success (Frevola and Maidique, 1988, pp. 407–409).

Platform Strategy & Product Family – To commercialize a technology and exhaust all success from it, an elaborate platform strategy is essential. This is the basis for deriving a well-organized product family which builds the offer of a company to its market. A firm can take advantage of its platform and component commonality by sharing parts between its end-products. Nevertheless, products can be effectively differentiated in the eyes of the customer by e.g. various designs, equipment, and performance categories (Dahmus *et al.*, 2001, p. 409).

An outstanding example of an exceptional platform and portfolio management is covered in the case study of the Sony Walkman served by Sanderson and Uzumeri. In the 1980s, Sony offered almost 250 models just in the U.S. market. With the platforms as a basis, only small changes in features, packaging, and appearance were needed to create these models (Sanderson and Uzumeri, 1995, p. 770).

Strategic Alliances / Partnerships – The establishment of strategic alliances and partnerships could help a company to employ a technological innovation successfully. Partnerships are composed of the company's network of suppliers, customers, and partners. The aim is to utilize the synergy potential between the partners and to reduce costs, risks, and development time (Vahs and Brem, 2012, p. 84).

For commercializing the Wi-Fi-Technology which was the key element of the Centrino platform, Intel was dependent on two important partners: the hot-spot location owners and the Wi-Fi service provider. Hence, to guarantee broad Wi-Fi-availability for its laptops, Intel cooperated closely with airports and hotel chains as the majority of the users were corporate employees at the time of the Centrino-launch (Burgelman *et al.*, 2009, p. 1155).

4.3 Discussion and Limitations

In general, the two decisive criteria determining the quality of research undertaken are reliability and validity. Reliability describes the stability and accuracy of the measurement while validity reflects if it has been measured what was intended. Within the secondary case study analysis, reliability was reached by iterative feedback loops to check and revise the induced CSFs. To fulfill the criteria of validity, the case studies have been selected carefully (cf. Chapter 4.1.1). One fact additionally contributing to the achievement of validity with respect to construct validity is that all CSFs found in previous studies (cf. Chapter 2.2) have been detected by our analysis as well (Mayring, 2010, p. 116).

Essentially, theory generated from case studies is rich in detail about specific phenomena but lacks the simplicity of an overall perspective. The risks are that the theory describes a very idiosyncratic phenomenon and is thus, difficult to generalize (Eisenhardt, 1989, p. 547). However, analyzing multiple case studies has the advantage to gain access to condensed data of several radical technological innovation projects. 23 cases of companies with various sizes from different fields and industries that addressed different markets have been analyzed. Obviously, the cases are disparate in nature, but the involved companies were all technology driven and the cases fulfilled the initially described criteria for case selection. Correspondingly, this disparate set enriches the theory generalization as various fields are covered that all face a similar challenge. Thus, the capability for theory generalization rises with this case compilation as this cross-case analysis delivers success patterns in the domain of consideration. Nevertheless, one limitation of the chosen approach is the retrospective nature of the analyzed case studies. Hence, the processes have probably been viewed and reported as much more rational and well-ordered than they were in fact (Utterback, 1974, p. 625).

5 Qualitative Validation of Critical Success Factors

5.1 Literature Review

Linking scientific results to literature is important in most research, but it is particularly crucial to building theory based on case study research. Case study findings often rest on a very limited number of cases and the strength of the results can be supported and further validated by a link to existing literature (Eisenhardt, 1989, pp. 544–545). Similarly, because the TOMP framework is based on the analysis of only 23 case studies, a thorough literature review is critical.

5.1.1 Methodology

The comparison of generated theory with existent literature involves analyzing similarities, contradictions, and their underlying reasons. Conflicting literature is important for two reasons: first, the reader`s confidence might be reduced if conflicting findings would have been ignored by the researcher (a challenge of internal validity) or the reader may assume that the findings are idiosyncratic to the specific sample of the study (a challenge of generalizability). Second, the juxtaposition of conflicting literature represents an opportunity for researchers as they are forced to thoroughly question their findings to potentially achieve sharper theory and finally better results. Confirming results, on the other hand, is important as it ties together similarities of phenomena normally not associated with each other. Hence, the applicability of the underlying theory may be enlarged (Eisenhardt, 1989, pp. 544–545). In summation, comparing the TOMP framework with the existent literature corroborates its internal validity and generalizability for conflicting as well as for confirming results.

Taking the TOMP framework as a reference model and research guide, a structured and focused literature review of eleven standard books on the topic of radical technological innovation was conducted. With this approach, the aim was to compare, complement, and clarify the set of CSFs detailed in the TOMP framework.

The central research questions for the literature review were the following: Which factors are mentioned in the literature to be critical for the success of radical technological innovations? Are these factors congruent to the compiled set of CSFs in the TOMP framework? Are any factors missing or superfluous? Is there any distinction made between CSFs that are influenced by the innovation context and CSFs that are influenced by the innovation process? Do the four main categories of the TOMP framework (technology, organization, target market, and innovation process) serve as a sound classification of the relevant CSFs?

To answer these questions, the focus was laid on secondary literature, in particular, books. Books and monographs are written for specific audiences. Academic books follow an especially theoretical slant and provide a thorough overview of the state of research within a defined scope. The material is usually presented in a more ordered and accessible manner than it is in journals. Therefore, books are particularly useful when it comes to a comprehensive analysis of a complex topic – such as the realization of radical technological innovations (Saunders *et al.*, 2012, p. 88).

5.1.1.1 Sample of Books

Before conducting the focused literature review outlined in this chapter, a large number of academic textbooks that address the topic of technology and innovation management was checked for relevance. As it is impossible to review every single piece of literature, the purpose was to study the most relevant books that stress the central topic in the best way. For selecting appropriate books, clearly defined criteria were followed to evaluate the books' relevance. This included a consideration of the subject area, the overall quality, the literature type, the language of publication, the geographical area, and the publication period. The set of the ultimately selected books contains the most suitable books with respect to these criteria. To assess sufficiency, it was iteratively checked what constitutes an acceptable amount of content, in terms of both quality and quantity (Saunders *et al.*, 2012, p. 108, 2012, p. 115, 2012, p. 74, 2012, p. 91).

Finally, eleven books were chosen that address the topic of technology and innovation management on a holistic base and in a way that they have been adopted as academic standards for the aforementioned topics (cf. Table 3). The chosen books were published from 1978 until 2013 in the USA, UK, and Germany. Ten of the eleven books were written in English. The book written in German was deliberately added to at least take into account the German-speaking scientific literature. Timeless factual-books (e.g. Kelly and Kranzberg, 1978, Christensen, 1997) and multiple released academic textbooks (e.g. Tidd *et al.*, 2005, Schilling, 2010, Byers *et al.*, 2010) were selected. With respect to quality, a focus was placed on books that were based on sound data and were composed of recognized scholars within the field. The chosen Books should follow a clear scientific style, be quoted in renowned studies, and accurately utilize references.

5.1.1.2 Data Analysis

In order to derive both similarities and differences in the perception of the CSFs for radical technological innovation, the literature has been deductively scanned. The TOMP framework was taken as a research guide. The index and the table of contents of each book were scanned for each CSF. If a CSF was described in a book, the corresponding phrases were highlighted and a short summary of the author's opinion was written. Following this procedure, the eleven books were reviewed and each CSF was checked in a step-by-step progress. For collection, storage, organization, and categorization of the data, the reference management software Citavi 4 was used.

Table 3: List of Analyzed Books

Authors	Title	Year	Reference
Kelly & Kranzberg	Technological Innovation - A Critical Review of Current Knowledge	1978	(Kelly and Kranzberg, 1978)
Tornatzky, Fleischer & Chakrabarti	Processes of technological innovation	1990	(Tornatzky *et al.*, 1990)
Christensen	The Innovator's Dilemma - When New Technologies Cause Great Firms to Fail	1997	(Christensen, 1997)
Jolly	Commercializing New Technologies - Getting from mind to market	1997	(Jolly, 1997)
Tidd, Bessant & Pavitt	Managing Innovation - Integrating Technological, Market and Organizational Change	2005	(Tidd *et al.*, 2005)
White & Bruton	The Management of Technology and Innovation - A strategic approach	2007	(White and Bruton, 2007)
Boutellier, Gassmann & Zedtwitz	Managing Global Innovation - Uncovering the Secrets of Future Competitiveness	2008	(Boutellier *et al.*, 2008)
Schilling	Strategic management of technological innovation	2010	(Schilling, 2010)
Byers, Dorf & Nelson	Technology Ventures – From Idea to Enterprise	2010	(Byers *et al.*, 2010)
Trott	Innovation Management and New Product Development	2012	(Trott, 2012)
Vahs & Brem	Innovationsmanagement - Von der Idee zur erfolgreichen Vermarktung	2013	(Vahs and Brem, 2012)

5.1.2 Findings

5.1.2.1 Main Categories

Within the TOMP framework, a distinction was made between CSFs that are influenced by the innovation context on the one hand and the innovation process on the other hand. The analysis of the eleven books showed that most of the authors similarly distinguish between the innovation context and the innovation process. As the framework of Tornatzky and Fleischer and the frameworks of Cooper and Kleinschmidt (cf. Figure 12, Figure 11, and Figure 14) were used as a research roadmap for the secondary case study analysis, this basic differentiation of context and process is fundamental to the TOMP framework and based on the conception of these frameworks. Tornatzky and Fleischer state that the context in which technological innovation takes place can have a significant influence on the outcome of the innovation process. To further emphasize, the innovation context itself does indeed either constrain or facilitate the concrete process meaning that a perfectly executed process may even result in failure (Tornatzky and Fleischer, 1990, p. 174, 1990, p. 152).

Four CSF-categories are central to the TOMP framework: technology, organization, market, and process. It was estimated that there is a correlation between certain categories. To achieve success in innovation, the categories must also match. The organization needs to match to the target market. The technology needs to match to the organization and to the target market. Furthermore, the innovation process itself needs to match to the complete innovation context. These estimations were confirmed by the literature review. According to Christensen, exploiting radical technological innovations in commercial organizations requires that the addressed market matches the characteristics of the concrete organization. Regarding this, he emphasize that, for example, small, emerging markets cannot solve the near-term growth and profit requirements of large companies (Christensen, 1997, p. 121). Furthermore, Byers stresses that the customers in the addressed target market want a solution to their problem and usually do not care what technology is employed (Byers *et al.*, 2010, p. 27). Nevertheless, Trott outlines that excellent technology can help companies to achieve competitive advantage and long-term financial success (Trott, 2012, p. 2). According to Christensen, matching the market to the technology is decisive to success. It is important to find a market that values the characteristics of a concrete technology. While developing a concrete product is a technological challenge, finding the right market is a strategic marketing challenge (Christensen, 1997, pp. 226–227). Additionally, Schilling point out that numerous new products have offered technologically advanced features compared to its alternatives, but have failed to match customer requirements and were subsequently rejected by the market (Schilling, 2010, p. 240). In their efforts to provide better products than their competitors, suppliers often overshoot the requirements of their target market. They serve customers more than they need and are willing to pay for (Christensen, 1997, p. xvi). For the customers it is the ratio of benefits to cost that determines the value (Schilling, 2010, p. 77).

However, Trott emphasizes that technology by itself will not lead to success. Organizations must be able to convert intellect, knowledge, and technology into concrete products that customers want. Therefore, new ideas are the starting point for innovation. The process of transferring these intellectual thoughts into products represents innovation exploitation and thus, commercialization (Trott, 2012, p. 178, 2012, p. 15).

5.1.2.2 Concrete CSFs

As the four main categories of the TOMP framework (technology, organization, target market, and innovation process) have been found to be a sound classification of the CSFs for radical technological innovations, the concrete CSFs will be addressed by focusing on each of these categories. The origin of each statement taken from the analyzed books will be indicated by referencing the authors directly after each statement.

Due to the sample of eleven analyzed books the universality of the CSFs cannot be totally validated. However, to highlight the relevance of the CSFs, it could help to show the frequencies of each factor. Therefore, Table 4 delivers an overview of the concrete indications with page numbers that were found in the analyzed eleven books.

Table 4: List of Indications for CSFs Derived from Literature with Page Numbers

		Critical Success Factors	Kelly & Kranzburg (1978)	Tornatzky & Fleischer (1990)	Christensen (1997)	Jolly (1997)	Tidd, Bessant & Pavitt (2005)	White & Bruton (2007)	Boutellier, Gassmann & von Zedtwitz (2008)	Schilling (2010)	Byers, Dorf & Nelson (2010)	Trott (2012)	Vahs & Brem (2013)
Tech-nology		*Relative Advanta-geousness*		126-133	226		412	39-40 326-327	183	240	66-69		73
		Feasibility & Maturity	68	128-129									75
Target Market		*Market Match*			121 226-227		350-354		149-150	239-240		62	416-417
		Opportunity			38-39 164-165			68-69			258		
		Market Barriers	96-97		228			50-51	16-17	100-101 116	85-86		420-422
		Environmental Context	11-12	94-103 173-174			441-442	47-53		114-118	79-83	388-389	120-122
		Competition	95-96	169-171			146-152	51; 69		115	81	386-389	
Organization		*Company Culture*			180-181 219		327-328	136-137	28-29		294-297	94	190-220
		People	12-14	156-160	168-170	374-377	476-484		38-39	266-269	290-291	103-104	177-189
		Size, Flexibility & Autonomy	91	155-156 161-163	134-138		473-476	176-178	273-274	213-220	283-287	101-103	81-82
		Internal Communication		105-111			421	111 355-356	38	267-268		575-576	399-406
		Finance & Funding	71		103		536-539	71	196-199	136-152	391-453	295-298	80
		Management & Owner Commitment	192-202	160			413	112-113 130-131			291-293		
		Organizational Home			134-135					270-271			
Innovation Process	Product Development	*Intellectual Property*		94-96		110-119	259-263		85	188-205	237-238	156-189	458-466
		Lead User Integration					491		152	246	258	67	269
		Risk Management			227-228		413 378-384		27-28		138-157	95	
		Speed & Cost				312-318	387-388		18	240-241		436-437	46-50
	Market Introduction	*Value Proposition*	53		183-187		258-259			77-81	56-59		43; 73
		Cope with Uncertainty		170	156-157		330-332 378		168	97-98	138-146	85-89	32-33
		Sensitiveness to Market Needs	219-229	87	102-104 217-218		236-239	39	168	239-240	253-255	65	46; 417
		Timing			122-124	318-320			227-230	93-104	108-113	401-402	108-111 420-421
	Diffusion	*Marketing*	327		143		422-425			297-304	270-274	64-66	393-415
		Platform Strategy & Product Family					31-32	307-312	18-19	222-223	222	381-383	55
		Strategic Alliances & Partnerships		172-173		249-281	461-490	212-232	21-22	159-177	89-94	234-267	84-85

Technology

In the analyzed books, great importance is attached to the category of *technology*. Thereby, a technology's *relative advantageousness* seems to be crucial for the innovation success. However, it is not sufficient to carry out a simple technical comparison to gain the competitive advantage of a focal technology (Byers *et al.*, 2010, pp. 66–69). The customer's perception of the technology, rather, is key (Tidd *et al.*, 2005, p. 412). It is necessary to identify why a potential customer might look for an alternative to the existing solution. This may be caused by lower costs, superior performance, or greater reliability (Boutellier *et al.*, 2008, p. 183; Tidd *et al.*, 2005, p. 412).
Besides its advantages, the technology's behavior should be predictable and there should be few possibilities of errors (Tornatzky and Fleischer, 1990, pp. 128–129). Only a fully developed, high quality, and error-free product will be successful in the market. Therefore, the underlying technology needs to be *feasible and mature* (Vahs and Brem, 2012, p. 75).
Both factors *relative advantageousness* and *feasibility & maturity* are discussed in the studied books. However, the CSF relative advantageousness is described in much more detail (eight times) than the factor feasibility & maturity (three times). This is likely because a customer's perception of a technology mainly addresses the relative advantages of the technology. Nevertheless, the relative advantages of a technology depend on its *feasibility & maturity* and are thus, a precondition for the market success.

Target Market

Besides Jolly, all authors value the importance of the *target market* for radical technological innovations. The choice of the right target market is crucial (Vahs and Brem, 2012, p. 416) and the company has to make sure that there is an interesting market for their product with respect to market size and potential (White and Bruton, 2007, pp. 68–69). Therefore, the *opportunity* in that addressed market should be big enough. As already mentioned, this is a question of *market match*. Small markets do not satisfy the growth targets of big companies, but may be suitable for start-ups or medium-sized companies (Christensen, 1997, pp. 164–165). The innovating organization has to ensure that the intended product suits the market (Schilling, 2010, p. 240). Thus, the company has to assess its own technological capability and the current market needs (Trott, 2012, p. 62). At that point, it is important to monitor the market continuously and to be aware of what the market needs are. This is not only important for existing markets but also for new and changing markets and is especially crucial in dynamic market environments (Tidd *et al.*, 2005, pp. 350–354).

The ease of market entry depends on its structural characteristics. Potential market barriers are economies of scale, government regulations, switching costs, capital requirements or a patent situation that offers protection against competition (Byers *et al.*, 2010, pp. 85–86; White and Bruton, 2007, pp. 50–51). That these barriers are significant incentivizes innovation leaders to deliberately establish them to hinder their competitors to enter the market (Boutellier *et al.*, 2008, pp. 16–17). High entry barriers particularly discourage completely new entrants to the market as compared to existing competitors since they make it difficult or expensive to enter an industry. One way to deal with existing entry barriers is to choose a cooperative strategy, i.e. entering a partnership (Schilling, 2010, pp. 96–97; Vahs and Brem, 2012, p. 422).

Several of the authors value the analysis of a company's *environmental context* to be important for the subsequent innovation success. The goal is to detect possibilities and opportunities but also threats and problems from outside the organization. Two common tools for the external analysis are Porter's five-forces model, as well as stakeholder analysis (Schilling, 2010, pp. 110–114; Trott, 2012, pp. 388–389; White and Bruton, 2007, pp. 47–53). One important part of external monitoring is to pay attention to the *competition* in the target market. The company should have a competitive strategy which drives new product planning (Trott, 2012, pp. 386–389). Additionally, benchmarking and learning from competitors can help to strengthen the company's position in the market. Subsequently, there are positive and negative impacts of competitive rivalry on a company's innovativeness (Kelly and Kranzberg, 1978, pp. 95–96; Tornatzky and Fleischer, 1990, pp. 169, 171).

Nearly all five CSFs that have been assigned to the category *target market* in the TOMP framework are discussed in rich detail in the chosen sample of books. The factors *market match*, *market barriers, external environment,* and *competition* are each mentioned by five to eight authors. *Opportunity,* though, is only described three times. The fact that all the other CSFs contribute to the factor *opportunity* of a certain target market could explain this disparity. Depending on the level of *market barriers*, the *competitive situation*, the *external market environment*, and the *matching* of the market with the technology and the central organization, the attractiveness of the correlated market *opportunity* is shaped.

Organization

The conducted literature analysis highlights that the innovating *organization* has a huge impact on the probability of innovation success. The firm itself, its internal structure, and the degree to which it uses formalized and standardized procedures and controls can constrain or facilitate the realization of radical technological innovations (Schilling, 2010, p. 213). Tornatzky and Fleischer define the organizational context in terms of firm size, centralization & formalization, complexity of its managerial structure, internal communication, quality of its human resources, and the amount of slack resources available internally (Tornatzky and Fleischer, 1990, p. 153). Especially for radical innovations, an innovation-friendly *company culture* is crucial. This should be built on trust, openness, communication, creativity, conflict management, and error tolerance (Boutellier *et al.*, 2008, pp. 28–29; Byers *et al.*, 2010, pp. 294–297).

The influence of company *size* on innovation success, however, is ambiguous (Kelly and Kranzberg, 1978, p. 91). Size and the structure of a big company bring advantages like economies of scale in R&D and learning benefits, but similarly disadvantages such as inertia and governance problems (Schilling, 2010, pp. 208–216). The challenge is to find the most appropriate fit with the particular circumstances (Tidd *et al.*, 2005, pp. 473–476). When it comes to radical technological innovations, the organic and flexible structures of small units are more suitable than the mechanistic structures of big entities (Trott, 2012, pp. 101–103). *Flexible* structures facilitate free communication (Byers *et al.*, 2010, pp. 283–287). *Internal communication* is an important factor for successfully coordinating the innovation process and pursuing innovation goals (Vahs and Brem, 2012, pp. 399–406).

Since the innovation process is costly, securing *funds* is decisive for the success of an innovation project (Kelly and Kranzberg, 1978, p. 71). In big companies, new innovation projects have to compete with other projects whereas small companies and start-ups have to face the problem of finding external investors (Tidd *et al.*, 2005, pp. 536–539; Trott, 2012, pp. 295–298). As the realization of radical technological innovations is a very uncertain endeavor, *management and owner commitment* is important to encourage and motivate the operational team. The management should clearly communicate the organization's goals, foster a climate favorable for innovation, support the project, and strongly reward innovation success (Tornatzky and Fleischer, 1990, p. 160).

To fully reap the benefits of an innovation an adequate *organizational home* must be found. Companies should seek to embed the innovation project in an organization that fits the requirements of the innovation (Christensen, 1997, pp. 134–135). However, it is often hard to fold back the project team into the organization if the project is completed (Schilling, 2010, pp. 270–271).

The involved *people* are the most important element in the innovation process and should be motivated and enthusiastic (Kelly and Kranzberg, 1978, pp. 12–14). Cross-functional and interdisciplinary teams help to foster innovation and the management needs to assign the right people in the different stages of the innovation process (Jolly, 1997, pp. 374–377; Schilling, 2010, pp. 262–265).

The factors *company culture*, *internal communication*, *finance & funding*, and m*anagement & owner commitment* are described and analyzed in detail in the selected literature and thus, seem to be relevant factors for the realization of radical technological innovations. As the factors *people* and *size, flexibility & autonomy* are mentioned in ten of eleven books, these factors can be argued to have a great influence on the innovation success. The factor *organizational home* has not been emphasized and discussed in most of the reviewed literature (only twice). Moreover, the books by Tidd et al. (Tidd *et al.*, 2005), Schilling (Schilling, 2010), and Byers et al. (Byers *et al.*, 2010) emphasize the importance of a company's *strategic direction* for the success of a radical technological innovation.

Innovation Process

Product Development

At *product development*, the question of how to protect a company's *intellectual property* immediately arises. Since knowledge and innovation are vital for competitive success, the management of *intellectual property* is important (Byers *et al.*, 2010, pp. 237–239). Protecting an innovation ensures that the innovating company earns the majority of the returns created from introducing the innovation to the market (Schilling, 2010, pp. 198–199). The optimal protecting strategy has to be adjusted to the company-specific needs and should be linked to the commercialization strategy (Jolly, 1997, pp. 110–119; Vahs and Brem, 2012, p. 459). To ensure that the final product meets customer requirements, involving customers or end-users in the new product development process is crucial. *Lead user integration* is one possibility to get early market feedback and to support the diffusion process of technology-intensive products (Schilling, 2010, p. 240; Trott, 2012, p. 67). Dealing with radical technological innovation implies high risks and uncertainty. Risk can be described as the possibility of loss (Byers *et al.*, 2010, p. 138). Within radical innovation projects, risks have to be constantly identified and assessed. Finally, to take calculated risks, a sound *risk management* should be in place (Trott, 2012, p. 95). In the face of shorter product life-cycles, the time period to reap the returns is ever shrinking for the innovating company (Boutellier *et al.*, 2008, p. 18). Thus, being efficient with respect to *speed & costs* within product development is essential (Schilling, 2010, pp. 234–335).

The factors *intellectual property, lead user integration, risk management,* and *speed & costs* which have been assigned to the product development phase within the TOMP framework were found in several books. Each factor is mentioned five to eight times by the authors and described in rich detail. Hence, these factors can be considered crucial for the success of radical technological innovations.

Market Introduction

In the phase of *market introduction*, the *value proposition* of a product predetermines how an innovation will be accepted in the market (Kelly and Kranzberg, 1978, p. 53). The value of an innovation is multidimensional and comprises the worth, importance or usefulness to the customer (Byers *et al.*, 2010, p. 56). It forms the comparative advantage of an innovation over similar products in the market and depends on the customers' expectations and perceptions (Schilling, 2010, p. 77; Vahs and Brem, 2012, p. 43). This implies that innovative products have to meet customer needs and values to be successful (Byers *et al.*, 2010, p. 56). Therefore, *sensitiveness to market needs* and a strong customer focus is necessary (Boutellier *et al.*, 2008, p. 168). Especially at the beginning of the product lifecycle, it is crucial for a company to know who the customers are and why they might buy the product (Byers *et al.*, 2010, pp. 253–255). Numerous new products which offered technologically advanced features were rejected since they failed to match customer requirements (Schilling, 2010, pp. 233–234). For a commercially viable new product, bridging technological uncertainty and market needs is decisive (Trott, 2012, p. 65). Even if all technical problems are solved, the uncertainty of commercialization remains to be high (Boutellier *et al.*, 2008, p. 168). Uncertainty implies that the outcome of an action is not known or is likely to be variable (Byers *et al.*, 2010, pp. 138–146). *Coping with uncertainty* is a central task of managing the innovation process (Trott, 2012, pp. 85–89). Furthermore, the right *timing* of market entry is one of the most strategic decisions in innovation management (Christensen, 1997, pp. 122–124). The optimal *timing* depends on a variety of factors such as the innovation's advantages, the state of enabling technologies, the threat of competitive entry, and the customer expectations (Schilling, 2010, pp. 89–99). In principle, there are four strategic options: *leader*, *early follower*, *late follower*, and *me-too* (Vahs and Brem, 2012, pp. 108–110).

The importance of market introduction is described in all analyzed books. The four CSFs *value proposition, sensitiveness to market needs, cope with uncertainty*, and *timing* have been extensively illustrated and are each mentioned six to ten times. Correspondingly, they seem to be relevant.

Diffusion

From a business perspective, an innovation is not a success until it has not been established and leveraged throughout the market (Schilling, 2010, p. 229). The earlier discussion of market introduction highlighted some CSFs crucial to the launch strategy, but the act of bringing a product to the market is not an end in itself. On the contrary, it is the beginning of its commercialization (Trott, 2012, p. 402). Usually, there is a gap between the adoption of an innovation by early adopters and by the mainstream market. To get across this chasm, *marketing* is an important factor. Marketing is a set of activities with the objective of winning, serving, and retaining customers for the firm's product offering (Byers *et al.*, 2010, pp. 252, 270-274). Thus, customers are central and their needs should always be focused (Tidd *et al.*, 2005, pp. 422–425). A good chance to recoup the high initial investments of radical technological innovations is by sharing the underlying technology across different market fields and *product families* by deploying a *platform strategy* (Tidd *et al.*, 2005, pp. 31–32). Using standardized manufacturing platforms or components that can be mixed and matched in a modular production system is a good way to balance between efficiency and flexibility. This enables companies to achieve efficiency and reliability advantages at the component level while achieving variety and flexibility at the end product level (Schilling, 2010, p. 222). Innovation often demands collaboration, either in the development or commercialization process. *Strategic Alliances and Partnerships* can reduce the costs, risks, and time of development and commercialization (Boutellier *et al.*, 2008, pp. 21–22; Tidd *et al.*, 2005, pp. 461–490). Successful collaboration requires choosing partners that have both a resource fit and a strategic fit (Schilling, 2010, p. 177).

All reviewed books address the importance of the diffusion stage with the respective factors *marketing, platform strategy & product family*, and *strategic alliances & partnerships*. These factors are mentioned seven to nine times in the chosen sample of books and can be considered to be important for the success of radical technological innovations. Several authors assign the CSF *platform strategy & product family* to the later phases of the innovation process and, correspondingly, the diffusion phase. However, they emphasize that this factor is more an issue of the product development strategy (Trott, 2012, p. 381). Furthermore, the factor, *strategic alliances and partnerships,* was allocated in the TOMP framework to the diffusion phase and thus, to the later stages of the innovation process. This allocation should be questioned as several authors emphasize the importance of collaboration in the product development phase as well.

5.1.2.3 Summary

When analyzing the sample of eleven standard books from innovation management literature, it becomes obvious that each book has a certain focus. Some books mainly address the innovation context for the emergence of radical technological innovations (Kelly and Kranzberg, 1978), (Tornatzky *et al.*, 1990), (White and Bruton, 2007), while Jolly is targeting primarily the innovation process (Jolly, 1997). The remaining seven books discuss the innovation context and simultaneously the innovation process as parallel phenomena (Christensen, 1997), (Tidd *et al.*, 2005), (Boutellier *et al.*, 2008), (Schilling, 2010), (Byers *et al.*, 2010), (Trott, 2012), (Vahs and Brem, 2012). White & Bruton and Boutellier et al. focus on big established organizations (Boutellier *et al.*, 2008; White and Bruton, 2007), while Byers et al. mainly target new ventures (Byers *et al.*, 2010). Trott, Schilling, Tidd et al., and Vahs & Brem present the topic of radical technological innovations from both perspectives – established organizations and new ventures (Trott, 2012), (Schilling, 2010), (Tidd *et al.*, 2005), (Vahs and Brem, 2012). Some books highlight the contrast of new, disruptive technologies and sustaining technologies, and the correlated consequences for the organizational structure of the innovating company (Christensen, 1997), (Jolly, 1997), (Trott, 2012).

With these different perspectives on the topic of radical technological innovation, it becomes clear that their realization is strongly dependent on the respective innovation context. Correspondingly, there seems to be no universal set of factors for predicting the success of a specific radical technological innovation as the relative importance of the factors would be different depending on the contextual nature of the particular innovation. Depending on the situation, different CSFs will be more or less crucial, and some factors may even hinder rather than support the success of an innovation (Balachandra and Friar, 1997, pp. 284–285). Besides the distinction of the innovation context and the innovation process, the four main categories of the TOMP framework and their necessity to match to each other, were validated by the literature analysis.

Furthermore, the general arrangement and the concrete 25 CSFs within the TOMP framework were found to be sound. In the considered sample of books, the concrete CSFs of the categories *target market* and *technology* are described in detail. Within the category *organization,* the factor *organizational home* is not emphasized or discussed in depth. *Organizational home* addresses the necessity that a radical innovation eventually has to be integrated into the coherent whole of the company's organizational structure if it is not to be totally spun out. That this factor is not detailed in the analyzed books is interesting. Immediately the question emerges if this factor is not critical for the success of radical technological innovations or if this represents a lack in literature. Furthermore, the books by Tidd et al. (Tidd *et al.*, 2005), Schilling (Schilling, 2010), and Byers et al. (Byers *et al.*, 2010) claim that an organization's strategy is equally important for the success of a radical technological innovation and that the respective innovation should be compatible to the company's strategic direction. This factor has not been part of the original TOMP framework.

The factors that have been allocated to the *product development* and *market introduction* phases were validated by the literature review. With respect to the *diffusion* phase, several authors describe the CSF *platform strategy & product family* to be late in the *innovation process*. However, in contrast to the TOMP framework, they assign this factor to be part of the *product development* strategy. Additionally, some authors emphasize that in the *product development* phase, collaboration is of great importance for radical technological innovations. Previously the factor *strategic alliances and partnerships* was allocated to the *diffusion* phase. This should be analyzed in more detail. It is likely that the types of strategic alliances change along the innovation process. While in the early stages strategically involving customers and *lead users* is important to *cope with uncertainty* and design a product in accordance with the *market needs*, setting up a strategic network of suppliers, customers, and partners is crucial to the broad market penetration in the diffusion stage.

In the TOMP framework, the innovation process is composed of the chronologically ordered phases of *product development, market introduction*, and *diffusion*. Perhaps it is prudent to classify these stages as three correlated fields of action and not chronological phases.

5.1.3 Discussion and Limitations

There are some limitations with respect to the conducted structured and focused literature review. Since the central research objective was to evaluate the TOMP framework, one limitation is the fact that the research project was not started in an unbiased way. Furthermore, due to the sample size with just eleven books, the results of the analysis are not generalizable. Although there has been a structured preselection of the ultimately analyzed books, this number represents just a small excerpt of the overall existing literature and thus, cannot claim universality. Extending this sample might lead to a better basement for the derived results. Moreover, books may contain out-of-date material even by the time they are published (Saunders *et al.*, 2012, p. 88). Another limitation could be the fact that there is no uniform concept of the central terminologies. This involves a slightly differing understanding of the central concepts in the analyzed literature. The definitions the author is following are presented in chapter 2.1.

Through the analysis, the distinction of the innovation context and the innovation process was found to be central to the CSFs of radical technological innovations. Moreover, most of the CSFs of the TOMP framework could be identified in the reviewed books as well. More research is required to clarify how the innovation context concretely affects the innovation process. Therefore, the central questions are which factors constitute the sphere of concern and which the sphere of influence. As the realization of radical technological innovations is a very complex endeavor, a qualitative research approach seems to be appropriate. Thus, non-standardized, guided interviews with experts in the field of technological innovation could help to generate an answer to these questions and validate the CSFs detailed in the TOMP framework.

5.2 Expert Interviews

According to the Oxford dictionary, an expert is a person who is very knowledgeable about or skillful in a particular area (Oxford dictionary, 2015). Experts have acquired knowledge that is not easily attainable to common sense through their specific educational and professional background. Systematically harvesting this knowledge can significantly foster the understanding and perception of a particular topic like the realization of radical technological innovations (Bogner *et al.*, 2014, pp. 9–10; Flick, 2007, p. 215). Accordingly, conducting expert interviews was meant to evaluate, expand, and clarify the set of CSFs detailed in the TOMP framework.

5.2.1 Methodology

To find access to the subjective knowledge of experts in a methodologically controlled manner with limited time and a specific focus, a non-standardized, guided interview format is appropriate (Flick, 2007, p. 219). In non-standardized interviews, neither the questions of the interviewer nor the answers of the interviewee are standardized. An interview guide helps to address all important aspects of the focal topic and to structure the interview (Gläser and Laudel, 2010, p. 111, 2010, p. 41).

In the study, two rounds of expert interviews were conducted. In the first round, nine experts were interviewed in a rather inductive and unbiased mode. The questions were more open and free than in round two and detached from the TOMP framework. In the second round, ten experts were interviewed. In a deductive style, the questions were consequently focused on the TOMP framework and the containing CSFs. At the end of the interviews in round two, the TOMP framework was shown to the experts and they were asked for feedback. According to the different purposes of the two interview rounds, two separate interview guides have been developed. The interview guides formed the basis for the interviews and served as a memory aid and orientation framework. They consisted of a prepared list of open, clear, and neutral questions to be asked and answered in the interviews. Neither the formulation nor the order of the questions was binding (Gläser and Laudel, 2010, p. 149, 2010, p. 143, 2010, p. 111; Lamnek, 2005, p. 367).

To check the quality of the two interview guides, the first interview in each round was set up as a pretest. In both pretests, only slight modifications of the interview guide were needed. The final interview guides were used situation-related with respect to the wording, the order, and the timing of the questions. Both interview guides can be found in Appendix II – 1 & 2.

5.2.1.1 Expert Sample

According to the principle of theoretical sampling, selecting experts was carried out deliberately. It was a requirement that the potential interview partners had been involved in the realization of radical technological innovations. Intentionally, the sample of interviewees was heterogenic, consisting of experts from organizations of different size and structure, which allowed for the gaining of a holistic perspective on the topic. The interviewed experts work as innovation managers, technology scouts, design and application engineers, business consultants, entrepreneurs, and scholars, and have different levels of work experience.

The aim was to have a comparable sample of experts in both interview rounds. The recruitment of the experts was done from the southern part of Germany via the personal and business network of the author. Furthermore, the lists of participants of diverse industry and research conferences were screened for potential interview partners. In sum, 19 interviews were conducted – nine interviews in the first and ten in the second round. An overview of the interviewees of both rounds is given in Table 5. In Appendix II – 3 & 4 a more detailed description of the expert profiles is provided.

5.2.1.2 Data Collection and Preparation

The first interview round was conducted between April and July 2014 while the second round was conducted between August and October 2014. All interviews of the first round were recorded with a digital voice recorder. In round two, nine interviews were recorded and only for one interview, a protocol was prepared, as the corresponding expert refused to get recorded. In both rounds, two interviews were conducted in the premises of the researchers' institute and the remaining interviews (seven in round one and eight in round two) were conducted at the respective workplace of the expert. The interviews of both rounds were scheduled for 90 minutes and lasted between 60 and 110 minutes while the arithmetic mean amounts to 88 minutes. The total recording time of the 19 interviews accumulate to 28 hours.

Table 5: Overview of the Interviewed Experts

Abbreviation	Context	Job Description	Work Experience [in years]	Organization Size [number of employees]
Round 1				
E1a	Science	Business Developer	1-3	1,000-10,000
E1b	Industry	Independent Scientist and Consultant	> 15	< 25
E1c	Industry	Entrepreneur, CEO	7 - 15	25-100
E1d	Industry	Manager Application Engineering	> 15	> 10,000
E1e	Industry	Entrepreneur, CEO	> 15	25-100
E1f	Science	Managing Director of a Research Institute	> 15	100-1,000
E1g	Industry	Head of New Technologies	> 15	> 10.000
E1h	Industry	Entrepreneur, CEO	7 - 15	< 25
E1i	Industry	Innovation Manager	> 15	1,000-10,000
Round 2				
E2a	Industry	Entrepreneur, CEO	7 - 15	25-100
E2b	Science	Managing Director of a Research Institute	> 15	100-1,000
E2c	Science	Head of Technology Transfer	> 15	1,000-10,000
E2d	Industry	Head of Innovation Department	> 15	> 10,000
E2e	Industry	Innovation Manager	> 15	> 10,000
E2f	Industry	Business Consultant	> 15	< 25
E2g	Industry	Business Developer	1-3	> 10,000
E2h	Industry	Head of Business Development	7 - 15	100-1,000
E2i	Industry	Head of Advanced Development	> 15	> 10,000
E2j	Industry	Head of Innovation Department	> 15	1,000-10,000

Four of the interviews of round one and all interviews of round two have been conducted in a team. The team in round one was composed of the author and Konstantin Yakubovich, who was supervised in his master thesis by the author (cf. Yakubovich, 2014 for further details). In round two, the author was supported by Louisa Hellmann, who was similarly supervised in her master thesis by the author (cf. Hellmann, 2014 for further details). Generally, the idea was that two interviewers hear and see more than a single interviewer. Correspondingly, the interview quality could be enlarged (Gläser and Laudel, 2010, pp. 154–155).

Before analysis, the data was prepared and processed. In the case of interview data, the audio material, stored on the digital voice recorder, was transcribed for being available in a readable form (Lamnek, 2005, pp. 402–404). Mayring defines transcription as a complete textual capturing of the collected oral material that forms the foundation for the subsequent interpretative evaluation (Mayring, 2002, p. 89). All of the recorded interviews were transcribed by using the F4-software. By following Kuckartz (Kuckartz, 2012), a set of rules was established to standardize transcription (cf. Appendix II – 5). The 19 interviews accumulate to roughly 270,000 words and 780 pages of written text.

5.2.1.3 Data Analysis

Data analysis was carried out by using the software MAXQDA 11 and by following the method of qualitative content analysis, in particular, content structuring. For content structuring, Mayring presents a general process model for systematically scanning texts for particular information. This process contains ten steps (cf. Figure 19). Relevant information is taken from the text and assigned to a category system which is the central instrument for content analysis (Mayring, 2010, p. 98). This process was followed to analyze the 19 interview transcripts.

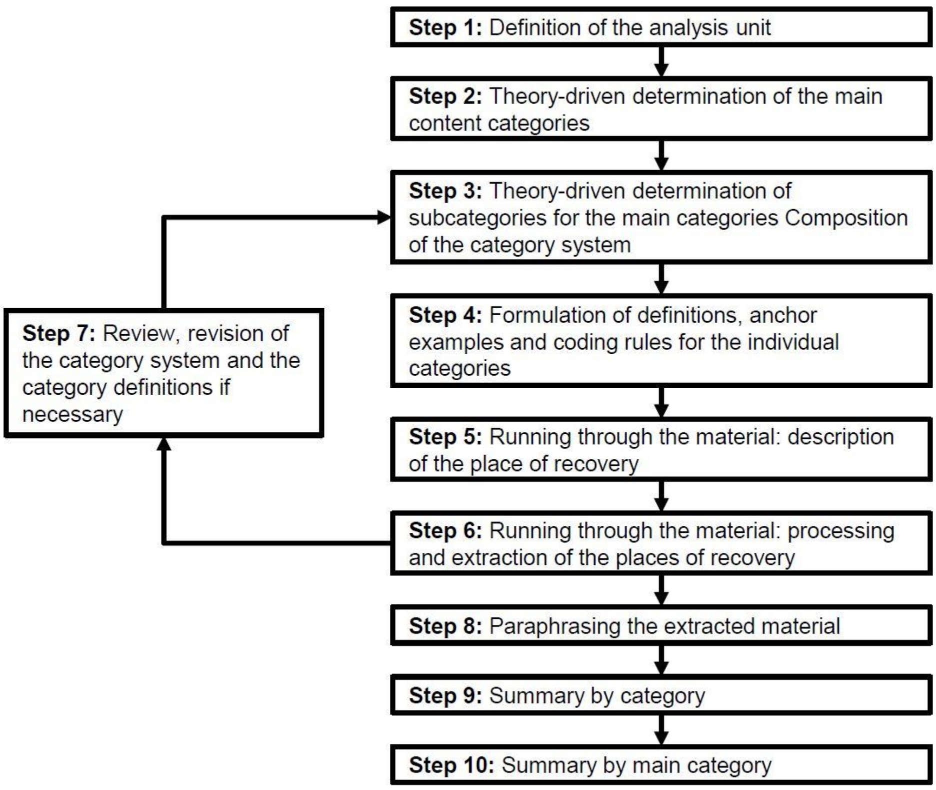


Figure 19: Process Model for Content Structuring (Mayring, 2010, pp. 93, 99)

For defining the analysis unit, the smallest and largest part of the material that can be assigned to a category needs to be defined. The smallest part can be a segment of a sentence and the largest part can be whole sections of the conversation with more than one speaker change. Taking the TOMP framework as a basis, the initial category system was established (cf. Appendix II – 6). A concrete coding agenda with definitions, anchor examples, and coding rules was set up while running through the first few interviews. Afterward, all interview transcripts were scanned by documenting each indication and the associated place of recovery for the corresponding CSFs. During this proceeding, the initial category system – derived from the TOMP framework – was iteratively reviewed and revised. Finally, the extracted text passages were paraphrased and a summary for the main categories and their subcategories (the CSFs) was written.

5.2.1.4 Quality Criteria

There is an ongoing discussion related to the question of which criteria should be applied for evaluating the scientific quality of the qualitative research approach of expert interviews. As the common quality criteria of quantitative research (with respect to objectivity, reliability, and validity) are not easily transferable, Mayring proposed six quality criteria which were followed in this thesis: *process documentation, argumentative protection of the interpretation, rule-based approach, proximity to the object, communicative validation,* and *triangulation* (Bogner *et al.*, 2014, p. 92; Mayring, 2002, pp. 144–149).

Process documentation – Data collection, preparation, and analysis need to be documented in detail to be traceable. In the previous part of this chapter, the crucial process steps, decisions, and associated reasons were described in detail. Moreover, besides one, each interview was recorded and stored together with the interview transcripts on the server of the EnTechnon. The interview guides of both rounds can be found in Appendix II – 1 & 2.

Argumentative protection of the interpretation – As it is hardly possible to prove that an interpretation is correct, all interpretations should be conclusive and supported by arguments. In the subsequent results chapter, each statement and interpretation are supported by citations of the experts to back up the argumentations and conclusions. Furthermore, an explanatory and illustrative writing style has been chosen.

Rule-based approach – Qualitative research may not be chaotic, but has to follow systematic rules. For each research phase, clearly defined rules have been followed. At the data collection phase, explicit criteria were applied for the expert selection and the preparation of the interview guides. Both interview guides were tested in a pretest. For data preparation, similarly clear rules were followed at transcription. At data analysis, the content structuring approach of Mayring was used for the content analysis of the interview transcripts.

Proximity to the object – Qualitative research aims to be close to the research object and to his everyday world. In both rounds, just two interviews were conducted on the premises of the authors' institute and the remaining interviews were conducted at the respective workplace of the expert.

Communicative validation – The validity of research results can also be proven by discussing them with the interview partners or further experts. In the second round of expert interviews, the experts were asked to give concrete feedback on the TOMP framework and the current state of knowledge was discussed with them at the end of the interview. Moreover, at the ISPIM Conference 2015 in Budapest, the results of this study were presented and discussed with an expert audience, which primarily consisted of innovation researchers and practitioners.

Triangulation – The quality of research can be increased by comparing the results with the conclusions of additional analysis rounds of further researchers. Four interviews of the first round were analyzed by Konstantin Yakubovich and all ten interviews of the second round by Louisa Hellmann. Their conclusions were compared with the analysis results of the author.

5.2.2 Findings: The ICPS Framework

In the following section, the findings are presented as summarized feedback by quoting the experts. The references are added in brackets utilizing abbreviations for the respective experts. Table 5 provides an overview of the assigned abbreviations.

At the end of interview round two, the TOMP framework was introduced and explained to the experts and they were asked to give feedback. Their spontaneous reaction was generally positive. The experts confirmed that the TOMP framework would capture the CSFs for radical technological innovations quite well and they generally found the framework in relation to its contents plausible and comprehensible (E2a, E2b, E2c). The interviewees followed the framework within its separation of context and process. They emphasized that several success factors of the innovation context could be addressed and shaped for maximizing the probability of success. However, the innovation context was cited to be much more difficult to influence than dealing with the success factors of the innovation process. The context for innovation forms the preconditions for the realization of innovations, which generally, cannot be influenced greatly or directly by innovation managers (E2d, E2h). Thus, in the interviewees' opinion, the innovating entity needs to deal with these conditions. In contrast, the innovation process itself can be handled much more flexibly and hence forms the direct sphere of influence for the innovation managers. Depending on the concrete innovation project, the process realization will be different (E2i). Accordingly, this would result in multiple permutations of the innovation process (E2h).

Nevertheless, several experts expressed some suggestions for improvement. These interviewees stressed that the *innovation success* forms the key target figure of any innovation project and should, therefore, be added to the framework. They pointed out, that in the end, this is the key aspect and central metric for assessing an innovation project (E1g, E2h, E2i).

The experts perceived the three main categories (*organization, technology,* and *target market*) of the innovation context in the TOMP framework to be sensible. However, they emphasized that there is another category that should range on the same level: the *entrepreneurial team*. In the TOMP framework, the factor *people* has been listed as a CSF within the main category *organization*. The unanimous assent of the experts was that the involved people and especially the *entrepreneurial team* are central for the realization of a radical technological innovation. Innovating people represent the key to success and thus, play an extremely important role in the realization of innovations (E2b, E2c, E2f, E2h).

Several experts missed the category *opportunity identification* (E2c, E2d, E2e, E2h). The question of how to get valuable ideas and to subsequently realize them if they indeed represent opportunities, should not be neglected (E2c). Furthermore, some experts criticized the schematic diagram of the innovation process as appearing to be sequential and determined (E2d, E2f, E2g). The innovation process should not be composed of three sequential stages as it is in the TOMP framework, but has to be iterative with integrated feedback-loops and interaction between its stages. This should be consciously visualized in the conceptual framework (E2b, E2g).

Based on the direct feedback of the experts on the TOMP framework in round two and on the overall results of the analysis in both interview rounds, the TOMP framework has been revised. In particular, the general arrangement, the main categories, and the concrete set of CSFs have been reworked. The resulting framework (cf. Figure 20) contains 25 CSFs. These were arranged in the two dimensions *innovation context* and *innovation process* and have an impact on the ultimate *innovation success*. Correspondingly, the framework will be named Innovation-Context-Process-Success (ICPS) framework and forms a conceptual framework for the further research process. As suggested by the experts, *entrepreneurial team* has been integrated as a main category within the innovation context. Thus, the innovation context is shaped by the four main categories *technology, target market, organization,* and *entrepreneurial team*. In the TOMP framework, the innovation process was composed of the chronologically ordered phases of *product development, market introduction,* and *diffusion*. After reworking the model, the different stages will be perceived as iterative fields of action instead of chronological phases. Consequently, the *market introduction* and *diffusion* stages have been combined into the *commercialization* action field as both stages address the commercial exploitation of the central innovation. Moreover, *opportunity identification* has been added as another action field. Accordingly, the innovation process consists of the following three iterative fields of action: *opportunity identification, product development,* and *commercialization*. Due to being the key target figure of each innovation project, *innovation success* has been added as a third dimension to the framework. A professional graphical designer has been involved for the graphical preparation of the ICPS framework. The initial version is printed in Appendix II – 8 and a larger version of the ICPS framework in Appendix II – 7.

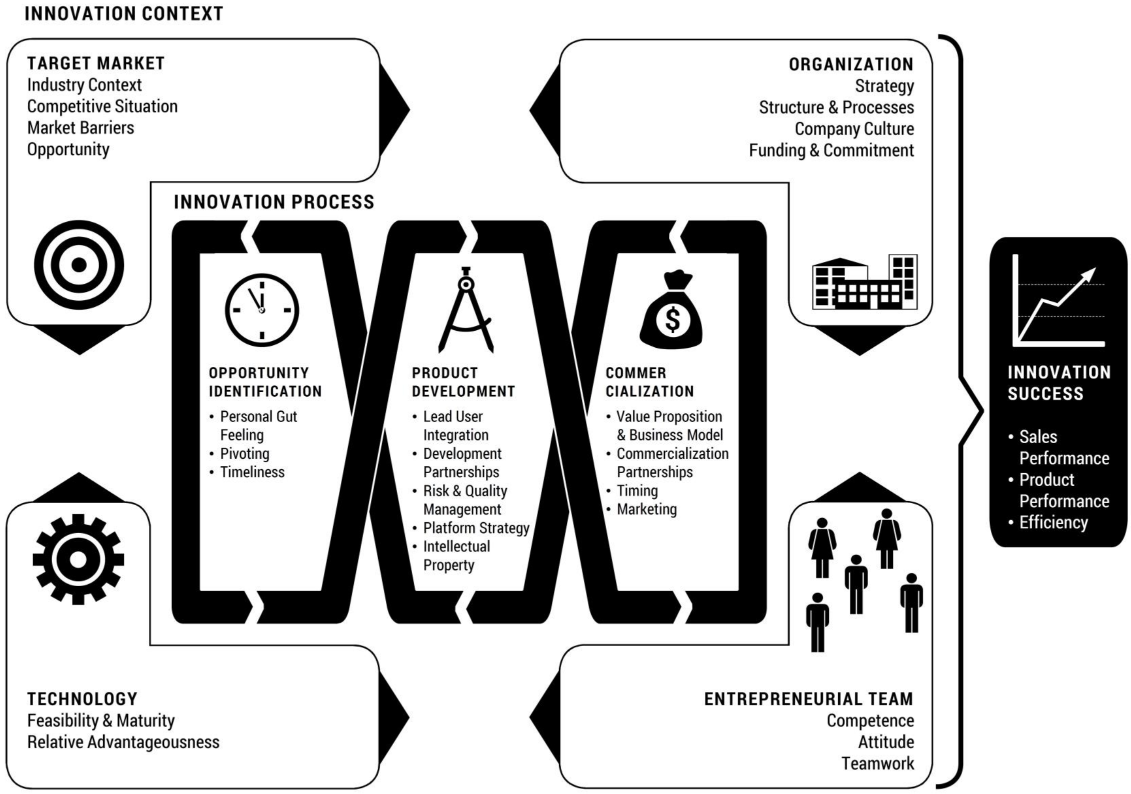


Figure 20: ICPS Framework

In the following, the concrete CSFs are outlined and discussed within the three dimensions of the ICPS framework: *innovation context, innovation process,* and *innovation success*.

5.2.2.1 Innovation Context

Technology

Several experts valued the technology that underlies an innovation as being a major driving force for the innovation (E1a, E2b, E2c). The CSFs *feasibility & maturity* and *relative advantageousness* of the *technology* category in the TOMP framework have been kept in the ICPS framework, as the experts noted their importance. For commercializing, the technology has to have a certain maturity level (E2b, E2c, E2e, E2g). It has to be proven that an industrial user can integrate the technology into his products without larger efforts (E1e, E2d). It should be functional, error-free, and ready to use before market introduction since the market does not tolerate many attempts and errors (E1a, E2c, E2d, E2j). At the latest, when series production starts, the technology should be developed to an extent that it works reliably (E2d).

Furthermore, the *relative advantageousness* of a technology is decisive for its acceptance. The competitive advantage and the concrete customer benefit compared to existing alternatives are crucial (E1a, E1e, E1f). Therefore, potential alternatives need to be monitored (E1f). And there are always alternatives, even if the alternative is doing nothing (E1g, E1i). Especially in the case of radical innovations or when entering new markets, the competitive benefit has to be very distinct to overcome the market acceptance hurdles (E1a, E1h, E2d, E2g). This benefit results from a combined effect of the market needs and the technology offer (E2a, E2b).

Target Market

Only after being implemented on a market, an idea becomes an innovation (E1f). Finally, the market determines what will be successful. Correspondingly, the *target market* plays a fundamental role in each innovation (E1f, E2i). The main category, *target market,* within the ICPS framework, is composed of the CSFs *industry context, competitive situation, market barriers*, and *opportunity*. Besides some minor naming changes compared to the TOMP framework, the factor *market match* has been integrated into the *opportunity* factor. This is because a specific market needs to match to the respective technology and organization to represent an adequate market opportunity.

The *industry context* shapes the overall circumstances for commercializing an innovation on a market. Influencing factors are political regulations, subventions, or lobbyism (E1b, E1e, E1h, E2e, E2g). Moreover, economic cycles, business hypes, and trends impact the market situation (E1c, E2a, E2h). Another critical factor is the *competitive situation* within a market (E1b, E1g, E2d). The strengths and weaknesses of competitors have to be monitored continuously (E1f, E1h). Especially in a dynamic environment, competitor analysis is important (E1b, E2h). Strong competition can be a high *market barrier* (E2a). Further barriers are a broad patent protection of established market players (E1d, E2a) and reluctant business policies regarding start-ups and newcomers (E1f, E2d, E2e). However, the highest market barrier is the problem of acceptance by customers, due to which organizations do not dare to adopt radical innovations based on their newness and differentness (E1e, E1h, E2h, E2j). Nearly all experts described the market *opportunity* to be central to the subsequent innovation success. A target market needs to be big enough, profitable, and should exhibit a high potential for market growth (E1b – E1i, E2a, E2b, E2d – E2j). Furthermore, the innovation has to match to the market and its requirements (E1h, E2b, E2j).

Organization

The innovating organization constitutes the internal circumstances for innovation realization (E1d, E2c, E2d). Within the main category *organization* in the ICPS framework, several CSFs of the TOMP framework have been summarized. The factors *size, flexibility, & autonomy* and *organizational home* have been combined to the factor *structure & processes*. Similarly, the factors *finance & funding* and *management & owner commitment* have been reduced to the overall factor *funding & commitment*. As the experts perceive the factor *internal communication* as a part of *company culture*, it has been removed. Moreover, the CSF *strategy* has been added to the *organization* category, because the experts value the strategic direction of an organization to be decisive for the realization of radical technological innovations. As mentioned before, the *entrepreneurial team* has been integrated as a main category within the innovation context instead of listing the factor *people* within the main category *organization*.

The *strategy* of an organization indicates its business direction and similarly its general objectives for innovation creation (E1g, E1i, E2a). It forms the guardrails and legitimations for each innovation activity. If a project does not fit the overall strategy, there would be no mandate to execute it (E1e, E1g, E1i, E2e, E2g, E2h, E2j). Furthermore, it is a strategic decision to strive for innovation leadership or price leadership (E2b, E2d). This decision has fundamental consequences for an organization`s set up regarding its *structure and processes*. Especially at realizing radical innovations, the employees need a certain level of freedom from their everyday business (E1d, E2d, E2h, E2i). Thus, flexible structures and low hierarchies are crucial for being successful (E2b, E2g, E2f). However, the degree of freedom needs to be reduced in the course of the project. It is desirable to establish processes that enable the creation of many ideas which will subsequently be evaluated according to clear abort criteria, and which will be realized in an efficient process afterward (E1g, E2a, E2b, E2d, E2f, E2h, E2j). Another important factor when it comes to organizational preconditions for innovations is *company culture* (E1g, E1i, E2b). Radical technological innovations are very risky and many fail during realization (E2b). Thus, tolerance regarding mistakes and uncertainty is needed (E2a, E2d, E2f, E2i). Occurred mistakes must not be punished (E2j, E2b). Otherwise, no one will dare to break new ground (E1d, E2j). In contrary, an innovation-friendly company culture has to be characterized by an atmosphere of openness regarding novelty and change (E1e, E1i, E2a, E2j). For the actual realization of an innovation project, adequate *funding and commitment* have to be granted (E1e, E2e, E2h). There has to be a clear intention of the investor or respectively the involved management that warrants a sufficient budget (E1d, E1i, E2b, E2f). If this support is missing, the innovation realization will be hopeless (E1c, E14, E2i).

Entrepreneurial Team

Several experts valued the *entrepreneurial team* as being most important for the realization of radical technological innovations (E1e, E1f, E2b, E2c, E2f, E2h). Three CSFs have been described by the experts to be central for an *entrepreneurial team*. The team should be composed of people that have the appropriate *competences* and *attitude* and they need to work as a team. The involved people should display profound professional competences on the one hand, and soft skills on the other hand (E1e, E2b, E2i). For being successful, it is necessary to recognize and adequately utilize the strengths and weaknesses of each team member (E1f, E2a). Thereby, it is necessary to reach a good composition of a complementary, multifaceted, and diverse team that can properly work together (E1h, E2a, E2d, E2f, E2g). Nevertheless, the *attitude* and mindset of the involved people are crucial. The team members should be passionate, enthusiastic, and highly motivated to bring the innovation to success (E2c, E2d, E2j). As radical innovations are risky and uncertain, the innovating people need to have a high level of personal initiative and perseverance (E1i, E2a, E2c, E2d, E2e).

5.2.2.2 Innovation Process

Opportunity Identification

Before realization of a radical idea can take place, it has to be identified that there is actually a promising opportunity. Without *opportunity identification,* there will be no innovation. As several experts missed the category *opportunity identification* in the TOMP framework, this category has been added to the *innovation process* dimension in the ICPS framework (E2c, E2d, E2e, E2h). According to the experts, recognizing an opportunity depends on *personal gut feeling, pivoting,* and *timeliness*. The former factors *sensitiveness to market needs* and *coping with uncertainty* previously located in the market introduction phase have been assessed by several experts to be more or less congruent. Moreover, the experts emphasized that addressing these factors is already important at identifying an opportunity and could be realized by *pivoting* (E1b, E1c, E1g, E1h, E2d, E2h). Correspondingly, these factors have been left out in the ICPS framework and the factor *pivoting* has been included.

The *personal gut feeling* is a soft factor and quite intangible. It is based on personal market knowledge and work experience of the idea provider. However, radical ideas correlate with a high level of uncertainty and predicting their success probability is like looking into a crystal ball (E1g, E1i, E2h). Thus, in the end, *opportunity identification* depends on a disproportionate amount of instinct (E1a, E2c, E2e, E2h). Moreover, the initial market conceptions should be tested, evaluated, and adjusted in an iterative, agile, and repetitive approach as soon as possible (E1c, E1i, E2a, E2f, E2g, E2i). *Pivoting* supports an effective and efficient evaluation of the focal opportunity (E1d, E1i, E2f). Therefore, customers should be involved in an early stage of the innovation process to generate concrete feedback on the actual market needs with respect to the aimed products and business models (E1i, E2f, E2g, E2j). Mostly, time slots for potential opportunities are limited and narrow (E1c, E2j). *Timeliness* is correspondingly a crucial prerequisite for being successful. In the case of entering the market too late, the addressed market needs may already be satisfied (E1c, E2a, E2c, E2d, E2e). Being too early may also be problematic if the market is not ready to adopt the innovation (E1h, E2j).

Product Development

For *product development*, the experts have emphasized the following CSFs: *lead user integration, development partnerships, risk & quality management, platform strategy*, and *intellectual property*. Compared to the TOMP framework, the factor *strategic alliances / partnerships* previously located in the diffusion phase has been split into two different types of partnerships, as both are important in their respective action fields: *development partnerships* and *commercialization partnerships*. Furthermore, the factor *platform strategy* has been integrated into the *product development* action field of the ICPS framework, as it is more a development rather than a commercialization issue. The former factor, *risk management,* has been expanded by the task of *quality management* as both tasks address similar directions. Finally, the factor *speed & costs* previously included in the *product development* phase of the TOMP framework has been relocated to the *innovation success* dimension and has been renamed as *efficiency* in the ICPS framework.

Conventional market research methods face limitations when it comes to radical technological innovations, as customers often cannot express their needs explicitly or even do not know them (E1c, E2i). *Lead user integration* can help to overcome this uncertainty as they reflect needs earlier than mainstream users and can thusly serve as orientation (E2a, E2b, E2d). Lead users are ahead of the mainstream market and have a strong interest in a technical solution for their problems (E2b, E2h). Furthermore, they can serve as references, which are very important for radical innovations (E1d, E1g, E1i, E2a, E2j). Similarly, *strategic partnerships*, e.g. with customers or research institutes, can vastly foster the development process. By sharing knowledge and resources, partners can utilize synergies and take advantage of their cooperation (E1c, E1e, E1i, E2a, E2b, E2d, E2h). Radical innovation projects are risky undertakings. Thus, preventing risks is impossible. However, figuring out the greatest technical and business-related risks is crucial for taking deliberate decisions (E2b, E2d, E2i). *Risk & quality management* helps to improve the overall probability of success by steering the innovation process (E1f, E1g, E1i, E2a). Nevertheless, not everything is ascertainable and too much formalism could hamper the speed and progress of the innovation process (E2b, E2h).

In the later phases of the innovation process, it is decisive to think about reducing production costs and rising *efficiency* (E2a, E2b, E2h). An adequate instrument therefor is *platform strategy*. Without much effort, customer-specific adjustments of the basic components and thus, faster development cycles are realizable (E1b, E1g, E2h, E2i). Another important aspect of the innovation process is protecting *intellectual property*. However, patent registration is expensive (E1e, E1g). Correspondingly, an organization should carefully consider in which situation filing for a patent is sensible (E1g, E1h, E1i). This also depends on the enforceability of a concrete patent idea and the overall intellectual property strategy of an organization (E2a, E2b, E2e, E2f, E2h, E2j).

Commercialization

In the ICPS framework, the former *market introduction* and *diffusion* stages have been combined to the *commercialization* action field. Correspondingly, the CSFs of both previous categories are contained in the united *commercialization* category: *value proposition & business model, commercializa-*

tion partnerships, timing, and *marketing*. As written above, the former factors *sensitiveness to market needs* and *coping with uncertainty* have been combined, relocated to *opportunity identification*, and renamed as *pivoting*. Furthermore, some experts underlined that the factor *value proposition* should be expanded by the associated *business model*.

The centerpiece of an organization's *value proposition* is customer benefit (E1c, E2i, E2j). This depends on customer needs and the associated added value of the organization's market offer compared with alternative solutions (E1h, E2b, E2e). If the focal market offer has no added value for the customer, it will not be successful (E1d, E2h). Apart from the *value proposition,* the associated *business model* is decisive for the *innovation success* (E1e). The *business model* describes the way the organization creates value and how it generates profit (E1f, E1i). In this context, *commercialization partnerships* become important. Strategic suppliers support the organization with value creation and strategic sales partners while customers support with revenue generation (E1e, E2b). Exchangeability of partners is often impossible as radical innovations are mostly associated with a high level of complexity. Hence, partnerships thrive on mutual trust and long-term relationships (E1d, E1g, E2a, E2d, E2i). The *timing* of market introduction depends on the strategic direction of the organization regarding the chosen pioneer or follower strategy (E2b, E2d). In principle, an innovation should be introduced to the market as fast as possible after reaching technological maturity (E1d, E1e). Nevertheless, further factors like the competitive situation and market readiness affect the appropriate time to launch (E2b, E2h). A sound *marketing* concept should accompany the market launch (E1d, E2a). However, *marketing* in the B2B-sector, is quite different from the B2C-sector, especially for technically complex innovations that require explanation. B2B-marketing has to be more rational, less emotional, and based on a sound technical argumentation (E1e, E2d). Effective B2B-marketing channels are trade shows, press releases, and technical press (E1f, E2e, E2h).

5.2.2.3 Innovation Success

Promising prospects of *innovation success* are the underlying motivation for starting any innovation project (E1g, E2h, E2i). As it forms the key target figure for innovation projects this dimension has been added to the ICPS framework. The interviewed experts expressed three factors contributing to innovation success: *sales performance, product performance,* and *efficiency*. These metrics are difficult to capture in the beginning. However, in the end, they manifest whether an innovation project is determined successful (E2g, E2i).

Finally, an organization wants to make money with the innovation (E2d, E2i). Therefore, the central figures reflecting *sales performance* are revenue and profit (E2d, E2g). In general, the aim is to achieve a quick return on investment (E1g, E2a). However, to obtain sustainable earnings, a high market share and prospective revenue growth are addressed (E1i, E2d, E2h). *Product performance* is another important assessment criterion for innovation success. The quality and performance of the central innovation are crucial for customer satisfaction (E2h). Only if the customers are satisfied with the product performance they will report positively about the innovation (E2d, E2e, E2i). This is an essential prerequisite for sustainable sales that furthermore contributes to a positive reputation of the organization (E2c, E2e). Moreover, *efficiency* within the innovation process plays a major role in the overall innovation success (E1c, E2e). The challenge is to achieve an error-free product without major failures and with a limited amount of time and budget. Hence, a sensible combination of effectivity and efficiency needs to be reached (E2a, E2d, E2h).

5.2.3 Discussion and Limitations

There are some limitations with respect to the research approach outlined in this chapter. Large sample sizes are generally not possible with qualitative expert interviews (Lamnek, 2005, p. 365). In order to counter this, 19 experts have been deliberately selected with the method of theoretical sampling. However, these interviews only reflect the opinions of a small group and the results of the interview analysis are thus, not generalizable. Moreover, the interviews followed a retrospective nature. The experts were asked to report about their experience with radical technological innovation projects. In retrospect, the projects may potentially seem to be more rational and well-ordered than they originally were.

As detected during the literature review, there is no uniform concept of the innovation terminology. Similarly, to the authors of the analyzed books, the understanding of the term innovation differs considerably among the experts. On the one hand, all experts agreed that an innovation has to reflect a certain level of newness. On the other hand, the experts disagreed on the second prerequisite for innovation – commercial exploitation. Certain experts required market implementation while others claimed an economic benefit for the innovating organization, and still others demanded overall market success of the innovation. These different conceptions of innovation had to be considered when analyzing the interviews. Furthermore, the research approach was not started in an unbiased way, as the TOMP framework was used as a research guide for conducting the interviews. Nevertheless, the six quality criteria for evaluating the scientific quality of qualitative research proposed by Mayring have been accurately applied as reported in chapter 5.2.1.4.

5.3 Primary Case Study Research

In principle, radical innovations are unique (Abetti, 2000, p. 208). Depending on the situation, the company type, and the respective industry, different CSFs probably become more or less important. Thus, the ICPS framework, which seeks to capture an overall and comparative understanding of radical innovation, should be tested in real life environment for verification and validation. To gain a deeper systemic, holistic view with respect to the specific combination, peculiarity, and significance of the identified CSFs, primary case studies can help. These are multi-perspectival analyzes that serve as an instrument to analyze and to understand complex issues in real life (Tellis, 1997). This method is most likely to be appropriate for "how" and "why" questions (Yin, 2009, p. 27). Therefore, taking the ICPS framework as a theory model, three real life cases of radical technological innovations within the mechanical engineering industry have been studied: P1.18 bicycle transmission by Pinion, Friction Disc by SKF, and cryogenic machining by 5ME.

5.3.1 Methodology

5.3.1.1 Case Study Design

The multiple-case study design has been chosen to analyze the realization of radical technological innovations with varying innovation contexts. Yin proposes a procedural model (cf. Figure 21) for conducting multiple-case studies that has been followed. The initial steps were theory development, case selection, and design of the case specific data collection protocols. Within this study, the ICPS framework represented the underlying theory (cf. Figure 20) and was used as a reference model and research guide. Each individual case study consisted of a whole study, in which convergent evidence was sought regarding each CSF of the ICPS framework. Afterward the results of the individual case studies were compared and cross-case conclusions were drawn. Thereby, it was checked if modifying the ICPS framework was needed. The findings and associated strategy implications for innovating organizations were documented in the cross-case report of the multiple-case study (cf. Wohlfeil and Terzidis, 2015b). The dashed-line feedback loop in Figure 21 indicates that case study research follows an iterative approach (Yin, 2009, pp. 56–58).

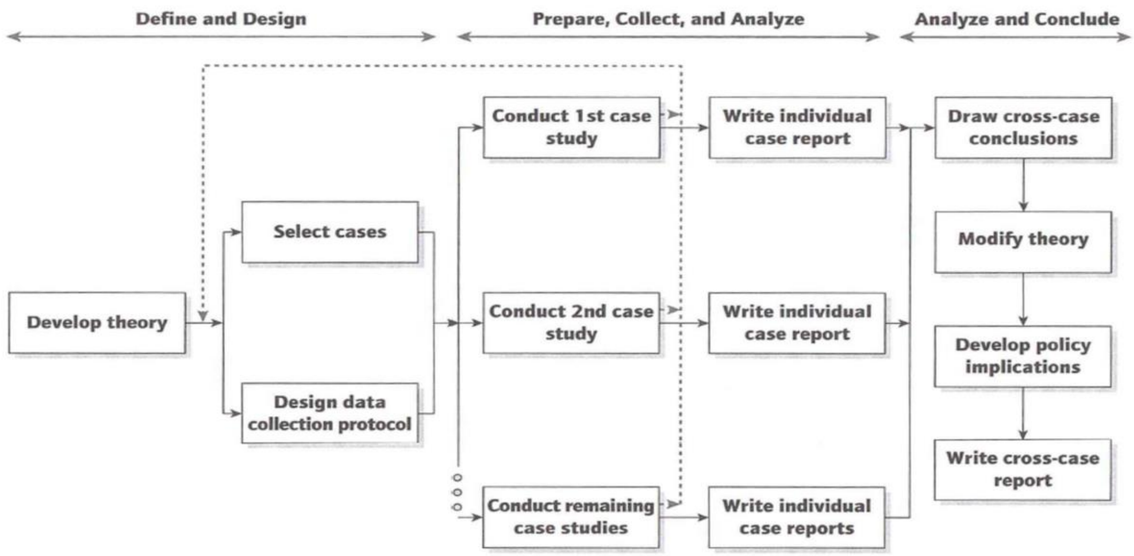


Figure 21: Multiple-Case Study Procedure (Yin, 2009, p. 57)

5.3.1.2 Case Selection

Case selection was based on theoretical replication logic. Therefore, a defined set of operational criteria to select appropriate cases was followed (Yin, 2009, p. 91). The main criterion for choosing cases was their relevance for the current topic: radical technological innovation within the mechanical engineering industry. The search was focused on product and process innovations with a high level of novelty. These innovations should have reached application maturity and should have already been implemented in the market. Furthermore, the innovation contexts of the potential case study candidates should have varied. Another distinguishing characteristic of the case sample was the innovation trigger in the sense of technology-push and market-pull. For not implementing too many degrees of freedom into the case study design primarily successful innovations were focused. Moreover, several research-related pragmatic factors were considered (e.g. data access).

Consequently, three cases were selected: P1.18 gearbox transmission by Pinion as competitive shifting system for bicycles, Friction Disc by SKF as intermediate disc for highly loaded flange couplings in the industrial drive branch to lift the friction coefficient between the contact surfaces, and cryogenic machining by 5ME as alternative to traditional flood coolants for industrial machining processes. Each of these innovations represented a product or in the case of 5ME, a process innovation within the mechanical engineering industry that exhibited a high level of novelty compared to the established solutions. The selected cases were successfully implemented in the market and the specific contexts of these innovations were different. Each case had a different type of organizational background (start-up, major corporation, spin-off), target industry (bicycles, wind power, machine tools), and of course, entrepreneurial team. The innovation trigger for the SKF Friction Disc was market-pull while it was technology-push for the Pinion P1.18 and cryogenic machining by 5ME.

5.3.1.3 Data Collection

In case studies, the richness of phenomenon, the extensiveness of real-life context, and the absence of routine procedures turn data collection into a complex endeavor. In response, Yin postulates three principles of data collection for high-quality case studies: (a) using multiple, not just single, sources of evidence; (b) creating a case study database; and (c) maintaining a chain of evidence (Yin, 2009, p. 100).

Following these recommendations, data for this study were collected from multiple sources, including primary (expert interviews and discussions), as well as secondary sources (e.g. presentations, data sheets, test reports, research papers, and press releases), for reasons of triangulation. The main data source formed the conducted non-standardized, guided interviews with key stakeholders and experts that were responsible for the realization of the addressed innovations. Furthermore, the software “Citavi 4 Pro” was used to establish a database that contained the raw data in an orderly and retrievable compilation. To maintain a chain of evidence, the reader of the case study reports should be able to follow the derivation of any evidence from the initial research questions to the ultimate case study conclusions. Thus, the report needs to contain a clear link to the underlying data (Yin, 2009, pp. 122–123). To achieve this, any data were documented and archived in the database (e.g. by recording interviews and storing internet links). Lastly, a data collection protocol for each individual case was prepared that contained the specific circumstances for data collection and the concrete case study questions. In Appendix III – 1 an aggregated version of the three protocols can be found.

5.3.1.4 Data Analysis

Data analysis on the single case level consisted of examining, categorizing, testing, and recombining evidence, to draw empirically based conclusions. The ICPS framework served as the theoretical orientation guiding the case study analysis as a general analytic strategy. This approach helped to focus attention on certain data, to ignore other data, and to organize the entire case study (Yin, 2009, pp. 126–131). Correspondingly, each case was analyzed based on the three fundamental dimensions (innovation context, innovation process, and innovation success) and the associated CSFs.

Additionally, the technique of explanation building was utilized. Explanation building aims to analyze the single case study data by building an explanation about the case. Explaining a phenomenon is to stipulate a presumed set of causal links about it (Yin, 2009, p. 141). Therefore, the specific characteristics of each CSF within the concrete innovation projects were studied to investigate the impacts on the overall innovation success. On the multiple-case study level, the results of the individual case studies were compared and cross-case conclusions were drawn.

5.3.1.5 Quality Criteria

For judging the quality of case study research, four dimensions are essential: *construct validity, internal validity, external validity,* and *reliability*. Yin presents certain tactics to address these quality criteria within the different research phases (cf. Appendix II - 2). Each of his recommendations has been applied successfully.

The quality test *construct validity* judges if the operational measures for the concepts being studied are correct. The advised usage of multiple sources of evidence and the establishment of a chain of evidence has been previously described in the data collection section (cf. 5.3.1.3). Having key informants review the draft of the case study reports is an additional method that has been followed. Their feedback has been integrated into the final case study version. Informants may disagree with an investigator’s conclusions and interpretations, but should not disagree over the actual facts of the case. This is a way of corroborating the essential facts and evidence presented in the case report (Yin, 2009, pp. 182–183).

A high level of *internal validity* can be achieved by establishing a stringent causal relationship from raw data to conclusions. This is primary an issue of the data analysis. As written above, the analysis technique of explanation building was utilized (Yin, 2009, p. 40).

External validity is tested to check if a study's findings can be generalized to the domain the research design pretends. This can be addressed by using straightforward theory in single case studies and following replication logic in multiple-case studies (Yin, 2009, p. 40). Within the single cases, data collection was based on the ICPS framework and overall case selection was done deliberately following theoretical replication logic.

Demonstrating that the operations of a study can be repeated, with the same results is represented by the quality criteria of *reliability* (Yin, 2009, p. 40). To address this issue, a case study protocol was elaborated for each single case study and a case study database was developed (cf. 5.3.1.3).

5.3.2 Case 1: P1.18 Bicycle Transmission by Pinion

Two engineers founded the Pinion GmbH to develop and exploit the P1.18 gearbox transmission concept as a competitive shifting system for bicycles to overcome the existent disadvantages of traditional derailleur systems and internal gear hubs.

5.3.2.1 Innovation Context

Technology

The P1.18 was designed as a spur gear consisting of two transmission structures that were connected in series. It was placed at the bottom bracket and had thus, an optimal position within the two-wheeled vehicle bicycle. Via pedal, the first of the two parallel partial shaft transmissions, equipped with three pairs of gears, was driven. The second shaft transmitted the power on six pairs of gears. The multiplication of six by three ratios gave 18 real ratios (Pinion, 2013a, pp. 3–6). In principle, there were two basic alternatives to the Pinion transmission: internal gear hubs and derailleur systems.

Figure 22: P1.18 Gearbox (Reidl, 2012)

To get a better overview of the relative advantages of the P1.18 bicycle transmission, three of the most competitive internal gear hub concepts and one representative and widespread derailleur concept have been compared to the P1.18. Therefore, eight evaluation criteria have been derived from diverse bicycle test reports. The different shifting systems have been evaluated with respect to the degree of which they met these evaluation criteria on a ten-stage scale (cf. Figure 23). The detailed comparison is available in Appendix III – 3.

Compared to its alternatives, the advantages of the P1.18 gearbox were the great overall ratio range, the number of real gears, and the position of the center of gravity. In contrast, the high system weight, the obligatory need for frame construction change, and the currently high price were its disadvantages. The deployed technology of the P1.18 was mature and entered series production in July 2012 (Schäfer, 2013). Thus, the Pinion team brought their technology from TRL 4 (as the fundamental concept was transferred) to TRL 9.

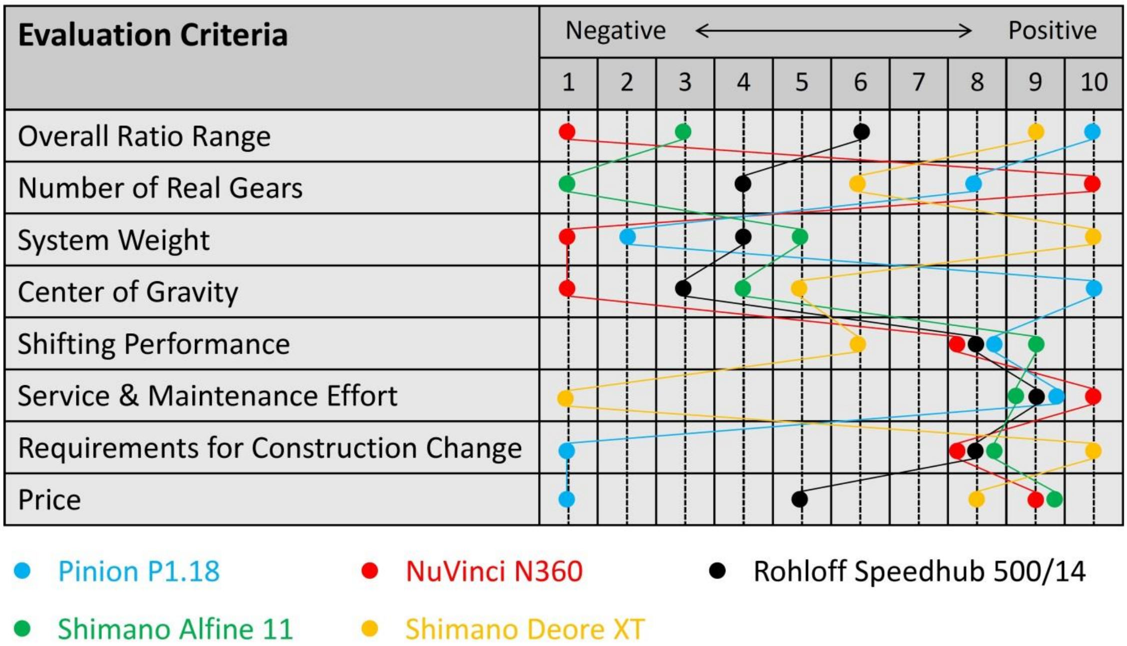


Figure 23: Overview of the Relative Advantages of the P1.18

Target Market

The P1.18 was meant to be a premium product. With the German niche market for the high-end mountain, trekking, and touring bikes, Pinion had a regional, model segment, and quality level focus. However, the company was planning to cover the entire bicycle market little by little in Europe and at some point afterward, globally. In both model segments, the advantages of the gear-box were highly visible. Overall, the industry context was predominantly positive for Pinion. Environment and sustainability have become important topics in society and politics. Different laws and regulations already reflected this growing environmental awareness. A maintenance free bicycle gearbox seemed to match the spirit of the time and to be a product with good prospects (Pinion, 2013b, 2013a, p. 16).

Pinion was the only company to distribute this specific gearbox technology. Thus, it just had to compete with its technological alternatives. The main barrier that hampered the market introduction of the P1.18 was the skepticism towards the new technology and even more towards the young start-up company. Regarding absolute numbers, the German bicycle market was very big and even the high-end sector of a submarket served a very attractive opportunity for a start-up like Pinion. There were still several thousand gearboxes potentially saleable (Pinion, 2013b).

Organization

It was the strategy of the two engineers to develop and commercialize the P1.18 bicycle transmission in accordance with automotive standards. To reach this goal, Pinion developed primarily independently and waited long before presenting their gearbox to the public. The Pinion GmbH, the company's full name to include the German legal form abbreviation, had a small size and correspondingly, the structure and processes were relative loose. The company had a flat hierarchy and few predefined processes including a low level of bureaucracy. Accordingly, the company culture was very innovation-friendly and open-minded with respect to new ideas (Pinion, 2013b, 2014b).

As gear manufacturing, in particular, the creation of prototypes, was expensive, the company had to search for financial resources quite early. Pinion had an advantage in this search, as their product innovation was already quite tangible. This meant it was not a big challenge for the team to get access to potential investors. The team finally met an investor who was a supplier of the automotive industry and showed great interest in the project. After several discussions and tough negotiations, the team officially founded the company together with this investor in October 2008. Nevertheless, with the emergence of the automobile crisis by the end of 2008, this investor abandoned his short-term cooperation (Pinion, 2013b; Reidl, 2012). After some unoccupied months, the team got in contact with another investor and signed a partnership contract with him in October 2009. The team was quite lucky, as their new investor was enthusiastic about the product and provided not just money, but additionally technical and personal interest (Donner, 2012). He was not just an investor but a mentor and consultant as well (Reidl, 2012).

Entrepreneurial Team

Since the beginning of 2014, Pinion has nine employees not counting the two founders. The newly recruited staff mainly consisted of university graduates and first-time employees. These young, enthusiastic employees were very motivated, creative, had many ideas, and worked together as a team. Nevertheless, Pinion lacked experienced personnel that possessed serenity, sovereignty, and know-how to deal with challenging situations. The two founders were aware of this and were, therefore, planning to hire, preferentially, senior professionals within the next recruiting round (Pinion, 2013b, 2014b).

5.3.2.2 Innovation Process

Opportunity Identification

For the Pinion team, the ambition to solve the central technological challenge was the main trigger to start their own business. The enthusiastic mountain bikers were unsatisfied with traditional derailleur systems with their typical problems of stuck chains, bent derailleurs, and the need for time-consuming care and maintenance after each ride. They asked themselves why there should be maintenance free gearboxes in cars and motorbikes but not in bicycles. Having found no satisfactory answer to this question, the time seemed right to realize their vision of developing a competitive gearbox for bicycles in accordance with automotive standards in order to offer a real alternative to the traditional derailleur system. Starting with rough paper sketches, various transmission concepts were developed, discarded, and revised on their way to a mature product (Pinion, 2013b).

Product Development

At product development, Pinion integrated lead users to test gearbox prototypes. Primarily, these were skilled amateur cyclists that contributed to product development by providing detailed feedback. The breakthrough of the P1.18 was accomplished when in 2010 a friend of the two Pinion founders and extreme cyclist crossed the Himalayas riding a P1.18. Naturally, Pinion had to cooperate with frame-builders that designed and produced the modified frames for the gearbox. Apart from that, Pinion followed an autonomous development approach (Pinion, 2013b).

The company had no structured risk and quality management system. Intuition and collective decision making after a short conversation among the founders formed the main basis for their risk evaluation. As much as possible, Pinion was trying to establish a common part and platform strategy. During the development of the P1.18, the company had developed a modularized system with different components and mechanisms. At the conception of new products, these could be transferred with little modification as the basic development has been done. Obtaining a patent for the fundamental gearbox concept has not been possible as this idea was not new. As a result, Pinion strived for protecting individual aspects of the principle concept. Further, the IP-strategy of the company was dependent on its financial situation. In general, Pinion filed for patent protection with respect to inventions that were strategically decisive from a market point of view (Pinion, 2014b).

Commercialization

Besides the technical and economic benefits, the value proposition of a company is shaped by its service benefits. By offering a complete spare parts program, Pinion tried to ease and support the use of the P1.18 for its customers. As the company did not directly sell their gearboxes to the end-user, the P1.18 was solely available as an OEM component for volume bicycle manufacturers. Thus, they cooperated with several bicycle manufacturers, who were Pinion's customers and the de facto technology disseminators. Finally, the bicycle dealers sold Pinion equipped bicycles to the end-users. All parts of the gearbox were completely developed and designed by Pinion but fabricated in contract production by strategic suppliers (Pinion, 2013b). Pinion deliberately chose their first trade fair attendance in 2010. As Pinion's customers needed one to two years for preparing bicycle models for the usage with the P1.18, Pinion had to assume the specific moment in time when the P1.18 had achieved a maturity level that series production of the gearbox could be reached within the next one to two years. Pinion's assumptions were good as the company reached series maturity in 2012. Since their first attendance, Pinion steadily exhibits at big trade fairs and strategically plans its marketing efforts (Pinion, 2014b).

5.3.2.3 Innovation Success

By 2014, more than 1,000 gearboxes have been sold since the P1.18 entered series production. Pinion expected to reach sales figures of the mid-four-digit range within the subsequent years. On a scale from great skepticism if Pinion would still have a product on the market in the future until the P1.18 was a natural alternative to the established shifting components, Pinion estimated to be positioned right in the middle (Pinion, 2013b).

The P1.18 gearbox was a mature product by 2014 that met its high requirements with respect to load, durability, and performance. Several benchmark tests have been conducted and the reaction and response to the gearbox were predominantly positive (Reidl, 2012). In comparison with alternative shifting systems, the P1.18 had concrete advantages as well as concrete disadvantages (cf. Figure 23). Therefore, it was essential to hit the customer preferences of the chosen target group.

Since idea generation, it took Pinion seven years to gain a mature product. For the sake of efficiency, the team tried to save costs as much as possible. The founders did not take high salaries, first worked with student licensees of their CAD-software, and installed an own test rig since external testing was very expensive (Pinion, 2013b).

5.3.3 Case 2: Friction Disc by SKF

The requirements for power transmission within the industrial drive branch increased over the recent years. To satisfy this demand SKF engineers developed the Friction Disc as intermediate disc for highly loaded flange couplings to lift the friction coefficient between the contact surfaces. Consequently, the power transmission could be clearly enhanced (Gläntz, 2011).

5.3.3.1 Innovation Context

Technology

The Friction Disc consisted of a defined sum of sector shaped elements that were inserted into the interspace of a flange coupling and screw-fastened. These elements were coated on both sides with a galvanic hard-dispersion layer which contained hard particles (Baumann, 2009, p. 38).

At screw-fastening, the hard particles were pressed into the flange material and achieved a mechanical interlock between the device and the two shaft ends. Therewith it was possible to significantly increase the transmissible torque and thus, reduce the main dimensions of the powertrain. Furthermore, the assembly process could be considerably shortened. (SKF, 2014b; Baumann, 2009, p. 38; Gläntz, 2011).

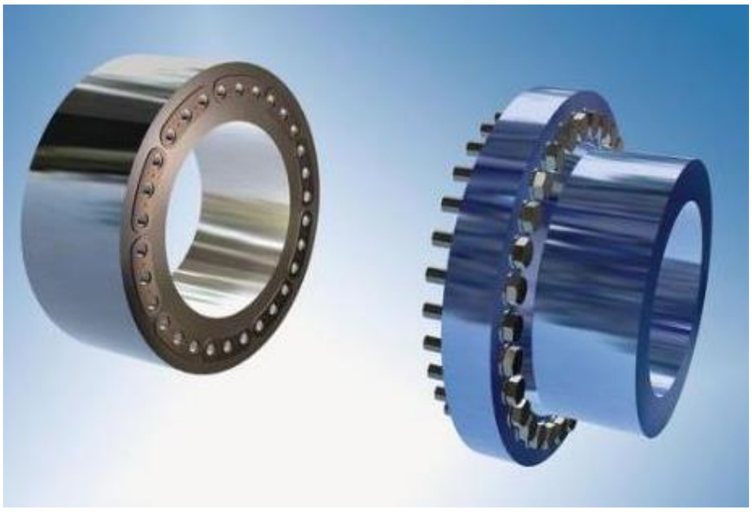


Figure 24: Friction Disc (Gläntz, 2011)

In general, there were three potential alternatives to the Friction Disc to transmit the operating torque in the drive train of a wind turbine: friction shims, shrink discs, and blank flange couplings. For assessing the relative advantages of these solutions, eight evaluation criteria have been established in consultation with a team member of the Friction Disc project at SKF. Based on these criteria, the technological alternatives have been assessed with respect to the degree to which they met the eight evaluation criteria on a ten-point scale (cf. Figure 25).

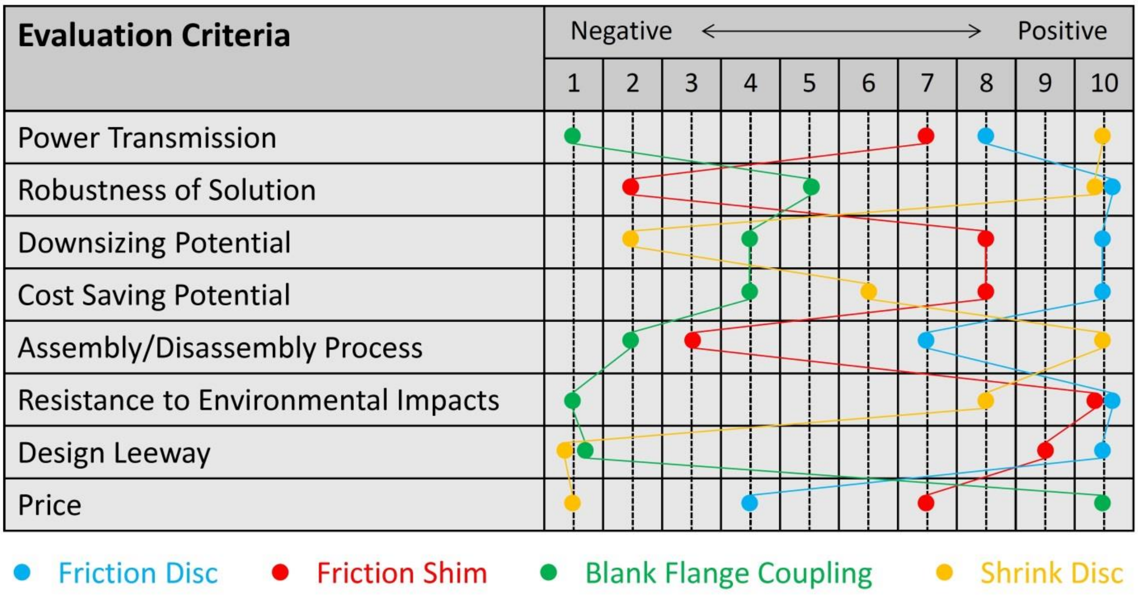


Figure 25: Overview of Relative Advantages of the Friction Disc

The unique advantage of the Friction Disc compared to its alternatives was the great downsizing potential for the wind turbine that ultimately could lead to huge cost savings. The Friction Disc offered much leeway for the designer and opened up great opportunities to create new and innovative solutions. However, the corresponding price of the Friction Disc had to be considered.

As the Friction Disc was introduced to the market in 2009, the product was mature and achieved TRL 9. Before technological development started, the friction increasing coating procedure had just been applied for relatively small surfaces like drills and tools. Thus, the technology was on the maturity level TRL 3.

Target Market

The field of application for the Friction Disc was heavy mechanical engineering. Initially, the wind industry was addressed as a first target market. In 2006, the development was started for Senvion's 3.3-megawatt onshore turbine. SKF and its customer established a development contract and assured mutual exclusivity within the wind industry (SKF, 2014b, 2014d; Senvion, 2014, p. 1). The industry context for wind turbines had been mainly positive. Wind energy was clearly on the rise and characterized by a massive increase of power range. Similarly, keeping the individual item weights within the nacelle controllable was a central task. The Friction Disc helped to deal with this challenge (Gläntz, 2011).

As SKF was single supplier of the Friction Disc, there was no competition for this innovation. A general prerequisite to entering the wind energy market was the certification process. With its partners, SKF managed to achieve the required certification and thereby the permission to enter the market. Further market barriers were the requirements of SKF's customer, but SKF was able to satisfy these needs (SKF, 2014b, 2014d). Due to the mutual exclusiveness, SKF's success was linked to its customer's success (SKF, 2014d). This appeared not to have a negative effect, as the market for 3.3-MW wind turbines – the primary application area of the Friction Disc – grew steadily over several years (p. 32). Moreover, there were additional opportunities for the Friction Disc each time it was required to transmit high torques, e.g. in industries like rolling mills, turbo-machines, marine, or power plant construction (SKF, 2014d).

Organization

The Friction Disc has been developed within SKF Germany. The SKF Group being a leading global supplier of products, solutions, and services within rolling bearings, seals, mechatronics, services, and lubrication systems had more than 45,000 employees by 2014 (SKF, 2014a, p. 1). The project has been initiated within the innovation department Flexi Force and was carried out by a cross-functional project team. With the Friction Disc project, a dedicated customer focus when delivering sustainable value was realized. Thus, the project was actually in line with the SKF group goals as well as with the Flexi Force department goals (SKF, 2014b, 2015, p. 11).

The product innovation process of the Friction Disc was realized based on the Stage-Gate process according to Cooper. The process worked well and allowed enough flexibility for the team. On the other hand, the transfer into series production turned out to be more difficult. The Friction Disc was meant to be a niche product. While the SKF was well positioned to handle high volumes, the handling of brand-new innovations was challenging due to the initially low volumes. Correspondingly, the overall company culture was mainly shaped by a low level of failure acceptance and little appreciation for radical innovative initiatives like the Friction Disc. This situation presented real challenges for the project. In the beginning, the team had to defend their project against tough internal criticism. Thus, an essential support for the team to overcome these internal hurdles was the high level of upper management commitment. When the first test results turned out to be positive, any further expenses were sanctioned without major discussions having to take place (SKF, 2014b, 2014d).

Entrepreneurial Team

The core entrepreneurial team within SKF was composed of three persons: an innovation manager, a project manager, and the key account manager for SKF's customer. The people fulfilling these roles had a high level of experience and professional competence. Correspondingly, the team saved a lot of time and costs during the innovation process. Despite several setbacks during the project caused by internal and external skepticism and contradictions, the core team members showed great perseverance. They were highly motivated to make the project a success and were convinced of its potential. Furthermore, they trusted each other and worked as a team. After the development contract with the customer was signed, the core team was joined by further representatives from production, design, and quality management. Having this broad and profound team network in place ensured an efficient innovation process (SKF, 2014b, 2014d).

5.3.3.2 Innovation Process

Opportunity Identification

SKF's key account manager had to constantly have his finger on the pulse when it came to the customer and had to monitor the market closely. He observed that SKF's customer faced technical challenges during the conception phase of the 3.3-MW wind turbine, the largest onshore wind turbine at that point in time. A major challenge was to design the turbine in such a way that it was still transportable on the streets. Based on discussions with the customer, the idea emerged that a friction increasing intermediate disc for flange couplings could enhance the transmissible torque capacity. According to his personal gut feeling, he realized that this represented an opportunity for SKF. The time was right as SKF's customer was just starting the development of its new wind turbine. The team followed an iterative process to align the customer needs to the product (SKF, 2014b, 2014c, 2014d).

Product Development

In the case of the Friction Disc, SKF's customer was also the lead user of the product. Both parties signed a non-disclosure agreement and subsequently concluded a development contract as a basis for their cooperation. Thus, SKF's customer was closely integrated into the product development and was updated frequently on a regular basis. SKF involved two further strategic partners in the development process. One partner took responsibility for the coating process. Furthermore, SKF cooperated with the technical university of Chemnitz for testing the ultimate friction coefficient (SKF, 2014b, 2014d).

During the process, SKF followed a detailed risk and quality management. Potential risks were constantly analyzed and every process step was documented in detail (SKF, 2014b). SKF finally achieved an assured coating process that could be utilized not just for the Friction Disc, but for many other shapes of blanks. SKF's customer was the patent owner and SKF received the license to produce the Friction Disc. SKF subsequently protected the coating process, its associated measurement method, and the technical configuration of the Friction Disc (SKF, 2014b, 2014d).

Commercialization

Because of the mutual exclusivity regulated in the contractual agreement, commercialization of the Friction Disc in the wind industry was limited to this customer. In other industries, SKF was free to commercialize. The central value proposition of the Friction Disc was the possibility to downsize the main dimensions of the powertrain, its associated potential for weight reduction, and the simplified assembly process. Moreover, SKF consulted, extensively, its customers regarding application engineering. In general, the SKF value creation contained product development, application engineering, parts of the manufacturing process, and taking the overall responsibility for the final product. For any further value-creating step, partners were involved. Thus, SKF strategically cooperated with a supplier that produced the disc blanks and with another company that took responsibility for the coating process. The timing of market introduction was exactly right, as SKF managed to synchronize the development process of the Friction Disc with that of the wind turbine powertrain of SKF's customer. A few trade fair exhibitions and some supporting promotional material attracted some customer attention. However, to increase customer awareness of the Friction Disc and its benefits, a greater focus on marketing should have taken place (SKF, 2014b, 2014d).

5.3.3.3 Innovation Success

By 2014, every wind turbine of SKF's customer in the 3.3-MW-class was equipped with the Friction Disc. Since its market introduction in 2009, the yearly sales figures have been constantly rising and by 2014, a medium three-digit sales number has been reached. The Friction Disc became a particularly profitable and sustainable business for SKF and overall it has provided a very good return on investment. However, notwithstanding the great potential of the Friction Disc for further applications in other industries, there were just a few alternative applications that have been equipped with the Friction Disc (SKF, 2014b, 2014c, 2014d).

The product performance of the Friction Disc was very high and met the exact requirements of the customer. Several field tests have proven its performance and the friction coefficient, which was the main feature of the Friction Disc, has been certified by an accredited certification organization. Even after several years of use, the Friction Disc exhibited no loss of quality and by 2014, SKF had not a single return from the customer (SKF, 2014d).

The overall efficiency of the innovation process was considered quite high regarding both dimensions – costs and duration. The period between the first customer contact and series production of the Friction Disc amounted to a very short duration of 2.5 years. Furthermore, the team took particular care to keep the development costs down (SKF, 2014b, 2014d).

5.3.4 Case 3: Cryogenic Machining by 5ME

5ME was founded as a spin-off from the global machine tool manufacturer MAG IAS to develop and implement cryogenic machining on the market for industrial machining processes. In contrast to traditional flood coolants, the cutting heat was dissipated by means of liquid nitrogen.

5.3.4.1 Innovation Context

Technology

Machining generates heat at the cutting edge due to friction, shearing, and abrasion. The faster the cutting speeds, the higher the heat. With rising heat, tool wear and thus, costs increase rapidly. Correspondingly, the heat needs to be dissipated. Any cooling media helps to reduce the cutting heat (5ME, 2014c).

The 5ME technology utilized vacuum jacketed feed lines for transmitting small flow rates of liquid nitrogen at -196°C through the machine, through the spindle, and through the tool directly to the cutting edge to maximize cooling effectiveness (5ME, 2014i, p. 32; MAG IAS, p. 2). The tools for cryogenic machining needed to be specifically designed to interface with the cryogenic system for reasons of proper functionality and safety (5ME, 2014g).

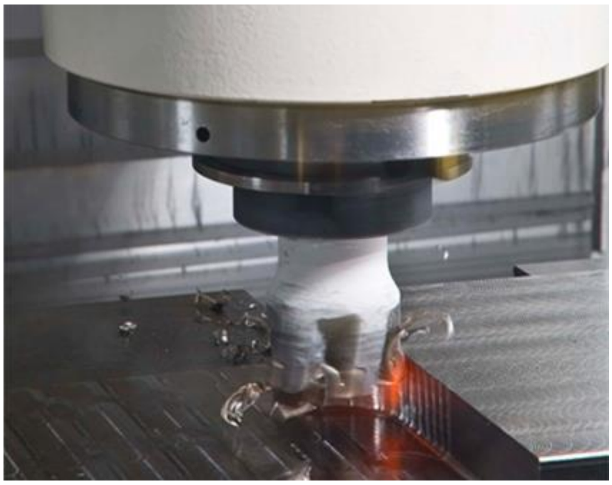


Figure 26: Cryogenic Machining (5ME, 2014i, p. 30)

There were several alternative cooling methods to dissipate the heat generated by the machining process. 5ME targeted hard to machine materials and thus, just these technological alternatives have been analyzed that also addressed this kind of material. According to 5ME, there were five alternatives worth analyzing. To gain the relative advantageousness of the LN_2 cryogenic machining, ten evaluation criteria have been derived in consultation with 5ME's Cryogenic Engineering Manager (5ME, 2014k). With respect to the degree of which they met these criteria on a ten-stage ordinate scale, the cooling alternatives have been assessed (cf. Figure 27).

Especially, for tough-to-machine materials, the technology had great advantages regarding tool life, cycle time, and product quality. Accordingly, the productivity of this process was on a very high level compared to its alternatives. This became additionally apparent if the low running costs and low downtime rates were placed as the focus, which led to a higher profitability of the overall process. Furthermore, LN_2 cryogenic machining was a green and safe technology. Nevertheless, regarding investment costs and construction change the technology was among the lowest ranked.

In 2007, MAG IAS took over the technology from an engineering and development firm that validated its applicability in a laboratory environment (TRL 4). From 2007 until 2013, MAG IAS developed the technology further until TRL 7 and showcased a prototype machine at several industry trade shows (5ME, 2014n). With spinning-off, 5ME pushed the technology development. By the end of 2014, the first machine was shipped and was brought into industrial use in the first quarter of 2015. Thus, the technology had reached application maturity and achieved TRL 9. Nevertheless, the market was not properly familiar with the technology by 2015 (5ME, 2014j).

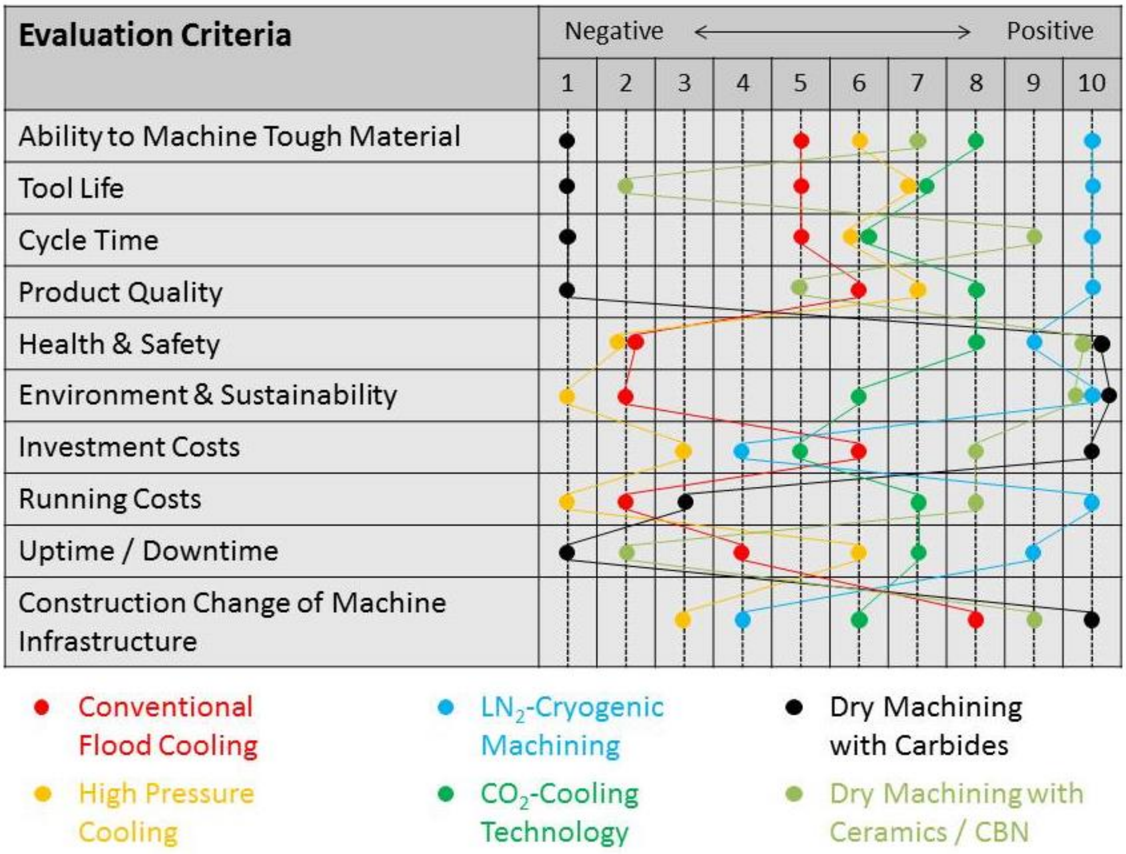


Figure 27: Overview of Relative Advantages of 5ME`s LN_2 Cryogenic Machining

Target Market

5ME's long-term vision was to eliminate coolants on every machining operation and shift the market to cryogenic machining. In the short term, 5ME was focusing on the difficult-to-machine materials as these applications gained an intermediate effect from the new technology (5ME, 2014j). These materials were most commonly used in four industries, which correspondingly form the target market of 5ME: aerospace, oil & gas, automotive, and construction and agriculture. The initial geographic focus was the Northern American market (5ME, 2014l). From a customer standpoint, 5ME addressed companies that machined parts and machine tool builders. For the first group, 5ME aimed to sell the cryogenic system in the form of retrofit kits. With the other group of customers, 5ME planned to cooperate by applying cryogenic machining to their machines before they would have been shipped to end-users (5ME, 2014n).

Within the American metalworking machinery manufacturing industry, improving business conditions have led to an increased demand for machine tools by 2015 (Gardner Research, 2014, p. 2). These industry trends strongly supported the establishment of cryogenic machining. From a market opportunity standpoint, there were several thousands of machines that fitted the criteria of cryogenic machining. One of the basic barriers to entering the market with cryogenic machining was obligatory approvals, especially in the aerospace industry. 5ME already achieved approvals for several processes and was constantly working on further ones. Apart from the certification requirements, cryogenic machining was a radical new technology that required a lot of change. Understandably, this led to a great uncertainty on the customer side. Most of the potential customers wanted to see references. With respect to cryogenic machining, there was actually no competitor in the market. 5ME's job was more about convincing the end-user to change the way they traditionally machined parts (5ME, 2014j, 2014n, 2014o).

Organization

The non-machinery units of the former MAG IAS machine tool manufacturer were spun-off and emerged as 5ME from then on. Their strategy was to increase their customers' manufacturing efficiency to generate profitable, competitive, and sustainable businesses. The organization was very flat and flexible from an organizational standpoint (5ME, 2014n). Correspondingly, the decision making processes within the company were very lean. Due to the flexibility of a start-up, 5ME was able to adapt its technology goals and strategy roadmap very quickly according to the feedback of its customers (5ME, 2014n). Overall, the innovation climate was very good within 5ME and the whole team was absolutely committed to the technology and the company (5ME, 2014l). 5ME had a single investor that owned the company and allocated the funds. In the face of this risky endeavor, strong management and owner commitment was essential and, in the case of 5ME, present (5ME, 2014l, 2014n).

Entrepreneurial Team

By 2015, 5ME had about 45 employees. The team consisted of managers, engineers, and employees that have originally worked for the former MAG IAS business units, which have been incorporated when spinning-off. With respect to their machine tool background and the standard machining operations, the team was very experienced right from the start. According to 5ME's president, the team was strongly committed to the company's goals, passionate regarding technology commercialization, and willing to take risks (5ME, 2014n).

5.3.4.2 Innovation Process

Opportunity Identification

As mentioned, MAG IAS took over the technology from an engineering and development firm that validated its applicability in a laboratory environment. In 2007, a visit of their laboratories was made by the MAG IAS management team. Once they witnessed what the engineering and development firm was doing, they realized the big opportunities of cryogenic machining (5ME, 2014n). After profound technology development and spinning-off, the timeliness for commercializing cryogenic machining within 5ME's focus industries seemed perfect by the end of 2014. Large customers in the automotive and oil & gas industry made significant capital investment approximately 15 to 20 years ago and were up to retool their facilities. In the aerospace industry, the F-35 Joint Strike Fighter program reflected another great chance for cryogenic machining, as the technology had great advantages for machining the F-35 titanium components (5ME, 2014o). 5ME started with a concrete roadmap of technology goals, but as the company was closely in touch with its customers and constantly asked questions, 5ME altered its roadmap based on this market feedback and pivoted. Interestingly, the first order the company received was of hardened steel, this was completely different from what 5ME initially focused on, but represented a good chance for initial business success (5ME, 2014n).

Product Development

At product development, lead-user integration played a big role for 5ME. By listening to these lead-users, 5ME understood their needs and derived the markets, where to commercialize first. Especially in the ramp-up phase of a radical new technology, it was essential to have a close relationship with the first users. Not everything went right at the forefront of technology implementation. Thus, it was important to find those customers that have the right culture and mindset to dare the risks. In these early phases, constant feedback was decisive. Furthermore, these users helped 5ME to offset their development costs by funding test runs (5ME, 2014n, 2014o).

5ME also established a limited number of strategically chosen development partnerships with several customers and certain universities (5ME, 2014n). They closely cooperated at bringing cryogenic machining to practice. 5ME did not have a detailed risk and quality management system but established some instruments to deal with emerging risks and quality issues. By 2014, the company was working towards a platform strategy to share common parts. However, everything up to this point had been unique regarding the first sets of machines (5ME, 2014o). Any time, 5ME came up with a good idea that had a vital commercial potential, the company tried to protect it and filed for a patent (5ME, 2014j).

Commercialization

The customer value 5ME was addressing with cryogenic machining was manufacturing efficiency. 5ME's business model was to generate the main revenue out of the peripheral tooling and selling the cryogenic kits cheap. The company expected that this would lower the entrance barriers and foster the commercialization of cryogenic machining. As the margins were even higher for the tools, the revenue opportunities of cutting tools were much higher than for the kits (5ME, 2014j, 2014o).

The company designed and engineered all parts of the cryogenic system, but did not produce them. All components were manufactured by suppliers according to 5ME's specification and shipped to 5ME. Therefore, the company had established several strategic relationships with specifically selected suppliers (5ME, 2014j). Since spinning out, 5ME did considerably more marketing. The company addressed the market with a new brand-name (5ME, 2014n). With a focused marketing approach, 5ME was positioning cryogenic machining as a premium solution for niche applications of tough material completely dedicated to manufacturing efficiency. Thereby, the company followed the timing strategy of a pioneer (5ME, 2014l).

5.3.4.3 Innovation Success

Until the end of 2014, virtually all of 5ME's revenue was generated by customer testing. The first customer machine was shipped and was going into production in the first quarter of 2015. Due to positive test runs in 2014, 5ME expected to win another eight to ten retrofit orders during 2015. This would start to cover 5ME's investments. Because of the lead times of these systems, 5ME estimated to reach the break-even point for cryogenic machining within 2017. From then on, the cryogenic machining business would be profitable (5ME, 2014n).

The performance results of cryogenic machining in the tech center were robust, repeatable, and thus reliable. Hence, the involved customers were very excited with respect to the achieved test results. However, no industry performance data were available by the end of 2014 (5ME, 2014o).

To keep the costs down, 5ME tried to get test funding from its customers. Moreover, the engineering team saved time and resources by following a smart testing approach. Overall, the company worked quite efficiently. However, commercializing this radical technology took time and investment. With respect to commercialization, the low amount of incoming orders was frustrating as 5ME wants to see things happen much faster. On a scale from one to ten, 5ME ascribed the technological development a seven and the commercialization a five by the end of 2014 (5ME, 2014n).

5.3.5 Cross-Case Conclusions

In fact, it was found that each company chose a unique strategic approach to realize their innovation that could be clearly reported on the basis of the ICPS framework. Depending on their individual context and the innovation trigger, the innovation process was organized. Some CSF characteristics were quite similar and some rather different. In the following, these similarities and differences will be reported within the three dimensions of the ICPS framework: *innovation context, innovation process,* and *innovation success*.

5.3.5.1 Innovation Context

The biggest differences about the innovation context were found in the organizational characteristics of the analyzed cases. 5ME and Pinion were founded for realizing their innovation. Thus, the structures and processes, as well as the strategic direction, were completely arranged to bring the innovation to success. Accordingly, the company culture was shaped by a great innovation climate. In contrast, the Friction Disc was developed within the cumbersome structures and processes of a major corporation. The strategic direction of SKF has been aligned to high-volumes and incremental advancements of existing products. Thus, the resulting situation caused challenges for the Friction Disc project. On the other hand, funding and resource allocation was easier for SKF. Equally, 5ME was in a comfortable situation as the company owner was the single investor at the same time. Pinion, on the contrary, had to struggle for sufficient investments while not giving away too many company shares. The investor commitment was good for each of the companies.

Regarding the technologies that underlay the respective innovations, there were similarities. All technologies were mature, as the associated innovations had already been implemented in the market. Furthermore, these technologies had distinct technological advantages compared to their alternatives. A common disadvantage of the technologies was their high price. In the case of Pinion and 5ME, a further handicap was their need to rebuild or construct infrastructure.

Another similarity of the analyzed cases was the fact that the involved people realizing the innovation projects formed a great entrepreneurial team. The teams were characterized by a high level of professional competence and experience. They were highly motivated, showed a great level of perseverance, and worked as a team.

The situation with respect to the target markets for the analyzed innovations exhibited both differences and similarities. The industry contexts and the overall opportunities were promising for the central innovations and offered enormous potential. On the other hand, the competitive situation and the market barriers differed for the three cases. 5ME and Pinion followed a technology-push approach. Thus, there were established alternatives on the market that the companies aimed to substitute based on their technological advantages. The innovation trigger for the SKF Friction Disc was market-pull, as SKF's customer had a concrete problem to solve. Hence, there was no technological alternative available. Correspondingly, the market barriers for SKF have just been technical ones. In the cases of Pinion and 5ME, the main obstacle, besides technological maturity, was to convince and persuade end-users to turn to their solution. However, they could potentially address any application in their target markets. In contrast, the Friction Disc was a solution that was specifically developed for the powertrain design of SKF's customer and was thus, not easily transferable to other wind turbines. Moreover, this was prohibited due to an exclusivity agreement. Hence, this agreement represented a temporal insurmountable hurdle for targeting the whole wind industry.

5.3.5.2 Innovation Process

Opportunity identification was quite similar. In each of the three cases, it was primarily based on the personal gut feeling of the respective protagonists who realized that the time was right for their invention. By pivoting, the companies figured out the requirements of their customers and elaborated a basic product concept.

Regarding product development, the three companies followed diverse strategies. Pinion followed a primarily autarkic approach while SKF and 5ME intensively involved external partners like research institutes and customers. All of the organizations involved lead users to gain concrete feedback. In the case of SKF, Senvion was both customer and lead user of the Friction Disc and thus, SKF intensively cooperated with this company. Risk and quality management was diversely formalized within the analyzed cases. Due to their company structures, SKF had the highest level of formalization followed by 5ME and Pinion. In general, all companies strove for common parts as much as possible. However, none of them had already achieved a sophisticated platform strategy, which was probably due to the high level of novelty of the analyzed innovations. The primary objective was the successful establishment of the innovation at their target market while standardization of the product components was a secondary goal. Just like the product development approaches differed, the strategies for protecting intellectual property varied within the three cases. Pinion and 5ME followed a broad protection strategy for their innovation to become the single patent owner while SKF shared the resulting intellectual property with its customer.

With respect to the commercialization strategy, many commonalities were observable within the three cases. The business models and commercialization partnerships were quite similar. Each company focused its value creation on engineering, and thus, the proportion of component suppliers was correspondingly high. The timing of market introduction of the analyzed innovations was primarily based on technological maturity. All companies followed the innovator strategy and wanted to access the market as fast as possible. Nevertheless, the marketing efforts differed for the analyzed cases. Presumably, due to the explicit focus on its single customer, SKF was comparably reluctant at promoting the Friction Disc. Pinion and 5ME, on the other hand, followed an intense marketing strategy to promote their innovation. This was probably due to the different kind of innovation trigger. As Pinion and 5ME followed a clear technology-push approach, they invested more than SKF who was following a market-pull approach.

5.3.5.3 Innovation Success

It was a precondition for case selection within the conducted study that the cases have been introduced to the market and exhibited a certain level of success. Since market introduction, Pinion's and SKF's product innovations were sold several hundred times. In contrast, 5ME had just introduced its innovation on the market and correspondingly only equipped one customer by 2014, the time the study was conducted. However, all products were mature, reliable, and the existing customers were satisfied with their quality. The efficiency of each innovation project has been very high. The companies tried to keep the costs on a low level and strived for quick innovation realization. Remarkably, it took SKF less than three years, Pinion less than five, and 5ME less than seven years to reach market introduction. The differing realization time might have been due to the clear application and customer focus of SKF and the broader market penetration strategy of Pinion and 5ME.

5.3.5.4 Summary

The main purpose of the conducted multiple-case study was to gain a deeper holistic view with respect to the specific combination, peculiarity, and significance of the CSFs and to ultimately validate the ICPS framework by applying it to real cases. Therefore, three cases of radical technological innovation within the mechanical engineering industry have been analyzed, namely P1.18 gearbox by Pinion, Friction Disc by SKF, and cryogenic machining by 5ME. Regarding the innovation context, the three cases differed mainly with respect to their organizational background and the characteristics of the addressed target market. Analyzing the different innovation processes, the cases varied mostly regarding the product development strategy. Furthermore, the marketing efforts of the different companies could be differentiated within the commercialization strategy. All analyzed innovation projects could be perceived as being successful.

Based on the varying contexts, each company followed a distinct, and with respect to the CSFs detailed in the ICPS framework, clearly differentiable strategy approach for the realization of their respective radical technological innovation. Depending on the situation, the organizational background, and the target market, CSFs like marketing or intellectual property protection became more or less important. Other CSFs like lead user integration and strategic partnerships were uniformly decisive while CSFs like platform strategy and deliberate timing strategies were less crucial within the analyzed cases. In general, the ICPS framework seems to be a sound basis to differentiate strategic approaches for the realization of radical technological innovations within the mechanical engineering industry. Each CSF detailed in the ICPS framework demonstrated its rationale, and in combination, they are a strong theory model of factors being crucial for the success of this kind of innovation. Based on the conducted multiple-case study, the ICPS framework does not need modification and thus, was confirmed.

5.3.6 Discussion and Limitations

There are several limitations associated with the conducted case study approach. One of the greatest concerns associated with case study research is the general allegation regarding lack of rigor and the absence of systematic procedures. To address this issue, Yin's guidelines for conducting high-quality case study research and his suggested quality tactics have been rigorously followed (cf. chapter 5.3.1 and 5.3.1.5). Nevertheless, the study is limited by the number of three analyzed cases. A natural suggestion for future research is therefore to increase the number of cases.

Another criticism is that the results of this qualitative multiple-case study may be rich in detail, but lack the simplicity of an overall perspective (Eisenhardt, 1989, p. 547). Correspondingly, a common concern is that case studies universally provide little basis for scientific generalization as the studied cases may describe only a very idiosyncratic phenomenon. According to Yin (2009), the short answer is that case studies, like experiments, are generalizable to theoretical propositions like the ICPS framework and not to populations. In this sense, the three cases do not represent a "sample", and in doing these case studies, the goal was to validate the ICPS framework (analytic generalization) and not to enumerate frequencies (statistical generalization). The ICPS framework is used as a template with which to compare the empirical results of the case studies. One goal was to build a general explanation that fits each individual case (CSFs detailed in the ICPS framework), even though the cases varied in their details. As the three cases showed to support this theory, replication can be claimed. The empirical results can be considered yet more potent as the cases support the same theory, but do not support an equally plausible, rival theory (Yin, 2009, p. 142, 2009, pp. 38–39, 2009, pp. 14–15). The issue of statistically testing the ICPS framework will be addressed by the conducted quantitative study (cf. chapter 6).

Another limitation that is inherent to the chosen study design is that only successful innovation projects have been analyzed in the study. This was mainly because the innovation projects should have run through all the phases of the innovation process for being able to completely analyze each CSF. Therefore, the perspective of innovation failures was not studied which has to be considered. Furthermore, the retrospective nature of the analyzed cases may have led to the situation that the innovation projects could have been viewed as much more rational and well-ordered by the key-informants than they were in fact (Utterback, 1974, p. 625).

6 Quantitative Validation of Critical Success Factors

6.1 Variables and Hypotheses

To quantitatively assess the impact of the individual CSFs on the innovation success, a theoretical framework for each category of the ICPS framework has been established. Theoretical frameworks represent relationships among variables and describe the nature and direction of these relations. Therefore, independent and dependent variables were differentiated. An independent variable influences a dependent variable in either a positive or negative way. For quantifying this impact, both variables need to be measured. As each factor detailed in the ICPS framework was not directly measurable, the CSFs were operationalized into observable elements to render them measurable in a tangible way by reducing the level of abstraction (Sekaran and Bougie, 2010, p. 127, 2010, p. 80, 2010, p. 72).

For this approach, previous studies were reviewed for existing measures of abstract factors (cf. Appendix V – 1). Based on the theoretical frameworks, five testable hypotheses have been derived. These hypothesized relationships were then tested by statistical analyses (cf. chapter 6.4.3). In the following, the variables, the theoretical frameworks, and the derived hypotheses will be delineated within the three dimensions of the ICPS framework. An overview of the operationalization can be found in Appendix IV.

Innovation Success

Innovation success forms the ultimate goal of each innovation project. Correspondingly, the three dimensions of innovation success form the three dependent variables of the elaborated theoretical frameworks. These variables are *sales performance*, *product performance*, and *efficiency*. As these variables are latent and thusly not directly measurable, they were further operationalized (cf. Appendix IV). Accordingly, *sales performance* was split up into the two elements *sales figures* and *market share*. *Product performance* is assessed by measuring the *product quality*, *customer satisfaction*, and *internal satisfaction*. Finally, efficiency was captured by evaluating emerging *costs* and the overall *speed* of the innovation process and the query if the process was *on time* and *in the budget*.

Innovation Context

The operationalization of the innovation context was elaborated within its four categories: *technology, target market, organization,* and *entrepreneurial team*. The derived elements represent independent variables that influence the three dependent variables *sales performance, product performance,* and *efficiency*. Accordingly, the respective hypotheses were generated.

Technology

The first dimension, *relative advantageousness,* from the category *technology,* was operationalized to the variables *performance advantages*, *cost advantages*, *reliability and safety,* and *technology potential*. The second dimension, *feasibility & maturity* was broken down to the variables *execution challenges*, *application maturity*, and *investment efforts* (cf. Appendix IV). In Figure 28, the theoretical framework I that has been associated with the technology category is depicted.

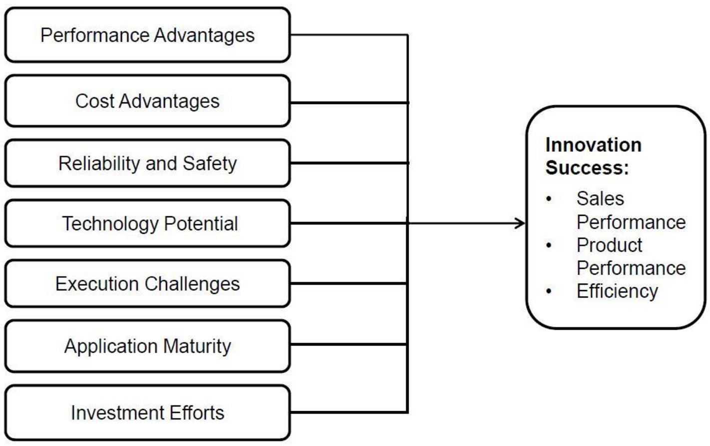


Figure 28: Theoretical Framework I Associated to Technology

Based on this theoretical framework, the following hypothesis is proposed:

H1: There is a significant correlation between each independent variable associated with the category *technology* and at least one of the three dependent variables of the overall innovation success, namely *sales performance, product performance,* and *efficiency*.

Target Market

The category *target market* has been operationalized to the following independent variables: *market size*, *market barriers, environmental impacts, competition, market match, timeliness,* and *market growth* (cf. Appendix IV). The factor *timeliness* was originally listed within the ICPS framework as a CSF of the *opportunity identification* action field. However, within the theoretical framework V associated to the category *innovation process* just controllable and measurable process instruments were considered. As the parameter *timeliness* additionally contributes to the opportunity caused by the target market, it was thusly relocated to this category. Figure 29 represents the respective theoretical framework II.

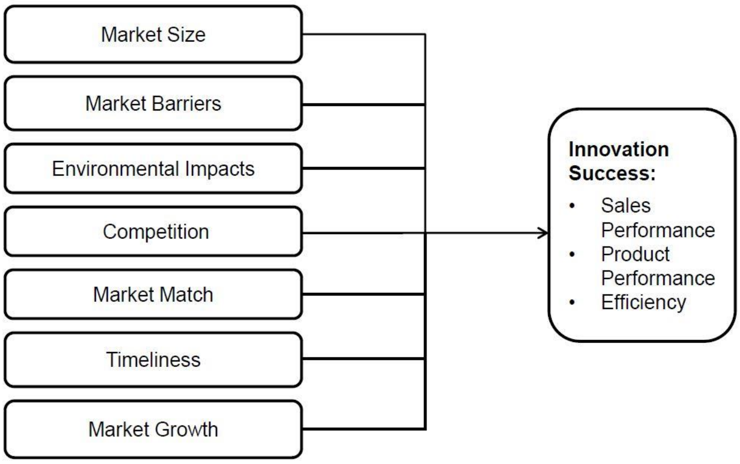


Figure 29: Theoretical Framework II Associated to Target Market

Accordingly, the second hypothesis was established:

H2: There is a significant correlation between each independent variable associated with the category *target market* and at least one of the three dependent variables of the overall *innovation success*, namely *sales performance, product performance,* and *efficiency*.

Organization

Within the category *organization,* three dimensions are differentiable: *culture, structure,* and *strategy*. Culture can be further operationalized to the variables *internal communication, adequate resource allocation, management support,* and *risk tolerance & failure acceptance*. Structure has been broken down to the variables *flexibility, product home,* and *lean decision making*. Finally, the strategy dimension has been split into the variables *strategy fit* and *dedication to innovation* (cf. Appendix IV). The corresponding theoretical framework III is depicted in Figure 30.

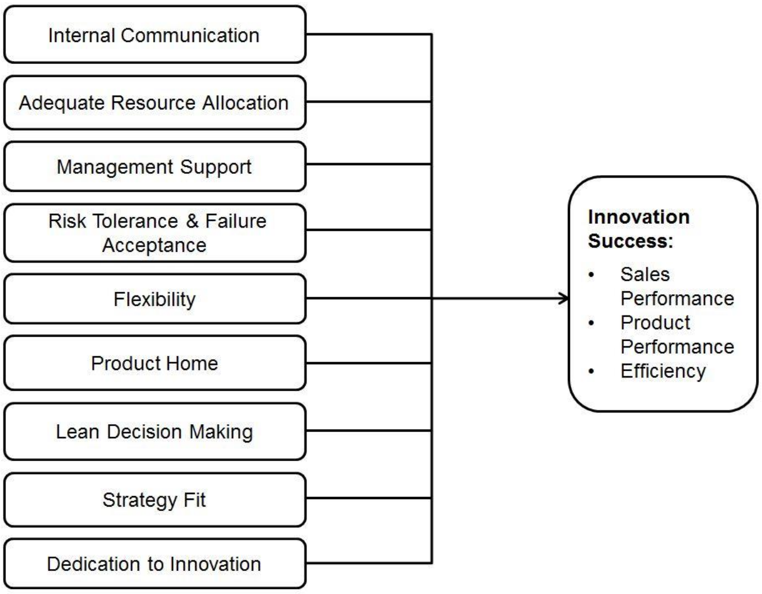


Figure 30: Theoretical Framework III Associated to Organization

The corresponding hypothesis is the following:

H3: There is a significant correlation between each independent variable associated with the category *organization* and at least one of the three dependent variables of the overall *innovation success*, namely *sales performance, product performance,* and *efficiency*.

Entrepreneurial Team

The following variables were derived from the category *entrepreneurial team*: *teamwork, professional competence, perseverance/attitude, social competence, interdisciplinarity, personal network,* and *experience* (cf. Appendix IV). Theoretical framework IV constitutes accordingly (cf. Figure 31).

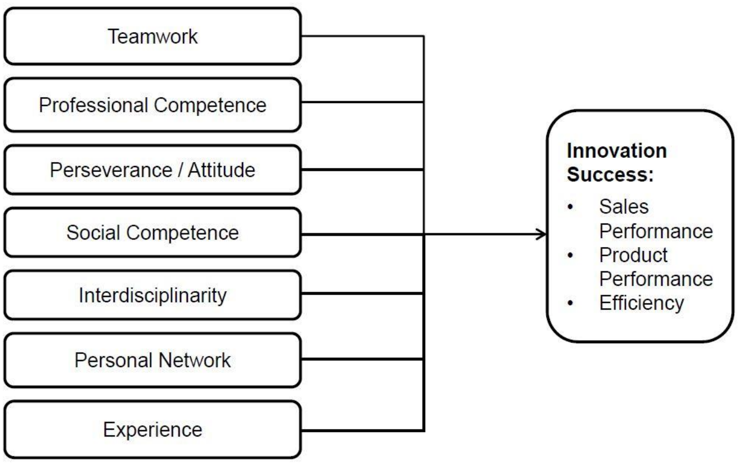


Figure 31: Theoretical Framework IV Associated to Entrepreneurial Team

Thus, hypothesis 4 reads as follows:

H4: There is a significant correlation between each independent variable associated with the category *entrepreneurial team* and at least one of the three dependent variables of the overall *innovation success*, namely *sales performance, product performance,* and *efficiency*.

Innovation Process

For quantitatively validating the success factors of the *innovation process*, only the controllable and measurable process instruments have been considered. There was no differentiation of the three separate action fields of the *innovation process* within the ICPS framework: *opportunity identification, product development,* and *commercialization*. This was due to the fact that some process instruments are relevant in various action fields. *Quality management* and *strategic partnerships,* for example, are decisive for *product development,* as well as for *commercialization*. Thus, a separate query would generate redundancies without major further insights and would cause a prolonged processing time. For these research pragmatic factors, the category *innovation process* has been broken down to the following process instruments that have been treated as independent variables in the subsequent analyses: *intellectual property protection, lead user integration, customer feedback, promotion, platform strategy, positioning, timing, strategic partnerships, quality management, risk management,* and *open innovation* (cf. Appendix IV). Figure 32 depicts the corresponding theoretical framework V.

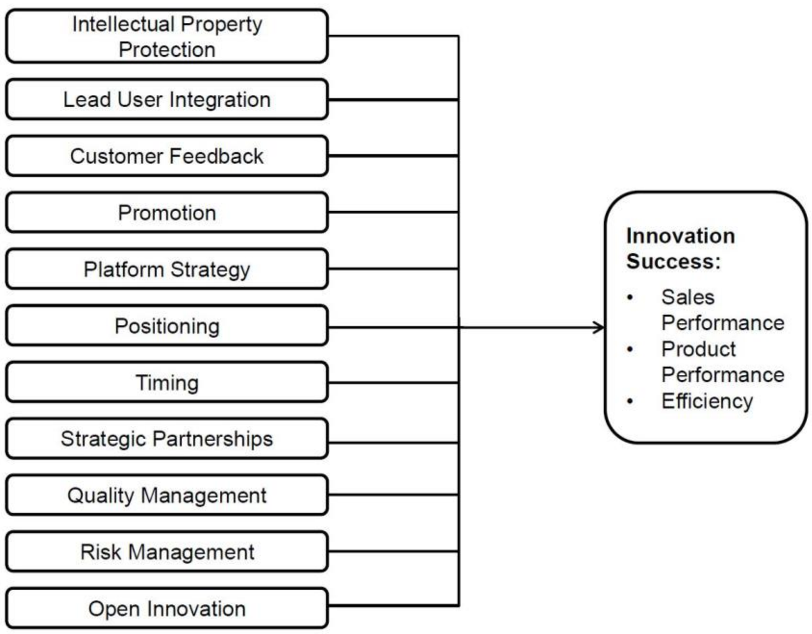


Figure 32: Theoretical Framework V Associated to Innovation Process

The fifth hypothesis claims the following:

H5: There is a significant correlation between each independent variable associated with the category *innovation process* and at least one of the three dependent variables of the overall *innovation success*, namely *sales performance, product performance,* and *efficiency*.

6.2 Design of the Survey Instrument and Pretest

To statistically test the five hypotheses, a quantitative survey was conducted within the German power transmission industry. Therefore, a standardized survey instrument, a questionnaire, was developed. Questionnaires are pre-formulated written sets of questions to which respondents record their answers. It is an efficient data collection mechanism (Sekaran and Bougie, 2010, p. 197).

6.2.1 Focus and Direction of the Survey

For the main part of the survey, the participants were asked to retrospectively relate their answers to a concrete project. They were explicitly requested to focus on one specific innovation project within the German power transmission industry (the target industry cf. chapter 6.3.1) in which they participated. The respective innovation should have represented a radical technological product innovation that was characterized by a high level of novelty. This product innovation should have been developed and subsequently introduced to the market. With this study design, it was possible to statistically assess the impact of each CSF on the innovation success on the basis of individual projects. This formed the basis for testing the five hypotheses. Nevertheless, abandoned and incomplete projects were not considered in this study. The latter projects have not gone through each phase of the innovation process and thus, no measurable innovation successes have been achieved (Dahl, 2015, pp. 46–47).

6.2.2 Wording and Scales

For constructing the questionnaire, question wordings and response scales are decisive and need to complement each other. Both dimensions are crucial for good survey results since the quality of verbalization directly affects data quality. A slight mistake can cause misunderstandings that induce potential problems in data analysis due to incorrect results (Dahl, 2015, pp. 50–52; Raab-Steiner and Benesch, 2008, pp. 47–48).

The first step of questionnaire construction was an analysis of previous studies for potential measures of the variables detailed in chapter 6.1. Proven question wordings and scales were utilized and adapted according to the purpose of each question. For variables without previously validated measures, these have been newly developed. All questions measuring the variables were posed close-ended which means that the answer options were predefined. However, the option "no response" was included for respondents that did not know or were not willing to give a concrete answer regarding the posed question. The queried variables were posed as statements and the respondents should indicate their consent on a five-point Likert scale. Although a Likert scale, technically, is an ordinal scale, it can approximate an interval-level measurement. Correspondingly, it is legitimate to use the collected data for parametric statistical tests and general quantitative analysis (Hilgers, 2015, p. 30; Norman, 2010, pp. 628–630). Furthermore, several qualitative questions were posed to gather descriptive information regarding the respective innovation projects. These questions were also closed-ended and utilized dichotomous, ordinal, nominal, interval, and also Likert scales, but were complemented with an open comment field (Dahl, 2015, pp. 50–54).

As the target group was the German power transmission industry, the questions were posed in German. In general, simple and short questions were preferred. Correspondingly, the danger of misunderstandings was reduced, and furthermore, the barriers to participating were lowered. Special attention was devoted to preventing socially desirable responses and double-barreled questions. Instead of phrasing all questions positively, some negatively worded questions were included as well for minimizing the tendency of respondents to mechanically circle the points toward one end of the scale (Sekaran and Bougie, 2010, pp. 199–202). An overview of the question wordings for measuring the variables and the corresponding measures of previous studies is depicted in Appendix V -1.

6.2.3 Questionnaire Design

The survey consisted in total of 76 questions which were arranged in six fundamental parts (cf. Appendix – 2). It was designed for self-administered completion. At first, the term radical innovation was explained to prevent misconceptions due to the underlying terminology. After several initiating and warm-up questions about the respondent himself, the interviewee was asked to focus on a specific innovation project from his past work experience within the power transmission industry as outlined in chapter 6.2.1 (Dahl, 2015, pp. 47–50; Hilgers, 2015, p. 29).

The following questions were focusing on the selected specific innovation project and constituted the main body of the survey. These questions were based on the variables outlined in chapter 6.1 that were developed through the conducted operationalization. Within the first part of the main survey body, the independent variables of the innovation context were addressed. Thus, questions regarding the target market, the organization, the technology, and the entrepreneurial team were posed. The next section targeted the dependent variables of the overall innovation success. Finally, the utilization of specific innovation process instruments was measured. Each question set of the main survey section was introduced with a short explanatory text which included concrete instructions and definitions of specific terms (Dahl, 2015, p. 51; Hilgers, 2015, p. 29).

The questionnaire was concluded by questions regarding firm demographics, a text box for additional comments or feedback, and the query if the respondent wants to receive the results of the study and wants to take part in a lottery for gift certificates. These were used as an incentive for participation (Hilgers, 2015, p. 30).

It was aimed to design a questionnaire as short as possible to lift the completion rate of participants. The completed printout version of the questionnaire can be found in Appendix V – 3. Furthermore, to make participation as easy and convenient as possible for the respondent, an online version was created using the web application of the freeware LimeSurvey (Dahl, 2015, p. 44).

6.2.4 Pretest

After completion of the questionnaire design, a pretest was conducted to test the capability of the survey instrument. Thereby, four main aspects deserved special attention: reliability and validity, linguistic and content-related comprehensibility of questions, the uniqueness of categories, and specific data gathering problems (Atteslander, 2008, pp. 277–278). To guide and support this process a feedback form was generated and distributed among the pretest participants (cf. Appendix V – 4). The feedback form contained questions regarding the usability of the questionnaire, linguistic and content-related comprehensibility of the questions (clear instructions, wording, terminology, content, possible bias due to directed questions), the related scales, and the processing time (Dahl, 2015, p. 60).

For the pretest, the online version of the survey was utilized. 20 invitations for participation have been sent to potential participants. Ultimately, 11 completed questionnaires were retrieved. The pretest participants consisted of three different groups of experts: the research methodology consulting at the House of Competence (HoC) at KIT, scientific staff members at EnTechnon and IPEK, and industrial experts of the power transmission industry. Additionally, two intense feedback sessions were conducted with the two scientific supervisors of the author by utilizing the technique “think-aloud”. Furthermore, the printout version was reviewed by 4 colleagues of the author for analyzing clarity and form of the questionnaire (not content). Consequently, the survey instrument was considered from a methodological, a scientific, and an industrial perspective. All pretest activities were conducted in October 2014 (Dahl, 2015, p. 60).

The linguistic and content-related comprehensibility of questions has been thoroughly analyzed. The suggested improvements were implemented and contained a few wording changes to question items, the sequence of several questions, and the content of the lead-in questions. In summary, the results of the pretest showed that the developed survey instrument hold for the criterion of validity. The posed questions were unambiguous and comprehensible. Due to the standardized form, the criterion of reliability was fulfilled. The uniqueness of categories within several descriptive queries could be confirmed, as well as the estimated processing time of roughly 15 minutes for survey participation. The web tool was reliably working and thus, no data gathering problems emerged (Dahl, 2015, pp. 59–61).

6.3 Data Collection and Preparation

6.3.1 The German Power Transmission Industry as Target Industry

The overall study of the thesis at hand addresses the mechanical engineering industry. However, this industry is quite diverse and contains several sub-branches, including, inter alia, textile machines, packaging machines, robotic & automation, and power transmission. Accordingly, the competitive conditions differ greatly within these branches (VDMA and McKinsey, 2014c, p. 12). This heterogeneity in the industry might have caused the situation that possibly few, or hardly any, statistically measurable relations were detectable. To have a realistic chance to detect statistically significant relations, it was decisive to choose a target industry with satisfactory homogeneity. Therefore, it seemed reasonable for data collection to focus on a distinct sub-branch within the mechanical engineering industry.

For the conducted study, the German power transmission industry has been chosen as a target industry. In 2014, this industry generated 17 billion € and therewith approximately 8% of the overall revenue of the German mechanical engineering and plant manufacturing industry (Statista; Statistisches Bundesamt, 2015). Thus, the power transmission industry was the biggest sub-branch of the mechanical engineering and plant manufacturing industry in Germany. Nearly all global innovation leaders within this branch are German companies that invest considerable resources in research and development. Accordingly, the patent intensity regarding product- and process innovations is quite high. Furthermore, the market is shaped by high domestic demand as important customers have production sites in Germany (VDMA and McKinsey, 2014a, pp. 22–24, 2014a, pp. 10–15).

Companies of the power transmission industry are engaged in drive train technologies, i.e. with technical systems that generate and transmit power. The products include rolling bearings, gearboxes, gears, and further drive elements. Accordingly, companies of this branch are mostly suppliers in the business-to-business (B2B) sector, especially for the mechanical engineering and the automotive industry (Hilgers, 2015, p. 13; Statista). Several industrial megatrends like electric mobility, energy efficiency, resource optimization, and industry 4.0 are directly affected by the products of the power transmission industry (Dahl, 2015, p. 56; VDMA and McKinsey, 2014a, p. 22).

In summary, the German power transmission industry was highly suitable as the target industry for the quantitative study. It provided a large sample of potential survey participants from different manufacturing industries with sufficient homogeneity due to its functional product purpose. In addition, the industry is characterized by a great economic importance and innovativeness. Furthermore, the branch comprises firms with different organizational sizes and structures. The different industrial and organizational backgrounds and their potential effects on the innovation process are interesting, especially regarding the variables and hypotheses outlined in chapter 6.1 (Dahl, 2015, pp. 56–57). Due to the focus on Germany, no language or cross-cultural issues emerged when designing the questionnaire. Moreover, potential differences regarding competitive conditions, political situation, and diverse business practices within different countries were prevented in advance (Sekaran and Bougie, 2010, p. 218).

6.3.2 Target Population, Survey Channels, and Response Rate

As outlined in chapter 6.2.1, the survey participants were requested to retrospectively relate their answers to a concrete project in which a radical technological innovation within the German power transmission industry was realized. To answer the questionnaire properly, the respondents needed a profound overview on each dimension of the innovation context, innovation process, and subsequently innovation success. Therefore, they should have been deeply involved in the respective project. The target population, then, for the survey was inter alia, project managers, marketing- and sales representatives, development engineers, production experts, and business developers that have been involved in the realization of a radical technological innovation for the German power transmission industry.

Experts that were interested in scientific research were most likely to respond. They have been attracted by the promise to receive the survey results after analysis. Additionally, three 30€-Amazon vouchers were raffled among the participants to lift the response rate. Moreover, the respondents have been assured anonymity and confidentiality.

For distributing the questionnaire, an online and a printout version were prepared in order to meet the personal preferences of the respondents and thus, increase the response rate. The online version was created with the web application of the freeware LimeSurvey and was available as a website on the WWW.[2] For reasons of better usability, an alternative URL was generated for the survey.[3] To reach the target population, three different survey channels were utilized.

A great number of potential respondents was addressed at the 43rd annual conference of the German Research Association for Power Transmission Engineering (Forschungsvereinigung Antriebstechnik, FVA) on the 2nd and 3rd of December 2014 in Würzburg. According to its website, the FVA is the globally leading innovation network within the target industry. It encourages general research, exchange of experience within the industry, and the education of young scientists. It supports and enables joint research projects between small, medium, and large companies, as well as research institutes. The diverse variety of members and a large number of participants at the conference helped to approach potential respondents (FVA; Hilgers, 2015, pp. 30–31).

A second approach was to search for representatives of the target population via the social networking platform XING[4]. In order to ensure that the professionals to be contacted correspond to the target population, filter criteria were defined. Only those candidates were included that worked in project management, technical development, production management, marketing, sales, consulting, or were responsible for decision making processes within the power transmission industry. Further keywords like power train, drive train, engine, coupling, gear box, transmission, gear unit, and differential were used to find appropriate participants for the survey. This group of people has subsequently been contacted by personal mail due to platform limitations of XING regarding the limits for sent messages. Four weeks after the first contact, a reminder has been sent (Dahl, 2015, pp. 57–58; Hilgers, 2015, p. 31).

Finally, the author made use of his personal network which he acquired during his previous professional career working for an established player of the power transmission industry. The online version of the survey was sent to his contacts in the industry kindly asking to respond and to forward it to their respective companies. Once again, a reminder has been sent four weeks after the first contact (Hilgers, 2015, p. 31).

The data collection period lasted from December 2014 until March 2015. At the FVA-conference, a total of 617 potential survey participants received the questionnaire. This number has been adapted by subtracting the number of 130 attending PhDs and PhD-Students, as they were not part of the target population. Thus, 487 potential respondents were addressed. 46 responses were collected which results in a response rate of 9.45%. Based on the XING-search, 372 people were contacted with 50 returns resulting in a response rate of 13.44%. The utilization of the author's personal network reached 173 professionals and resulted in 51 responses. The associated response

[2] http://kit-csf.limequery.com/index.php/365651/lang-de, now defunct
[3] http://www.kit-umfrage.de, now defunct
[4] http://www.xing.com

rate of 29.48% is by far the highest, as can be expected when using personal contacts. In total, 147 responses were collected after contacting 1032 potential survey participants within the target population. The resulting overall response rate is thereby 14.24%. 100 respondents completed the survey online while 47 chose the printout version. An overview of the response rates is depicted in Table 6 (Hilgers, 2015, p. 31).

Table 6: Survey Response Rate (Hilgers, 2015, p. 32)

	Potential Participants	minus University-employees	Potential Participants (adapted)	Online	Printout	Total Answers	Response Rate in %
FVA symposium	617	130	487	4	42	46	9.45
Xing	372	-	372	49	1	50	13.44
Personal Network	173	-	173	47	4	51	29.48
Sum	1162	130	1032	100	47	147	14.24

6.3.3 Data Preparation

The web application LimeSurvey allowed direct export of the collected data to the statistical analysis program SPSS Statistics[5] by IBM which was used for the subsequent analysis. Nevertheless, the printout responses had to be added manually to the data set. Before analysis, the variables had to be named properly. Each variable represented one question of the survey. LimeSurvey automatically named the variables using the corresponding question as a basis. To simplify the handling during analysis, the independent and dependent variables outlined in chapter 6.1 have been renamed. Therefore, abbreviations of the superordinate category names were used and the variables were enumerated based on their sequence in the questionnaire. The abbreviations were as follows: Innovation Success (IS), Target Market (TM), Organization (ORG), Technology (TEC), Entrepreneurial Team (ET), and Innovation Process Instruments (PI) (Hilgers, 2015, pp. 32–33).

Afterward, the problem of missing data had to be resolved. 147 questionnaires were completed but only 45 of these were free of missing data. When focusing on the main body of the survey measuring the variables described in chapter 6.1, 52% of the respondents did not answer at least one question. In total, 300 values were missing which corresponds to 4% of the overall captured values (cf. Figure 33). The observed cases of non-response are due to the offered “no-response”-option in the questionnaire, involuntary or voluntary omission of questions, or invalid answers. As most statistical procedures require complete data sets without any missing data, sophisticated methods of dealing with missing data had to be applied (Brosius, 2013, p. 284; Hilgers, 2015, p. 34).

[5] In the following just called SPSS

At first, the missing data were analyzed to identify the patterns and relationships underlying the missing data. By using Little's MCAR test, it could be determined that the data were missing completely at random (MCAR). In simple terms, this means, that the cases with missing data were indistinguishable from cases with complete data. This situation was preferable, as it allowed the widest range of potential remedies to deal with missing data (Hair, 2010, p. 49, 2010, p. 42; Hilgers, 2015, p. 33).

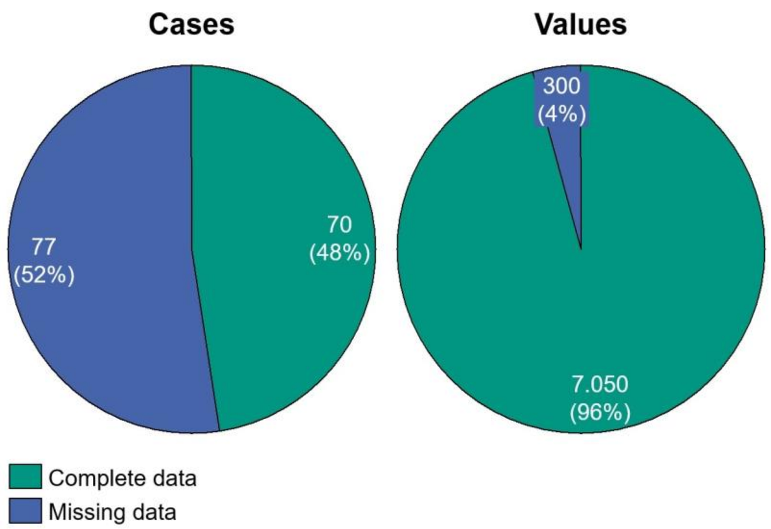


Figure 33: Overview of Missing Data (Hilgers, 2015, p. 34)

In general, there are two main categories of treating missing data: deletion and imputation. The first more traditional approach significantly reduces the sample size by deleting any case affected by missing data and was thus, not applied. In contrast, imputation procedures replace missing data. Correspondingly, it is possible to include all given responses in the subsequent analyses and thus, keep the sample size constant and on a maximum. For the study at hand, imputation was applied (Hair, 2010, p. 45; Hilgers, 2015, pp. 34–35).

Instead of mean or median imputation, the more sophisticated approach of regression imputation was combined with preceding maximum likelihood estimation. At first, the five theoretical frameworks of chapter 6.1 have been combined into an overall model containing all independent and dependent variables. By maximum likelihood estimation, several model parameters like variance and covariance of the initial model have been estimated. A linear regression utilizing these estimated parameters was used to predict the unobserved values for each case as a linear combination of the observed values for that same case. Predicted values are then plugged in for the missing values. The software IBM SPSS AMOS was used for the described procedure (Arbuckle, 2013, p. 461; Blunch, 2013, pp. 220–227; Enders, 2010, pp. 44–48; Hilgers, 2015, pp. 35–36).

After successfully dealing with missing data, negatively keyed items of the main survey part (cf. variables described in chapter 6.1) were recoded so that a high score on the Likert scale of the independent variables was expected to have a positive influence on the dependent variables. Subsequently, the suffix "_REC" was added to the names of the reverse-coded variables. As the last step of data preparation, outliers were searched by using the SPSS boxplot analysis. Even though some boxplot outliers could be identified for individual items, no respondent generated conspicuously many outliers which would have justified a deletion of the respective case (Hilgers, 2015, p. 36).

6.4 Data Analysis and Findings

6.4.1 Survey Sample

In summary, 147 representatives of the German power transmission industry took part in the survey. The two dominating industries, for which the respondents were working, were the mechanical engineering (40%) and the automotive industry (38%). Just 22% of the survey participants were working for other industries like electrical engineering or automation technologies. The big corporations with more than 10,000 employees were vastly dominating with a great majority of nearly 70%. The percentage of stock (60%) and limited companies (40%) was correspondingly high.

The most respondents have much professional experience. 49% have worked longer than 15 years and 30% worked between 7 and 15 years. Accordingly, the most survey participants have been involved in several innovation projects. Nearly 60% were involved in 2 to 5 projects, 15% in 6 to 10 projects, and 17% were involved in even more than 10 projects. With respect to their position within the concrete innovation project which they were focusing on in the survey, 43% were development engineers, 26% project managers, and 12% part of the decision committee. A clear majority of the survey participants were satisfied with the results of the project. 47% of the respondents were satisfied and even 28% were very satisfied. Thus, successful projects were predominantly selected within the survey. As depicted in chapter 6.2.1 this was part of the survey design and thus, expected.

30% of the survey participants indicated that the process of the innovation project was not standardized at all. 32% of the respondents pointed out that their innovation projects have been managed in accordance with a common process, but were not formally standardized. 38% of the respondents described the process of their selected innovation project as formally standardized. From the number of these formally standardized projects, 82% have been managed according to a stage-gate-process. Regarding the project organization, the matrix organization was greatly dominating with 74%. 24% of the projects have been carried out in an autonomous organization and just 2% of the projects were realized in a newly founded, own company.

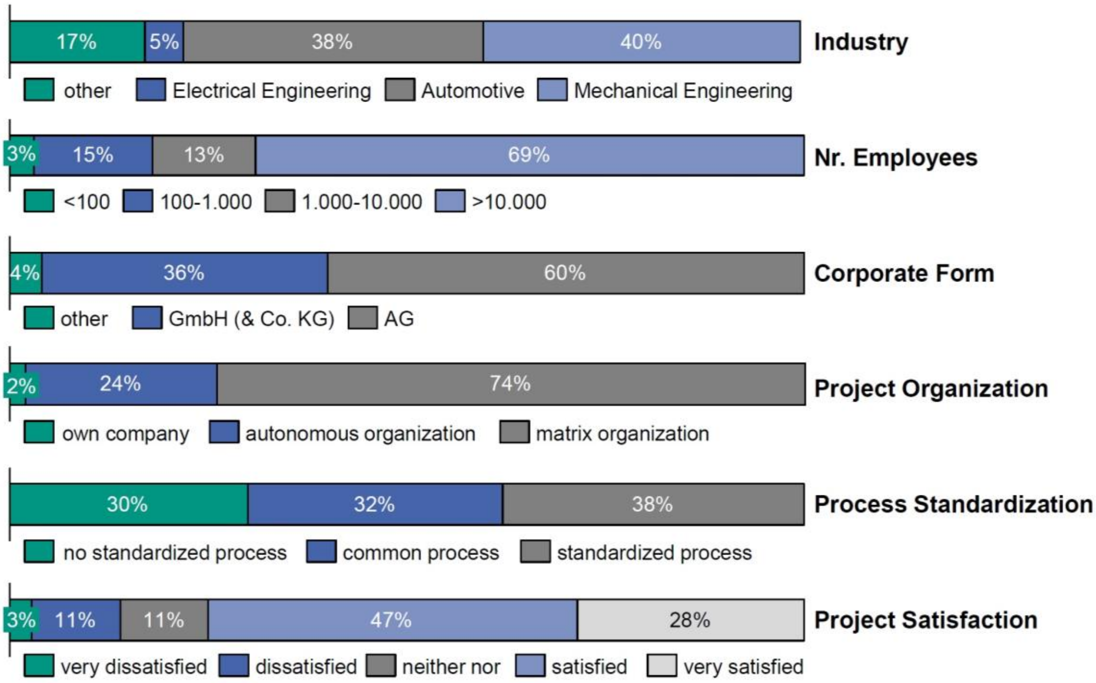


Figure 34: Overview Survey Sample (Hilgers, 2015, p. 46)

6.4.2 Goodness of Data and Measures

Before starting with statistical analyses, several quality tests with respect to the quality of data and the applied measures were conducted. This contributed to the scientific rigor that has gone into the conducted research study. First of all, it was essential to test the variables regarding normal distribution. Afterward, it was important to make sure that the developed instrument was accurately measuring the variables of interest and that it measured them accurately. Especially, the measurement of the dependent variables (innovation success) had to be analyzed as these variables were latent and were thus, not directly measurable. To establish construct validity of the measures, an explorative factor analysis was performed and to guarantee internal consistency, a reliability analysis based on Cronbach's alpha was carried out (Sekaran and Bougie, 2010, p. 157, p. 324).

6.4.2.1 Test of Normal Distribution

Numerous statistical procedures require that the data to be analyzed are parametric. Parametric variables are at least interval scaled and approximately normally distributed. As outlined in chapter 6.2.2, Likert scales can be treated as interval scaled. Thus, the measured independent and dependent variables of the survey had to be checked for normal distribution before conducting any statistical procedure based on parametric data (Wittenberg *et al.*, 2014, p. 150).

Normality of variables can be assessed by either statistical or graphical methods. As the sophisticated statistical Kolmogorov-Smirnov-test should just be applied for samples below 100, it could not be utilized for the conducted study. Instead, skewness and kurtosis have been analyzed to assess normality of the respective variables. Skewness reflects the symmetry and kurtosis the peakedness of the variable-distribution within the sample. There are significance tests for both parameters that test the obtained values against the null hypotheses of zero. Thus, the normal distribution assumption of a single variable could just be retained if the associated values of skewness and kurtosis lie within a critical range at a previously defined significance level (Tabachnick and Fidell, 2007, p. 79; Wittenberg *et al.*, 2014, p. 159).

According to Wittenberg et al., in order to retain the normal distribution assumption for the variables measured in the conducted study with a sample size of 147 (n>120), the values for skewness and kurtosis had to range from -1.96 to +1.96 for each variable at a significance level of α<0.05%. Besides one variable, the values of skewness and kurtosis of any measured variable in the survey laid within this value range (cf. Appendix V – 5). Correspondingly, these variables could be designated as approximately normally distributed with 95 percent accuracy (Wittenberg *et al.*, 2014, p. 159). Furthermore, the graphical analysis of the variable histograms confirmed these statistical results.

Just the kurtosis of the variable TEC_1 ("From the customer perspective, the technology was more powerful than potential alternatives"[6]) was out of range with a value of 2.007 (cf. Appendix V – 5). However, according to Tabachnick, the impact of departure from zero kurtosis diminishes in a large sample and like skewness, often does not deviate enough from normality to make a substantive difference in the analysis. Therefore, graphical analysis of frequency histograms is decisive to visually assess if the distribution of a variable is approximately normally distributed or not (Tabachnick and Fidell, 2007, pp. 80–81). This was conducted for the variable TEC_1. As depicted in Figure 83 the kurtosis of the variable is not that extreme (cf. Appendix V – 5). Hence, this variable was treated as approximately normally distributed within the subsequent statistical analyses.

6.4.2.2 Explorative Factor Analysis

Factor analysis is a multivariate technique to reduce complexity. In contrast to confirmatory factor analysis, the distinctive feature of explorative factor analysis (EFA) is that the factors are derived from statistical results and not from theory. Therefore, the data were systematically analyzed for underlying patterns that determine the factor structure. The EFA was conducted without knowing how many factors really exist or which items belong to these constructs. Established guidelines were utilized to determine which items load on the particular factors and how many factors were appropriate. Therewith, it was tested if the three dimensions of the ultimate innovation success

[6] „Aus Kundensicht war die Technologie leistungsfähiger als mögliche Alternativtechnologien"

(sales performance, product performance, and efficiency) could be found as underlying factors in the data and if their associated, operationally defined items (cf. Appendix IV) load on them. In general, EFA is an iterative process. On the search for a stable factor structure the following main steps were repeatedly taken: analysis of correlation matrix, factor extraction, rotation, factor interpretation, and factor estimation. Step-by-step, the EFA led to the omission of three items (IS 3, IS4, and IS5) as these prevented a stable factor solution. This was due to low factor loadings, loadings on two rival factors, or the loading on a separate factor (Brosius, 2013, p. 793; Hair, 2010, p. 693; Sekaran and Bougie, 2010, p. 161).

At the analysis of the fundamental correlation matrix, the detection of several high correlations between single items indicated the adequacy of the correlation matrix for factor analysis. Nevertheless, it was useful to take further statistical criteria into consideration. The highly significant Bartlett‘s test of sphericity (α = 0.000) of the final EFA admitted the rejection of the hypothesis that the items of the overall sample were uncorrelated (cf. Table 20; Appendix V – 6). Moreover, the Kaiser-Meyer-Olkin-criterion (KMO) was assessed, as it is regarded as the best available measure to test the correlation matrix. It indicates how the individual items belong together and if a factor analysis is useful. This criterion is based on the anti-image-correlation matrix and is also designated as a measure of sampling adequacy (MSA). Besides the overall correlation matrix, the assessment of single items is possible with the MSA. The MSA of the single items can be found in the diagonal of the anti-image-correlation matrix. The final EFA led to a KMO of 0.654 which caused a mediocre adequacy of the data for factor analysis. The MSA-values of the finally considered items fell in the range of 0.621 and 0.760. Thus, they indicated a mediocre or middling adequacy for factor analysis (cf. Table 20 – Table 22; Appendix V – 6) (Backhaus *et al.*, 2016, pp. 395–399; Brosius, 2013, pp. 794–798).

The two mostly applied factor extraction methods are principal axes factor analysis (PFA) and principal component analysis (PCA). In contrast to PFA, all variance is analyzed with PCA. However, the mathematical processes are similar, except in preparation of the observed correlation matrix for extraction (Tabachnick and Fidell, 2007, p. 609). In the conducted study, the PCA extraction method was utilized. For the actual factor extraction, the eigenvalues of the associated factors were considered. Eigenvalues represent the proportion of variance that is explained by each factor. The eigenvalue of 1 is called Kaiser-criterion and represents a sound basis for extraction. Additionally, the scree plot was analyzed. As a rule of thumb, the distinct number of factors should be extracted at which the graph exhibits a kink (the so-called elbow criterion). Correspondingly, three factors were extracted in the conducted study as their associated eigenvalues were above or approximately 1 and the graph indicates a kink at this number of factors. Ultimately, the cumulative percentage of variance explained by the factors accounted for 83.15% (cf. Table 23 & Figure 67; Appendix V – 6). The communalities of the considered variables ranged between 0.75 and 0.93 (cf. Table 24; Appendix V – 6). As these values approximated the value of 1, nearly the complete distribution of these variables was represented by the three factors (Brosius, 2013, pp. 800–802).

The extracted factors were initially difficult to interpret. As the factors were mathematical artifacts, it was possible to transform them without distortion. A common transformation is the rotation of the factor loading matrix. The underlying concept is the idea to exhibit the factor loadings in a coordinate system and rotate the axes at its origin. In general, this rotation could be performed orthogonally or obliquely. As oblique rotation is closer to the data than orthogonal rotation, oblique rotation, in particular, oblimin rotation with Kaiser-normalization, was performed in the conducted study. Kaiser-normalization should ensure that each variable had the same impact on the rotated factor solution (Backhaus *et al.*, 2016, p. 419; Brosius, 2013, pp. 806–807, Schendera, 2008, p. 211, 2008, p. 254). After six iterations, the final factor solution was found. The final pattern matrix contains the ultimate loadings of each variable on the extracted factors (cf. Table 25; Appendix V – 6).

Afterward, the extracted factors were interpreted, named, and compared with the initial theory. Similar to the theoretical operationalization of innovation success (cf. Appendix IV), *sales figures* (IS_8) and *market share* (IS_9) loaded on factor 1 (factor loadings: 0.95 and 0.937). Thus, this factor was named *sales performance*. *Speed* (IS_1) and *costs* (IS_2) loaded on factor 2 (factor loadings: 0.883 and 0.846) and *internal satisfaction* (IS_6) and *product quality* (IS_7) loaded on factor 3 (factor loadings: 0.845 and 0.835). Accordingly, factor 2 was named *efficiency* and factor 3 *product performance*.

Finally, the factor values had to be estimated and stored in the data set, as further statistical procedures should be performed. In the conducted study, the regression method was utilized as appropriate estimation method (Brosius, 2013, p. 811). Table 7 gives an overview of the results of the final EFA. In particular, the factor loadings of each item, the eigenvalues of the respective factors, and the percentage of variance of all items that was explained by each factor are depicted in this table.

Table 7: Overview of EFA Results

Items	Factor 1: *Sales Performance*	Factor 2: *Efficiency*	Factor 3: *Product Performance*
IS_8 Der erzielte Umsatz entsprach den zu Projektbeginn formulierten Erwartungen.	0.950	0.022	0.007
IS_9 Der mit der Innovation erreichte Marktanteil entsprach den zu Projektbeginn formulier-ten Erwartungen.	0.937	0.015	0.060
IS_1 Die Geschwindigkeit des Entwicklungsprojektes war hoch.	0.140	0.883	-0.176
IS_2 Die vorhandenen Res-sourcen wurden im Innovati-onsprojekt effizient eingesetzt.	-0.078	0.846	0.227
IS_6 Die Produktperformance der Innovation entsprach den zu Beginn des Projektes formu-lierten Vorgaben.	-0.032	0.118	0.845
IS_7 Die erreichte Qualität des neu entwickelten Produktes war auf einem hohen Niveau.	0.136	-0.099	0.835
Eigenvalues	2.856	1.159	0.1974
% of explained variance of all items	47.595	19.317	16.239
Remarks: Principal Component Analysis with Oblimin-Rotation; KMO = 0.654; Bartlett-Test Chi²=357.406, p<0.000			

6.4.2.3 Reliability Analysis

In general, reliability of a measure indicates the extent to which it is without bias and thus, ensures consistent measurement across time and across the various items in the instrument. In this study, interitem consistency reliability was tested based on Cronbach's alpha to analyze the consistency of respondents' answers to all the items in a measure. In particular, it was tested how well the items measuring the three innovation success factors hang together as a set. To the degree that items are independent measures of the same concept, they will be correlated with one another. Therefore, Cronbach's alpha is computed in terms of the average intercorrelations among the items measuring the associated factor. The closer Cronbach's alpha is to 1, the higher the interitem consistency reliability (Sekaran and Bougie, 2010, pp. 157, 161-162, 324).

According to Sekaran and Bougie, Cronbach's alpha values less than 0.60 are considered to be poor, those in the 0.70 range acceptable, and those over 0.80 good. In Table 8 the results of the conducted reliability analysis are presented. Cronbach's alpha of the factors 2 and 3 range around 0.70 and the first factor achieved a value of 0.924 (cf. Appendix V – 7). Hence, the interitem consistency reliabil-ity in this study can be considered to be acceptable for the efficiency and product performance factors and to be very good for the sales performance factor (Sekaran and Bougie, 2010, p. 325).

Table 8: Results of Reliability Analysis

Factor	Number of Items	Cronbach's alpha
Factor 1: Sales Performance	2	0.924
Factor 2: Efficiency	2	0.714
Factor 3: Product Performance	2	0.673

6.4.3 Methodology and Findings of Correlation Analysis

6.4.3.1 Methodology

To statistically test the five hypotheses described in chapter 6.1, several correlation analyses were conducted. The aim of these correlation analyses was to measure the degree of the linear relationships between the independent and the dependent variables. In general, there is a correlation between two variables if a variation of one variable has an impact on the variation of the second variable (e.g. high value of variable 1 → high value of variable 2). An appropriate measure for the strength and direction of a relationship between two interval-scaled variables is the Pearson correlation coefficient r. It is the most frequently used measure of association and the basis of many multivariate calculations. Pearson r is limited to identify linear relations and to quantify this by calculating a single value. It is computed by dividing the covariance between X and Y by the product of the standard deviations of X and Y. Its value ranges between -1.0 and +1.0. A positive value indicates a positive linear relationship; a negative value characterizes a negative linear relationship. The greater the value of Pearson r, the stronger is the relation between the analyzed variables. If Pearson r is equal to zero, there is no measurable association between the variables. For interpreting the detected r values, an orientation guideline developed by Brosius was applied (cf. Table 35; Appendix V – 8). Within the conducted study, just statistically significant correlations ($\alpha<0.05$ → symbol: * and $\alpha<0.01$ → symbol: **) were considered (Brosius, 2013, p. 517; Heumann and Toutenburg, 2006, p. 134; Sekaran and Bougie, 2010, p. 322; Tabachnick and Fidell, 2007, pp. 56–57). The superscript value of -1 within the illustrations of Figure 35 until Figure 39 indicates, that the corresponding items have been recoded to mainly have positive correlations.

6.4.3.2 Correlations of the Category "Technology" and "Innovation Success"

The theoretical framework I was associated with the *technology* that underlay the considered innovation (cf. Figure 35). Regarding the analyzed relationships, just three independent variables indicated a significantly positive correlation to at least one of the three dependent variables of the overall innovation success. In the case of three independent variables, no statistical evidence of significant associations with any of the three dependent success variables could be found. Moreover, the matter that the *technology has been implemented elsewhere* correlated significantly and negatively with all of the dependent success variables. The strengths of the detected correlations were in the weak and middling range. As the hypothesis H1 predicted a significant correlation between each independent variable associated with the category technology and at least one of the three dependent success variables, H1 was rejected. However, four technology associated CSFs have a significant correlation and their impact has to be considered at the realization of radical technological innovations.

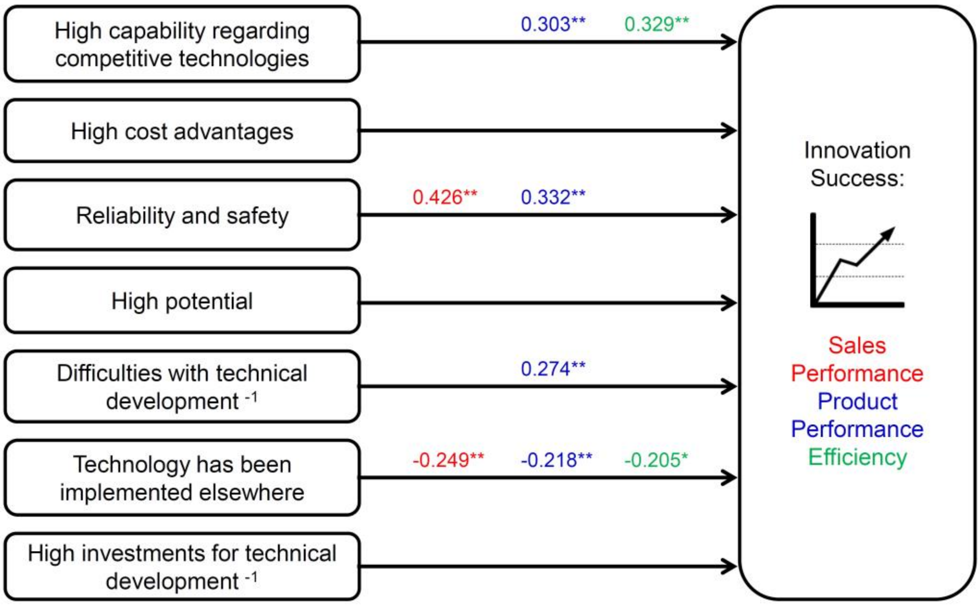


Figure 35: Correlations of the Category "Technology" and "Innovation Success"

It is quite understandable that *high cost advantages* do not necessarily correlate with *product performance* or *process efficiency*. However, the fact that *high cost advantages* do not correlate positively with *sales performance* was a surprise. The same was the case for the variable *high capability regarding competitive technologies*. Apparently, the reliability of a technology was primarily decisive for radical technological innovations in the power transmission industry instead of cost or performance advantages. A high *reliability and safety* of the technology exhibited a statistically significant positive relation between the dependent variables of *sales* and *product performance*. Probably this is due to the conservative mechanical engineering and automotive industry for which the power transmission industry is primarily developing. Not until the operability of a technology was demonstrated, the rather conservative users are willing to adopt despite the potential advantages regarding competitive and especially working technologies. Nevertheless, *product success* and process *efficiency* were dependent on the *performance capability* of the technology regarding potential alternatives. This was verified statistically. The less the *difficulties with technical development* were, the greater was *product success*. Interestingly, no statistically significant correlation was found with respect to process *efficiency*, although one could have expected that the process would have been faster and more economical in case of fewer *difficulties with technical development*. Similarly, no significant correlation was detected between *investment costs for tech-*

nical development and the three dependent success variables. To some extent, it is understandable that a *great potential* for further applications does not necessarily correlate significantly and positively with *sales* and *product performance* as well as with process *efficiency*.

However, the significant and negative correlations between the matter that the *technology has been implemented elsewhere* and the three dependent success variables were quite astonishing. The negative correlation of *sales performance* may be explained by the lower level of newness and the associated lower potential for differentiation. Potential customers may have felt a minor necessity substituting their working solution by a newly developed innovation. The significant negative association regarding process *efficiency* is also surprising, as one could expect that a higher maturity level of the central technology would enable a more economic and faster development. A potential reason may be the unbiased development approach for new developments in contrast to lengthy and cost intensive optimization efforts in case of further developments. A similar perspective might help to explain the significant negative correlation between *product performance* and the matter that *the technology has been implemented elsewhere*. An unbiased new development may potentially lead to higher performance increases regarding product performance and product quality compared to steady optimizations of existing solutions.

6.4.3.3 Correlations of the Category "Target Market" and "Innovation Success"

The theoretical framework II was elaborated for the category *target market* (cf. Figure 36). Similar to the category technology, there were just three independent variables associated with the target market category that demonstrated significant and positive correlations to at least one dependent success variable. The strengths of these correlations were on a weak level. Four analyzed independent variables did not have any statistically detectable relation to the dependent success variables. Thus, hypothesis H2 was rejected, as H2 predicted a significant correlation between each independent variable associated with the category target market and at least one of the three dependent success variables. Nevertheless, the influence of the mentioned three CSFs, which have a significant positive correlation to at least one of the three innovation success variables, cannot be neglected.

The recoded variable that *other markets would have had a better market fit* indicated a significant and positive correlation to *product performance* and *efficiency*. The better the market matched to the innovation idea, the more efficient was the innovation realization and the better the innovation satisfied the performance and quality requirements. At the same time, it was a surprise that the *market fit* did not correlate significantly and positively with *sales performance*. Similarly, one could have anticipated that a *low level of market barriers*, the *level of competition*, and an *interesting market size* would have been positively correlated with *sales performance*. With regard to *product performance* and *efficiency*, an *interesting market size* and the *level of competition* also did not play any traceable role. A *low level of market barriers* was found to correlate significantly and positively with *product performance*, but not with process *efficiency*. In the case of *low market barriers*, intuitively a faster and more economical process could have been expected. Moreover, the level of *obstacles caused by external impacts* did not exhibit any statistically verifiable association regarding the three dependent success variables.

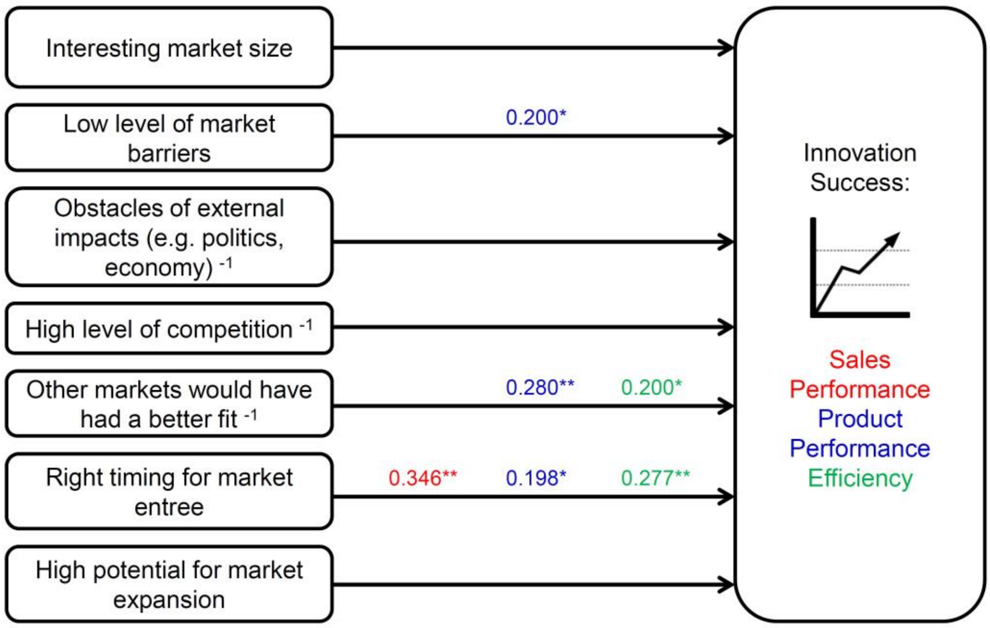


Figure 36: Correlations of the Category "Target Market" and "Innovation Success"

A potential explanation of the low level of significant correlations associated with the characteristics of the target market might be due to the fact that the German power transmission industry within the B2B-sector is shaped by a close customer-supplier-relation. Thus, lengthy customer relationships were established which stay relatively stable in economic fluctuations or even if the level of competition increases. Nevertheless, the right timing for market entry was found to be important for each success variable: *sales performance, product performance,* and *efficiency*.

It was quite understandable that a *high potential for market expansion* did not correlate significantly and positively with the current *sales performance* as this is probably more decisive for future sales success. The same explanation seemed to fit for the dependent variables of *product performance* and process *efficiency*.

6.4.3.4 Correlations of the Category "Organization" and "Innovation Success"

The independent variables associated with the category *organization* which were listed in the theoretical framework III, indicated significant and positive correlations to nearly each of the dependent success variables *sales performance*, *product performance*, and *efficiency* (cf. Figure 37). Just the variables *lean decision making* and *strong innovation culture* did not correlate significantly with *product performance*. The values of the associated correlation coefficients ranged primary on a weak to middling strength level. Hypothesis H3 predicted a significant correlation between each independent variable associated with the category organization and at least one of the three dependent success variables. Correspondingly, H3 was retained.

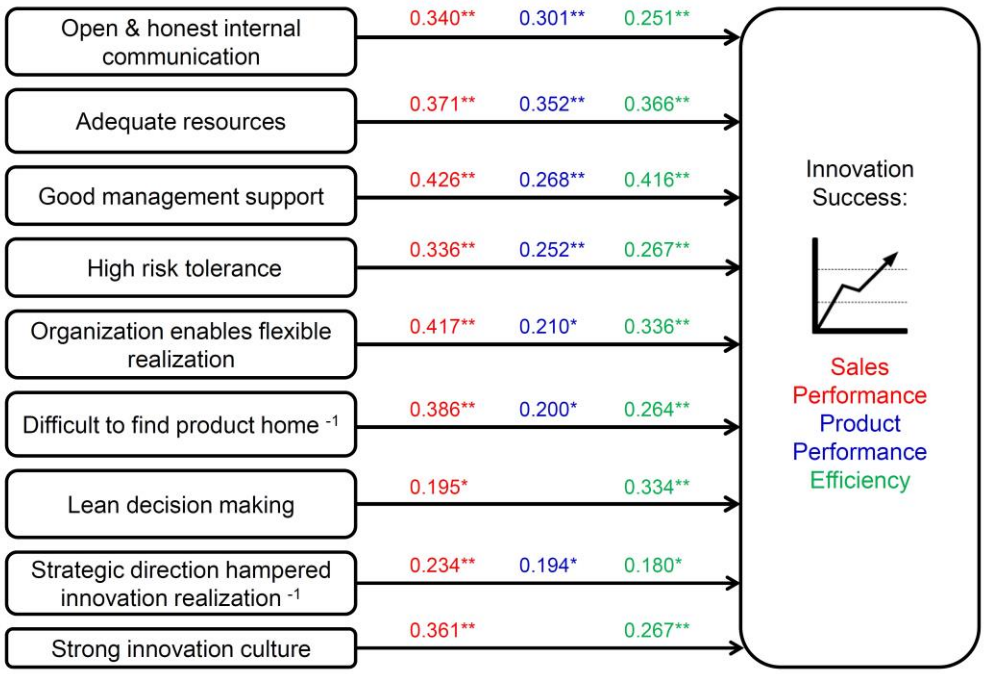


Figure 37: Correlations of the Category "Organization" and "Innovation Success"

The highest values of all correlation coefficients associated with the organization indicated the correlation between the independent variable of *good management support* and the dependent variables *sales performance* and process *efficiency*. As a further significant positive correlation to *product performance* was detected, *good management support* seems to be decisive for the success of the innovation project. Only if the management supports the project realization, the project can be successful. If this support would be missing, it would be very difficult for the project team to succeed. Besides the *management support,* the variables *open & honest internal com*munication and high *risk tolerance* exhibited statistically traceable positive associations with each of the three dependent success variables. Together with a *strong innovation culture* which correlated significantly and positively with *sales performance* and process *efficiency*, both are crucial for a positive climate for the innovation realization within the organization. This seems to be decisive to bring the innovation project to success. Furthermore, an *adequate resource* allocation is a precondition for success which could be validated by the significant positive correlations with each of the three dependent success variables. Additionally, the probability of success would be increased if the *organization enables a flexible realization* of the project and if the *decision making* processes are *lean*. Therefore, a faster and more efficient project realization will be possible. Moreover, it is easier to address customer requirements which additionally influences *sales performance* positively.

Finally, a significant positive correlation between the three success variables and the *strategic direction* of the organization as well as the ability *to find an adequate product home* within the organization were detected. If the parent company actually has a strategic interest in the innovation and could easily integrate it into its organizational structure, this tremendously eases innovation realization. Correspondingly, it would be certainly much easier to persuade potential project advocates and acquire resources.

Correlations of the Category "Entrepreneurial Team" and "Innovation Success"

Throughout each of the independent variables associated with the category *entrepreneurial team* being outlined in the theoretical framework IV, statistically significant and positive correlations were detected with at least one of the three dependent success variables (cf. Figure 38). The correlation values also ranged from weak to middling strength levels. As hypothesis H4 predicted a significant correlation between each independent variable associated with the category entrepreneurial team and at least one of the three dependent success variables, H4 was retained.

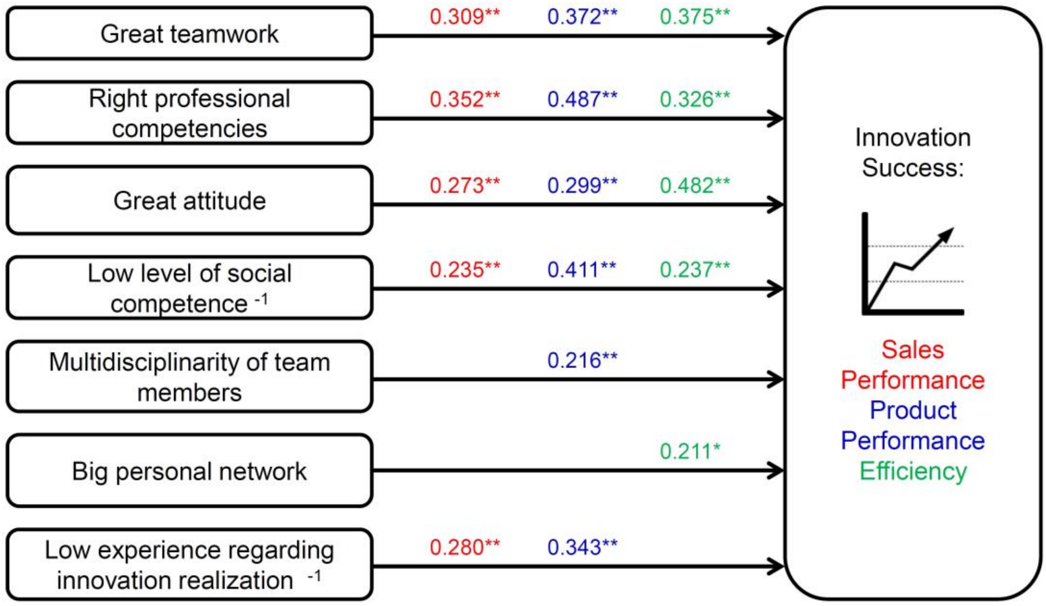


Figure 38: Correlations of the Category "Entrepreneurial Team" and "Innovation Success"

The *experience* of the team members *regarding innovation realization* of comparable projects correlated significantly and positively with *sales* and *product performance*. This result was not a surprise as the higher level of routine lifts the success probability. However, it was interesting that no statistical evidence was found for a significant correlation with process *efficiency* and the level of experience. Apparently, inexperienced teams could also be efficient at innovation realization maybe due to their unbiased and creative new approaches.

Multidisciplinarity of team members just correlated significantly and positively with *product performance*. With respect to *sales performance* and process *efficiency* no statistically traceable correlations were detected. In contrast, the variable that the *right professional competences* were present in the team indicated significant positive correlations to each of the three dependent success variables. For process *efficiency*, it did not seem to be crucial if the team itself is multidisciplinary as long as the team has access to the essential professional competences. The statistically demonstrated positive correlation of a *big personal network* of the team members and the subsequent process *efficiency* could serve as an evidence for this explanatory approach. However, *sales* and *product performance* did not correlate significantly with a *big personal network* of the team members. For these success dimensions, the team itself seemed to be more important. This estimation could be supported by the relatively high correlation values of the variable *right professional competences which* were present in the team and *sales* and *product performance*.

Besides the *professional competences*, a *great teamwork*, a *great attitude* of the team members, as well as their *level of social competence* were decisive for the innovation success. Each of these independent variables correlated significantly and positively with all three dependent innovation success variables. Especially with respect to process *efficiency*, the attitude of the team members was found to be crucial.

6.4.3.5 Correlations of the Category "Innovation Process" and "Innovation Success"

As outlined in chapter 6.1, just the controllable and measurable process instruments have been considered within the category *innovation process*. There was no differentiation of the three separate action fields: *opportunity identification, product development,* and *commercialization* which were arranged in the theoretical framework V. To support the interpretation of the detected correlations, several descriptive data which have been collected within the survey as well, were considered for the respective process instruments.

Besides *platform strategy* and the formation of *strategic partnerships* during innovation realization, any of the other nine process instruments which were listed in the theoretical framework V, exhibited significant and positive correlations to at least one of the dependent success variables (cf. Figure 39). However, the values of the correlation coefficients lay in a range from very weak to weak height. One reason could be the complexity of the overall innovation process which causes several process instruments to be important and not just a few being the main reasons for the subsequent innovation success. Hypothesis H5 predicted a significant correlation between each independent variable associated with the category innovation process and at least one of the three dependent success variables. Accordingly, H5 was rejected. Nevertheless, nine of eleven process instruments exhibited a significant positive correlation to at least one success dimension and hence should be considered at the realization of a radical technological innovation.

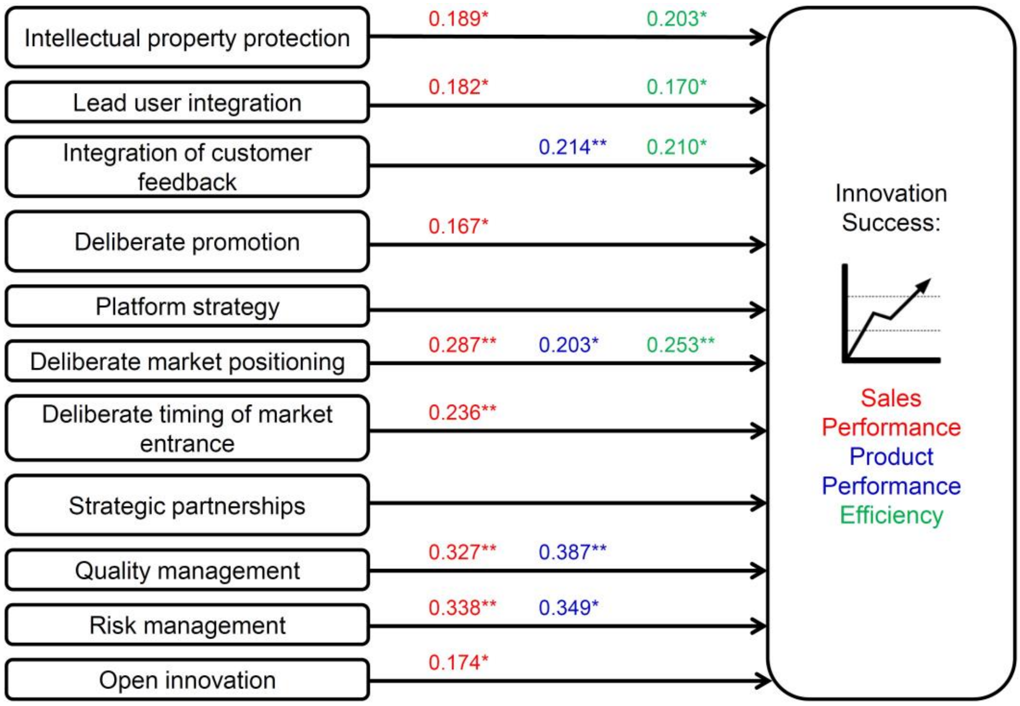


Figure 39: Correlations of the Category "Innovation Process" and "Innovation Success"

Concrete marketing instruments like *deliberate communication, market positioning,* and *timing of market entrance* correlated significantly and positively with *sales performance*. The more purposely the commercialization of an innovation was realized, the more successful was the innovation regarding market share and revenue. It was quite comprehensive that for *deliberate promotion* and for *timing of market entrance* no statistical correlation could be detected with *product performance* and process *efficiency*. In contrast, in the case of *deliberate positioning* of the innovation at the market e.g. as a premium product, a significant positive correlation could be detected regarding *product performance* and *efficiency*. One reason for this result could be the matter that due to the deliberate positioning goal, quality and performance were already focused during product development and therefore the process became quite efficient. Regarding market introduction, 71% of the participants indicated that they acted as a pioneer, 24% as a follower, and just 5% as a laggard. A great majority of 77% of all respondents articulated that they followed the differentiation strategy for market positioning, 18% followed the niche strategy, and nearly 5% stated that they strived for cost leadership. Looking at the purpose of the study addressing radical technological innovations, these results are not at all surprising.

The *integration of customer feedback* correlated significantly and positively with *product performance* and process *efficiency*. This is quite understandable, as the concrete cautiousness of customer requirements and product requirements enable a much faster and more economic realization of the innovation to achieve the required product quality and performance. Just 12% of the respondents stated to have never solicited customer feedback, 15% asked sporadically for feedback, 30% at certain milestones within the project, 20% frequently, and 23% continuously. This feedback was sporadically integrated into the development process by 15% of all survey participants, at certain milestones by 25%, frequently by 23%, continuously by 27%, and never by 10%. With respect to the way the customer feedback was collected, articulated 45% of the respondents via interview at the project start, 60% presentation of the product concept, 63% presentation of the prototype, 63% field test of the prototype, 51% field test of the end product at the customer side, 15% interview before market introduction, and 15% interview after market introduction.

In general, a profound *quality* and *risk management* supports the satisfaction of product requirements and thusly contributes to *product performance* and subsequently *sales performance*. This could be statistically validated by a significant and positive correlation. Maybe the additional documentation efforts prevented that *risk* and *quality management* correlated significantly and positively with process *efficiency*. Interestingly, no statistically traceable relation could be found between the establishment of a *platform strategy* for deliberate product portfolio planning and the three dependent success variables. Probably, such an extensive standardization of product components is not primary relevant for the realization of a radical innovation as the urgent issues are technical development and prompt market introduction. After the innovation has achieved series maturity, standardization projects to gain a more efficient production process are certainly very sensible.

Especially *open innovation* and the *integration of lead users* are meant to gain external impulses for innovation realization. These approaches are particularly useful for the development of a radical innovation, as the market requirements are often not clear in the beginning. *Open innovation*, as well as the integration of lead users, correlated significantly and positively with *sales performance*. Furthermore, a significant positive correlation of the *integration of lead users* and process *efficiency* was detected. The knowledge of actual requirements of real users could potentially ease the realization process quite a lot. Regarding the *integration of lead users* articulated 32% of the respondents that they have never involved lead users. 19% involved them at idea generation, 40% at requirements analysis, 36% at product development, 46% at product tests and 22% at market introduction.

With respect to the establishment of *strategic partnerships*, no significant positive correlations with the dependent success variables were found. This was additionally astonishing, as just 9% of the respondents articulated that they did not involve any strategic partners at the innovation realization. 68% articulated that they have involved suppliers, 62% integrated customers, 35% involved scientific institutes, 25% integrated end users, and 18% involved distribution partners at innovation realization. Besides the obligatory supplier-customer-relationships, the companies apparently did not put emphasis on the involvement of further strategic partners. Thus, they developed primarily independently.

A significant positive correlation was found between the *protection of intellectual property* and *sales performance*. An intellectual property offers a sales monopoly which is granted for a limited period of time for the underlying invention. Thus, intellectual properties potentially foster *sales performance*, as they prevent competitors from market engagement. Interestingly, an additional significant positive correlation could be detected between *intellectual property protection* and process *efficiency*. Intuitively, one would not expect an association. Probably, organizations that put emphasis on a proper intellectual property strategy are generally quite efficient regarding their project realization. This circumstance may cause the correlation. Furthermore, 55% of the survey participants stated that they have applied for intellectual properties protecting the underlying technology, 52% aimed to protect the core product, 43% wanted to protect additional components, and just 14% articulated that they did not file for any intellectual property application.

6.4.4 Summary and Adjusted ICPS-Framework

By conducting the correlation analyses, the five theoretical frameworks and associated hypotheses were statistically tested. As a result, several significant positive correlations were detected between the independent variables of the innovation context and innovation process and the dependent success variables *sales performance*, *product performance*, and *efficiency*. This result confirmed a statistically verifiable linear connection between these variables. All independent variables associated with the categories *organization* and *entrepreneurial team* indicated significant positive correlations to at least one of the three dependent success variables. With respect to the categories *technology* and *target market*, approximately half of the considered independent variables correlated significantly and positively with at least one dependent variable. Besides *platform strategy* and *strategic partnerships*, all of the analyzed instruments of the *innovation process* exhibited statistically verifiable correlations of this sort. The detected Pearson coefficients indicated just very weak to middling correlation strengths (0.16 – 0.49). However, this result was not surprising. It led to the conclusion that all of the independent variables, correlating significantly and positively with the dependent success variables, might influence the innovation success at approximately the same level. The realization of a radical technological innovation is a very complex endeavor with a lot of impact parameters. Correspondingly, there seems to be no limited set of factors with a dominating effect on the ultimate innovation success. Thus, any of the independent variables exhibiting a significant positive correlation with the dependent variables is supposed to be important and not just a few dominating factors. The corresponding hypotheses test recommended retaining the hypotheses H3 and H4, while rejecting the hypotheses H1, H2, and H5.

Based on the results of the correlation analyses, the ICPS framework was adjusted. Therefore, the independent variables, which correlated significantly with at least one of the three dependent success variables, were considered and listed within their associated categories in the adjusted ICPS framework (cf. Figure 40). The subsequent framework contains just statistically verified CSFs. These CSFs are less abstract and more concrete than the CSFs of the previous ICPS framework (cf. Figure 20), as they are the result of the conducted operationalization at the generation of the theoretical frameworks of chapter 6.1.

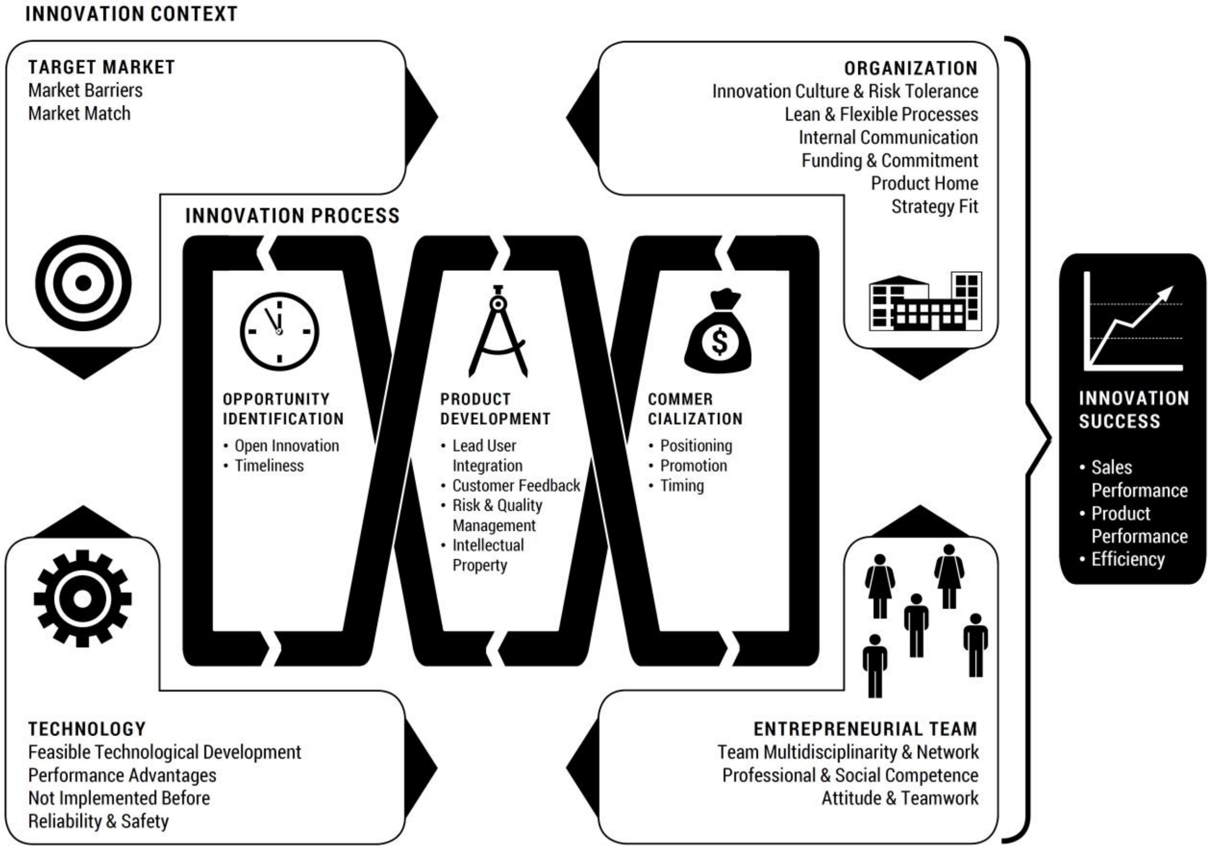


Figure 40: Adjusted ICPS Framework

For designing the survey instrument, no differentiation of the three separate action fields of the innovation process within the ICPS framework *opportunity identification*, *product development*, and *commercialization* was considered at the operationalization of the individual items. This was done for several research pragmatic reasons (cf. chapter 6.1). Accordingly, the operationalized items associated with the *innovation process* had to be rearranged when adjusting the ICPS framework.

As *open innovation* is a process instrument which is meant to gain external impulses, especially in the idea generation phase, this instrument was allocated to the *opportunity identification* action field. Within the original ICPS framework, the factor *timeliness* was listed as a CSF of the *opportunity identification* action field. However, in the survey, it was captured as a parameter of the theoretical framework II associated to the target market. This was due to the fact that just controllable and measurable process instruments were considered in the theoretical framework V associated with the *innovation process*. Nevertheless, when adjusting the ICPS framework, the CSF *timeliness* was rearranged to the *opportunity identification* action field within the *innovation process* category. According to the original ICPS framework, the factors *lead user integration*, *risk & quality management*, and *intellectual property* were listed within the product development action field. As the survey participants articulated to integrate *customer feedback* especially for *product development*, this factor was similarly arranged within this action field. In contrast, the three marketing instruments *positioning, promotion*, and *timing* were clearly assigned to the commercialization action field.

6.4.5 Discussion and Limitations

A sound methodological design and a good theoretical base add rigor to the conducted quantitative study. Therefore, the survey instrument was based on testable variables and hypotheses which were outlined in chapter 6.1. The aim of this study was to statistically test whether or not the data support these hypotheses that were developed after a careful qualitative pre-study of the problem situation (cf. chapter 5). To do this on a broad base, a questionnaire survey was applied. This method is best suited when information is to be obtained on a substantial scale through structured questions, at a reasonable cost, from a sample that is widely dispersed geographically (Sekaran and Bougie, 2010, p. 218, 2010, pp. 19–20). The target population for the survey included representatives of the German power transmission industry who have been involved in the realization of a radical technological innovation. Correspondingly, a questionnaire survey represented an adequate instrument for data gathering. To precisely study the CSFs of radical technological innovations, the participants were asked to retrospectively relate their answers to a concrete innovation project (cf. chapter 6.2.1). Thereby the CSFs which were relevant to this concrete project, were analyzed and their value not weakened by an abstract consideration of a variety of factors stemming from several different projects. Thus, the closeness of the findings to reality was respected (Sekaran and Bougie, 2010, p. 21).

The design, the wording, and the scales of the questionnaire were developed according to common research guidelines. Subsequently, a pretest was conducted to test the capability of the resulting survey instrument (cf. chapter 6.2). However, this content-validity check was qualitative as statistical measures could not be applied (Dahl, 2015, p. 65). A general limitation of questionnaires is that one cannot be sure if the data obtained are biased since the non-respondents may be different from those who did respond (Sekaran and Bougie, 2010, p. 218).

For the quantitative study, the German power transmission industry was chosen as target industry (cf. chapter 6.3.1). Correspondingly, a further limitation is that the survey results cannot be doubtlessly generalized to the mechanical engineering industry as the overall target industry of the thesis. Although the power transmission industry is a sub-sector of the mechanical engineering industry, the latter industry is quite diverse (Dahl, 2015, p. 65; VDMA and McKinsey, 2014c, p. 12). To enlarge the applicability of the research findings, the conducted survey needs to be replicated in the different sub-sectors of the mechanical engineering industry by further research (Sekaran and Bougie, 2010, p. 22).

Furthermore, it should be questioned if the survey sample really represents the target population. One of the main data collection channels was the FVA. The FVA includes many of the main players within the German power transmission industry, but not all companies being active in this branch. Correspondingly, the survey sample might represent the FVA-membership structure rather than the structure of the overall German power transmission industry. To address this issue, a triangulation of different data collection channels (FVA symposium, Xing, personal network) was established. Each survey channel contributed approximately the same number of respondents (roughly 50 each) to the overall amount of participants (cf. 6.3.2). Another way to deal with this potential bias was a comparison of the collected descriptive data about the survey sample (cf. 6.4.1) with the characteristics of the target population. Therefore, the study of the VDMA and McKinsey & Company (cf. chapter 2.2.1.1) and several information portals (Statista; Statistisches Bundesamt, 2015) were considered. Additionally, the survey results were discussed with several industry experts. These comparative analyses confirmed the representativeness of the sample on a qualitative basis.

A further potential bias may be due to the inconsistency regarding the concept of the innovation terminology. As it was with the literature review and the expert interviews, this issue emerged during the data collection at the FVA-symposium. Thus, one of the most frequent questions was how a radical technological innovation is defined. In the subsequent discussion, it became clear that the survey participants did not share a uniform concept of radical technological innovations. Because of the experience made in the qualitative pre-study, this was expected (Dahl, 2015, p. 64). Therefore, a detailed explanation was given at the first page of the questionnaire to prevent misconceptions (cf. 6.2.3). Furthermore, the newness of the respective innovation was inquired. Most of the respondents articulated that their innovation was at least new to the respective market. This meets the requirements for the considered innovation projects within the survey (cf. chapter 6.2.1).

As it was with the primary case study research, one limitation that is inherent to the study design is that mainly successful innovation projects were studied. For conscientiously answering the survey, it was important that the selected innovation project has gone through each phase of the innovation process. Thus, the respective innovations had to be implemented in the market. Failed innovation projects usually do not reach the commercialization stage and could therefore not be chosen by the survey participants. Additionally, there might be a bias towards more successful projects because it is usually more pleasant to look back upon successful than unsuccessful experiences. These effects might have caused a positive selection of the considered innovation projects. This suspected bias is reflected by the high satisfaction rates of the respondents with the selected projects (Hilgers, 2015, p. 80).

Before actual analysis, the collected data have been prepared. Therefore, missing data were replaced by imputation. Correspondingly, the subsequent statistical analyses were based on manipulated data. The central tradeoff lies in the loss of confidence due to the usage of estimated values and the profit of using sophisticated statistical methods. As the data were missing completely at random and the elaborate approach of regression imputation combined with preceding maximum likelihood estimation was utilized, the missing values were substituted quite realistically. Nevertheless, the achieved results have to be treated with caution (Brosius, 2013, p. 285).

Another limitation is caused by the applied explorative factor analysis. The specific goal of EFA is to reduce a large number of observed variables to a smaller number of factors. Thus, there is a general tradeoff between the level of dimension reduction, on the one hand, and explanation quality of the extracted factor model, on the other (Brosius, 2013, p. 792; Tabachnick and Fidell, 2007, p. 608). However, the factors were derived from statistical results, not from theory. Established guidelines were used to determine which variables load on which particular factor. Afterward, a reliability analysis verified the detected factor solution (Hair, 2010, p. 693).

To finally test the hypotheses outlined in chapter 6.1, correlation analyses were applied. The variables to be tested were measured on a Likert-scale and the subsequent data were normally distributed. Thus, the precondition of parametric data for this statistical technique was fulfilled. Due to the confidence level of $\alpha < 0.05$, the probability that the detected correlations are correct will be true in 95% of all cases and that there is only a 5% chance of being wrong. On the other hand, it is just an indication that the two variables are associated with each other. There is no evidence that one variable causes the other (Sekaran and Bougie, 2010, p. 322, 2010, p. 21).

By conducting the correlation analyses, several significant positive correlations were detected between the independent variables of the four innovation context categories (technology, target market, organization, and entrepreneurial team) as well as the innovation process and the dependent success variables. Nevertheless, the hypotheses associated to the five theoretical frameworks were just retained if each CSF within the respective framework exhibited a significant positive correlation to at least one of the three dependent variables of the overall innovation success. As a consequence, only the hypotheses H3 and H4 were retained, while the hypotheses H1, H2, and H5 were rejected. Maybe the granularity of the five hypotheses was too low and more detailed hypotheses on the CSFs-level would have been better. However, the results of the correlations analyses were utilized and an adjusted ICPS framework was created.

The adjusted CSF-framework highlights the statistically verified CSFs for the challenging task of realizing a radical technological innovation in an easy and accessible manner. Correspondingly, the adjusted ICPS framework meets the requirements of research parsimony (Sekaran and Bougie, 2010, p. 23). However, the chronological and factual contribution of each CSF to the overall innovation success is quite difficult. The great complexity of the innovation process with its manifold cause and effect relationships prevents, in general, an exact determination of the concrete impact of a specific factor on the subsequent innovation success (Vahs and Brem, 2012, p. 69). Nevertheless, the adjusted ICPS framework has highly managerial implications if the CSFs are taken as a lens for analysis and particular attention (Leidecker and Bruno, 1984, p. 23).

7 Innovation Archetypes

The implementation of a radical technological innovation in the mechanical engineering industry is highly complex. Therefore, the CSFs outlined in the ICPS-framework can help to reduce complexity within innovation realization. However, the relative importance of each CSF depends on the respective innovation context (Balachandra and Friar, 1997, pp. 284–285; Vahs and Brem, 2012, p. 69). This issue was addressed by the second central research question: are there certain distinguishable innovation archetypes based on the innovation context that suggest distinct realization strategies for the subsequent innovation process? To answer this question, the statistical technique of cluster analysis was utilized.

7.1 Cluster Analysis

7.1.1 Methodology

The primary purpose of cluster analysis is to group objects based on the characteristics they possess. The goal is that the objects in the same cluster are more similar to one another than they are to objects in other clusters. The intent is, therefore, to maximize the homogeneity of objects within the clusters, while also maximizing the heterogeneity between the clusters. Cluster analysis contains the following main steps: selecting variables, preparing the data, measuring similarity, selecting a clustering algorithm, and determining cluster size (Backhaus *et al.*, 2016, p. 456; Brosius, 2013, pp. 712–714; Hair, 2010, pp. 505–508).

According to the second central research questions, the variables associated with the innovation context were selected for the cluster analysis which exhibited significant positive correlations to at least one of the dependent success variables within the previously conducted correlation analyses. With these characteristics, an analysis should be conducted to determine whether there are distinct innovation archetypes that are based on the contextual circumstances.

A common form of data preparation is standardizing the variables. The process converts each raw data score into a standardized value with a mean of 0 and a standard deviation of 1, and in turn, eliminates the bias introduced by the differences in the scales of the considered variables. As the variables taken for cluster analysis within the study at hand were all measured on the same Likert-scale, no standardization was needed (Hair, 2010, p. 524).

As a next step, the similarity between the objects had to be measured. Similarity represents the degree of correspondence among objects across all of the characteristics used in the analysis (Hair, 2010, p. 511). Several similarity measures have been developed by previous research. Their appropriateness depends on the scales of the respective variables (Backhaus *et al.*, 2016, p. 458). For this study, the squared Euclidean distance was selected. It is the recommended distance measure for Ward's method of clustering which was utilized (Hair, 2010, p. 521).

The heart of cluster analysis lies in the clustering procedure. A multiplicity of potential methods was prepared for distinct scales and variable characteristics like size, shape, or distribution. In this research study, the hierarchical cluster analysis using Ward's method was utilized which is a common procedure for interval-scaled variables. In Ward's method, the clustering is based on the minimal increase in error sum of squares (Backhaus *et al.*, 2016, p. 484; Schendera, 2008, pp. 24–26).

As the last step, the cluster solution being most appropriate within the conducted analysis was determined. This was based on the dendogram which visualized the step-by-step clustering of the 147 cases (cf. Figure 86, Appendix V - 10). The length of the horizontal lines within the dendogram indicated the increasing heterogeneity of the associated cluster solutions. Finally, the conclusion was drawn that five clusters represented the most suitable number of clusters (Schendera, 2008, pp. 59–61).

7.1.2 Findings

The cluster analysis produced five clearly distinguishable clusters. As these clusters represented typical contextual project circumstances, they were thusly regarded as the sought innovation archetypes. The size of the respective clusters ranged from 20 to 40 cases, each representing a percentage of 18 – 27% regarding the overall 147 cases (cf. Figure 41). The cluster symbols were composed of the four colored sub-symbols of the associated categories *target market*, *organization*, *entrepreneurial team*, and *technology*. The coloration of the sub-symbols was due to the relative height of the arithmetic mean which was calculated from the average characteristics of the individual variables per category. Dark green means that within this cluster the arithmetic mean of the individual variables of this category was particularly positive compared to the other clusters. Light green indicates above-average, gray as average, orange as below-average, and red as particularly low characteristic of the arithmetic mean. According to their characteristics, the clusters were named as archetypical project contexts: cluster 1 as *inventor`s friendly innovation paradise*, cluster 2 as *conservative development sphere*, cluster 3 as *highly productive innovation system*, cluster 4 as *mediocre implementation circumstances*, and cluster 5 as *fruitless innovation wasteland*. The descriptive details for each cluster were described in chapter 7.3.

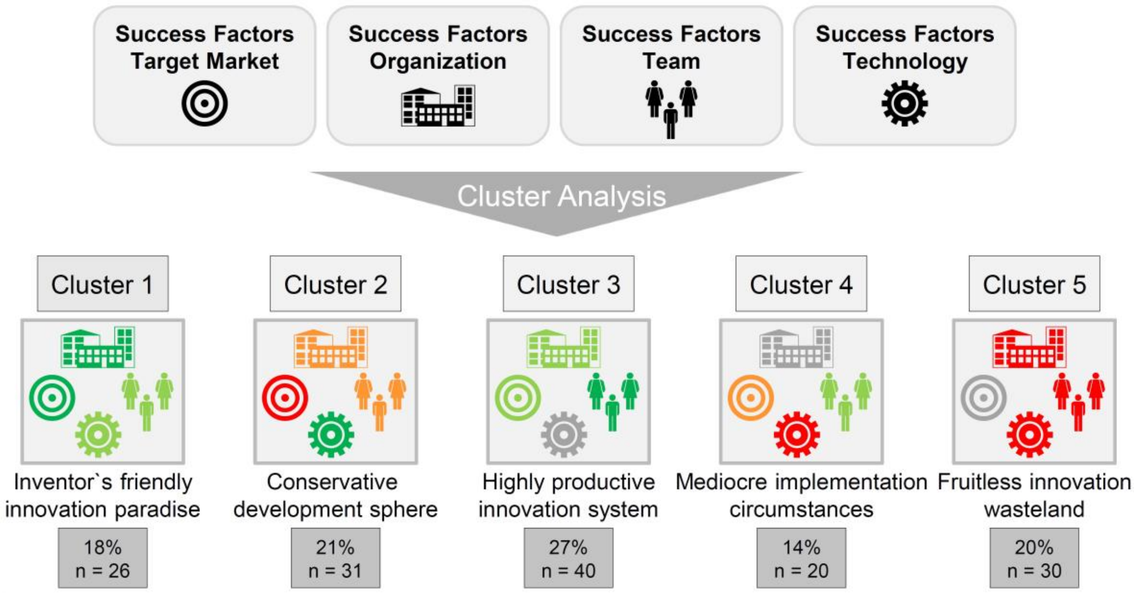


Figure 41: Process and Results of Cluster Analysis

7.2 Validation of the Cluster Solution

7.2.1 Analysis of Variance

7.2.1.1 Methodology

For validating the clusters as innovation archetypes, an analysis of variance (ANOVA) was conducted to test whether the clusters could be distinguished regarding their realization strategies for the innovation process. ANOVA is a statistical technique used to compare two or more means to see if there are any significant differences among them. To perform this analysis, the eleven process instruments were taken as dependent variables and were tested for equality across the groups (Hair, 2010, pp. 440–444; Tabachnick and Fidell, 2007, p. 37).

ANOVA is based on a comparison of two estimates of variance. The first estimate comes from differences among scores within each group and the second estimate comes from differences in group means. If these two estimates of variance do not differ appreciably, it is concluded that the entire group means come from the same sampling distribution of means and that the slight differences among them are due to random error. If on the other hand, the group means differ more than expected, it is concluded that they were drawn from different sampling distributions of means, and the null hypothesis that the means are the same should be rejected (Tabachnick and Fidell, 2007, p. 38). While a nominal scale is sufficient for the independent variable, the dependent variables need to be parametric and their variances have to be homogeneous (Brosius, 2013, p. 500). The cluster variable was nominally scaled and the innovation process instruments as dependent variables were parametrically scaled (cf. chapter 6.4.2). If these variables, additionally, exhibited variance, then homogeneity was tested by conducting a Levene-test. This test examined the null hypothesis that all variances of the respective variables were identical within each cluster on a significant level of $\alpha<0.10$[7]. In cases of values higher than 0.1, the null hypothesis was retained and in cases of values lower than 0.1, the hypothesis was rejected (Brosius, 2013, p. 500; Wittenberg *et al.*, 2014, p. 232).

For the variables with homogeneous variances, ANOVA represented the appropriate test. In contrast, for variables with inhomogeneous variances, a Welch-test was applied. This test is also based on the similarity of cluster means, obtains an approximate solution, and is well suited for unequal variances (Brosius, 2013, p. 514; Rüger, 2002, p. 135). Within SPSS, both tests were conducted for all variables. Accordingly, just the results of the relevant tests were considered for the respective variables.

7.2.1.2 Findings

The Levene-test indicated for the following five innovation process instruments a significance level of $\alpha>0.1$ and thusly variance homogeneity: PI_2, PI_4, PI_7, PI_8, and PI_10. For the following six process instruments, the significance level was lower than 0.1 and the null hypothesis that the variances of the associated variables were homogeneous was therefore rejected: PI_1, PI_3, PI_5, PI_6, PI_9, and PI_11 (cf. Table 36, Appendix V – 11).

Correspondingly, for the first half of the dependent variables the results of the ANOVA were considered. The results exhibited for PI_8 a significant level and for the other process instruments even a highly significant level (cf. Table 37, Appendix V – 11). The results of the Welch-test indicated a highly significant level for each of the process instruments from the second half of dependent variables (cf. Table 38, Appendix V -11).

These results clearly confirmed the detected five cluster solution. The innovation realization strategies of the five clusters could be then distinguished, as significant associations were detected throughout any of the eleven process instruments.

7.2.2 Analysis of Cramer's V

7.2.2.1 Methodology

With ANOVA, the clusters could be significantly distinguished regarding the characteristics of the process variables. To furthermore assess the individual strengths of the associations between each of the eleven process instruments and the cluster assignment, Cramer's V was calculated. In general, there is no universal measure of association which could be applied for any kind of scale.

[7] Significance level was lifted to reduce the risk of ß-error (Wittenberg and Cramer, 2000, p. 216)

Cramer's V is appropriate for nominal scales and naturally for upper measurement scales as well. As the cluster variable was nominally scaled, this measure was selected. Cramer's V is based on the chi-square-value and its values range from zero to one. However, a value near to one is quite rare and an accurate indication that the strength of association will not be possible. The coefficient is primarily appropriate for assessing the relative strength of association in comparison to content-related questions or with respect to previous experiences on similar matters (Backhaus *et al.*, 2000, p. 239; Brosius, 2013, pp. 432–434; Wittenberg *et al.*, 2014, p. 208). With this context in mind, the calculated values were mainly used for comparing the individual strengths of associations between each of the process instruments and the cluster assignment.

7.2.2.2 Findings

Besides PI_1, PI_8, and PI_11, the Cramer's V values of each process instrument indicated significant, or highly significant, associations with the cluster assignment (cf. Table 9). Even PI_1, PI_8, and PI_11 exhibited a significance level of at least $\alpha<0.1$. This means that the way the process instruments are realized is significantly associated with the clustering. Therefore, the initial estimation that there are innovation archetypes that determine the way the innovation process is arranged can be confirmed. The absolute values of the process variables were nearly in the same range from 0.278 to 0.439. Correspondingly, there is no individual process instrument that dominates the cluster assignment. The concrete manifestation of each process variable is decisive for the overall cluster-related strategy for the realization of the innovation process.

Table 9: Cramer's V for 5-Cluster Solution

	PI_1	PI_2	PI_3	PI_4	PI_5	PI_6	PI_7	PI_8	PI_9	PI_10	PI_11
Cramer's V	.278	.334	.369	.334	.399	.399	.437	.357	.411	.417	.439
Sig.	.057	.007	.000	.045	.009	.004	.000	.091	.000	.000	.065

7.2.2.3 Comparison of Cluster Solution with Top-Performer Classification

Intuitively, one might expect that the top performers should be taken as a role model for arranging the innovation process. It seems then sensible to analyze the way top performers, average performers, and worst performers are organizing their innovation processes. Based on this analysis, aligning the process strategy to the top performers does sound reasonable. This action strategy presumes that the arrangement of the process instruments is similar within these three categories. Correspondingly, it should be possible to detect strong significant associations between each of the eleven process instruments and the categorization of top performers, average performers, and worst performers. To test this assumption, the 147 cases have been categorized by three performer groups within the innovation success dimensions s*ales performance, product performance,* and *efficiency*. Therefore, the best quartile, the two medium quartiles, and the worst quartile with respect to the three innovation success dimensions were filtered from the 147 cases and grouped.

Based on this classification, Cramer's V was calculated for the individual associations between the process instruments and the performer group assignments. Accordingly, one table for each success dimension was created (cf. Table 10, Table 11, and Table 12).

Table 10: Cramer's V for Performer Groups regarding Sales Performance

	PI_1	PI_2	PI_3	PI_4	PI_5	PI_6	PI_7	PI_8	PI_9	PI_10	PI_11
Cramer's V	.197	.275	.187	.355	.349	.320	.316	.333	.289	.335	.383
Sig.	.781	.324	.591	.044	.292	.465	.600	.342	.137	.105	.590

Table 11: Cramer's V for Performer Groups regarding Product Performance

	PI_1	PI_2	PI_3	PI_4	PI_5	PI_6	PI_7	PI_8	PI_9	PI_10	PI_11
Cramer's V	.195	.239	.248	.311	.335	.399	.341	.321	.370	.366	.401
Sig.	.797	.666	.113	.243	.418	.026	.366	.449	.002	.025	.424

Table 12: Cramer's V for Performer Groups regarding Efficiency

	PI_1	PI_2	PI_3	PI_4	PI_5	PI_6	PI_7	PI_8	PI_9	PI_10	PI_11
Cramer's V	.241	.305	.248	.281	.329	.360	.333	.272	.279	.321	.423
Sig.	.380	.126	.115	.506	.475	.145	.441	.866	.192	.175	.233

When looking at the Cramer's V values, one will recognize that just a few variables indicated significant associations with the performer classification. These were the variables PI_4 within the *sales performance* dimension as well as PI_6, PI_9, and PI_10 within the *product performance* dimension. Correspondingly, none of the performer classifications is a good categorization with respect to significant associations to the process instruments.

In contrast, the five cluster solution indicated significant associations (at least $\alpha<0.1$) to each of the eleven process instruments (cf. Table 9). In the case of radical technological innovations for the German power transmission industry, it thusly seems rational to orientate the strategy for the innovation process on the five detected clusters. These clusters are based on the contextual circumstances and exhibit an overall innovation pattern for the subsequent innovation process. Hence, they could be regarded as innovation archetypes. Only looking at the top performers seems to be the wrong way of dealing with radical technological innovations. The innovation process is highly complex and strongly dependent on the innovation context. Therefore, it seemed reasonable to qualitatively study the contextual circumstances of the five innovation archetypes in depth, analyze the way they were arranging the innovation process and examine their subsequent innovation success (cf. chapter 7.3).

7.3 Descriptive Analysis of the Clusters

For the descriptive analysis of the five clusters, the cluster-specific characteristics and average means of the interval-scaled variables were compared to the sample averages to derive representative attributes for each cluster. Furthermore, the descriptive and qualitative data regarding the respective innovation projects and firm demographics were considered. Based on this information, the clusters were described and subsequently named.

Within the first part, descriptive information regarding the organizational background and the selected innovation projects of the different clusters will be presented. Then, the cluster specific innovation contexts with respect to its categories *organization, entrepreneurial team, technology,* and *target market* will be characterized. Afterward, the innovation process and corresponding utilization of distinct process instruments will be depicted. Finally, the subsequent innovation success will be outlined.

7.3.1 Cluster 1: Inventor`s Friendly Innovation Paradise

The conditions for the projects in cluster 1 were very positive for the realization of the respective innovations. Thus, cluster 1 was named *inventor's friendly innovation paradise*.

7.3.1.1 Cluster Description

26 cases were assigned to cluster 1. This accounts for a percentage of 18. The first half of the projects was realized in companies being active in the mechanical engineering industry and the second half in companies within the automotive industry. These companies were characterized by an extraordinarily high revenue share of products which were younger than five years. Nearly half of the firms had more than 10,000 employees while the other half was split into equal parts of organizations with 100 to 1,000 and organizations with 1,000 to 10,000 employees. Correspondingly, the two dominating corporate forms were stock and capital companies.

The considered innovation projects were primarily technology-push rather than market-pull innovations and represented mainly new-to-the-market innovations. Additionally, several new-to-the-world and new-to-the-firm innovations were among the cases of this cluster. Regarding the project organization, the matrix organization clearly formed the majority compared to just a few cases of autonomous project organization. With respect to process standardization, no distinct pattern could be derived, as the projects were conducted with an equal share of three types of processes: first, no standardized process approach at all, second, a common approach that was not formalized within the organization, and last, a formally standardized approach. If the process was formally standardized, in nearly all cases it was a stage gate process.

7.3.1.2 Innovation Context

The organizational context for the innovation projects of cluster 1 was very positive. The strategic direction of the respective companies was very supportive of the projects and the organizational structure enabled a particularly flexible realization or implementation. The processes for decision making were lean and there were no problems to find an organizational home for the product innovations within the corresponding companies. Both resource allocation and management support were also very good. Furthermore, the companies of cluster 1 were shaped by a strong innovation culture combined with a high risk tolerance and an open communication atmosphere.

In general, the innovating team was quite conducive for the realization of the innovation projects. Throughout all projects of cluster 1, fairly experienced people were involved with a high level of professional competence. The entrepreneurial teams were multidisciplinary but averagely networked. Moreover, the involved people were characterized by a high level of social competence, great teamwork, and a strong attitude to bring the innovation project to success despite all the setbacks.

The technologies which underlay the innovations, were very reliable and safe within the analyzed projects. From the customer perspective, they were more capable than potential alternatives but exhibited just average cost advantages. The utilized technologies were rarely implemented in existing products so far. However, they had a great potential to be implemented in further applications. Due to the great newness, the technological development until market maturity was associated with difficulties and high investments.

The target markets of the innovations of cluster 1 were generally very interesting. Accordingly, the markets were quite big and exhibited good chances for market growth. The market barriers were on an average level. Furthermore, there was just a low level of competition and hardly negative external market impacts like political or macroeconomic influences. From today's point of view, the respondents valued the market selection and the timing of market introduction as absolutely right.

7.3.1.3 Innovation Process

Regarding the innovation processes of cluster 1 projects, relatively low emphasis was put on strategic partnerships. If such cooperation was established, then mainly with customers, suppliers, and rarely research institutes. Accordingly, the open innovation approach was little utilized and the companies primarily followed an autonomous development approach. In order to include external impetuses in the development process, a deliberate strategy was the integration of lead users. This process instrument was applied intensively at the generation of requirements, within the actual product development phase, at product testing, and before market implementation. Gathering and integrating customer feedback in the innovation process was quite important on a regular basis, especially, the presentation of the product concept as well as the presentation and practical test of the prototype to the customer proved to be crucial.

During the development process, a lot of weight was attached to a sound quality and risk management strategy. Additionally, the protection of intellectual property was stringently implemented. In more than half of the projects, the companies have applied for intellectual property rights with respect to the underlying technology, the core product, as well as complementary components. The establishment of a platform strategy did not play an important role for the projects of cluster 1.

Very low importance was attached to a deliberate timing of market entrance. Most probably, this is due to the fact that the companies from cluster 1 mainly introduced their innovations as pioneers in the market. Therefore, in leading as pioneers, the technological maturity of the respective innovations was primarily crucial for the timing of market launch instead of external reasons like competitive situation or seasonal influences. Additionally, a deliberate promotion strategy was not stressed. In contrast, conscious positioning was realized. In this regard, the companies of cluster 1 mainly tried to stand out from their competitors by following the differentiation strategy.

7.3.1.4 Innovation Success

In general, the projects of cluster 1 were particularly successful. Correspondingly, the average satisfaction of the respondents with the project results achieved the highest level compared to the other clusters. The majority of survey participants was very satisfied while the remaining quarter was at least satisfied with the project results. Just in one case, a respondent was unsatisfied.

Both revenue and market share predominantly met the expectations. This confirmed the great success with respect to sales performance. At the moment of maximal market penetration, the product innovations on average had a market share of up to 10%. Accordingly, approximately half of the projects achieved a market share of up to 5% and almost a third of the projects obtained a market share between 5 and 10%.

Moreover, the success regarding product performance was extremely high. Thus, the quality of the newly developed products was excellent. Similarly, the product performance continuously met the requirements and achieved a particularly high customer satisfaction.

Compared to the other clusters, the projects of cluster 1 were quite efficient. Both speed of the innovation realization and consumption of available resources were primarily efficient. Nevertheless, the project teams rather could not adhere to the initial project schedule as well as to the initially calculated budget.

7.3.2 Cluster 2: Conservative Development Sphere

The characteristics of the contextual success factors were not so favorable for the realization of the innovation projects of cluster 2. Especially, the target market and the organizational context hampered the innovation process. Thus, this cluster was named *conservative development sphere.*

7.3.2.1 Cluster Description

Based on the cluster analysis, 31 cases were allocated to cluster 2 which represents an overall share of 21%. Most projects of this cluster were realized in companies of the mechanical engineering industry and just a few in companies of the automotive industry. Clearly dominating were large enterprises with more than 10,000 employees and a below average revenue share of products younger than five years. Nearly two thirds of the companies were stock companies and approximately one third had the corporate form of a capital company.

The projects were mainly based on technology-push innovations and made up either new-to-the-firm or new-to-the-market innovations. Regarding the form of project organization, the matrix organization clearly dominated compared to the autonomous organization. Moreover, there was no uniform approach for process standardization. The projects in cluster 2 were either not standardized at all, organized according to a common company-specific approach, or formalized according to a stage gate process.

7.3.2.2 Innovation Context

The organizational circumstances of the analyzed projects in cluster 2 were rather negative. Accordingly, the strategic direction of the companies, as well as the rigid organizational structure, impeded innovation realization. This also resulted in an unfavorable resource allocation and a low level of management support. All in all, the companies in cluster 2 were characterized by a weak innovation culture, little risk tolerance, and a bad internal communication. The decision making processes were lean only to a mediocre level. Additionally, it was not easy to find an adequate organizational home for the product innovations.

Similar to the organizational circumstances, the entrepreneurial team within the projects of cluster 2 hampered innovation realization. On the one hand, the involved people were highly motivated, but on the other hand, they had just average professional competence and little experience in the implementation of such innovation projects. However, the teams were shaped by a high level of multidisciplinarity and a great personal network. Nevertheless, their social competence and their teamwork were relatively weak.

The technologies that underlay the innovation projects of cluster 2 were quite advantageous. Although capability, reliability, and safety of the respective technologies were on an average level, the technologies had relatively high cost advantages. Primarily, technologies were applied which had already been implemented in previous products and which additionally exhibited huge further application potential. However, the technological development was elaborate.

The target markets for the respective innovations were very unfavorable. Despite the interesting market sizes and good prospects for market growth, the respondents retrospectively assessed the market selection and the timing of market introduction as wrong. This was mainly due to the high market barriers, the tough competitive situation, and the disadvantageous external market influences being characteristic to these markets.

7.3.2.3 Innovation Process

The innovation processes of cluster 2 projects were shaped by a strong focus on the establishment of strategic partnerships. The companies perceived, at various levels, their customers (in nearly all cases), suppliers, (often), research institutes (often), and end users (occasionally) as strategic partners. However, they did not go as far as opening up their innovation processes in terms of open innovation. Instead, a lot of weight was attached to regular customer feedback and to the integration of lead users. Especially, the companies of cluster 2 involved lead users at the generation of requirements, at the development process, and at product testing. Customer feedback was received through interviews at the project start, the presentation of the product concept, and the prototype, as well as the practical test of the prototype and the end product.

Relatively little emphasis was put on quality and risk management. The establishment of a platform strategy also did not play an important role. However, the filing for intellectual property rights was consequently realized. Thereby, primarily the core products, and additionally in half of the cases, the underlying technologies and complementary components were protected.

As it was with cluster 1, the timing for market introduction was not purposefully chosen. The pioneer-strategy was dominating, while in one third of all cases, the product innovation was introduced to the market right after other pioneering companies. Comparatively, low attention was put on deliberate promotion and positioning actions. In some projects of cluster 2, a market niche was addressed, but in general, the differentiation strategy was prevailing.

7.3.2.4 Innovation Success

The innovation projects of cluster 2 were generally less successful. In cluster comparison, the average satisfaction of the respondents exhibited the second lowest level. Nevertheless, more than half of the survey participants were still satisfied, and even two of them very satisfied, with the results of their particular projects. However, six respondents were not satisfied, and another six were undecided regarding their respective results.

Regarding sales performance, the success level was below average. The achieved revenues and market shares did not meet the expectations. Interestingly, there were two main groups with respect to market share at the moment of maximal market penetration. Each group accounted for approximately half of the projects. The first group obtained a market share of up to 5% and the second group a market share of 10 to 30%.

The product performance of the particular innovations mainly met the requirements and also the corresponding product quality was mostly on a high level. Accordingly, the customers were generally satisfied with the product innovations. Nevertheless, the overall result was below average compared to the results of the other clusters.

Similarly, process efficiency of the projects in cluster 2 was below average. The speed of innovation realization was rather low and the available resources were not utilized efficiently. Moreover, the initially set time schedule could not be realized, and also, the calculated budget was exceeded.

7.3.3 Cluster 3: Highly Productive Innovation System

The contextual circumstances were very beneficial for the implementation of the innovation process within the projects of cluster 3. The particular organizations were aligned to steadily generate innovations which were directly absorbed by the markets. Hence, cluster 3 was named *highly productive innovation system*.

7.3.3.1 Cluster Description

The third cluster contains 40 cases which make up an overall share of 27%. The projects were mainly realized in companies of the automotive industry, followed by companies in the mechanical engineering industry, and lastly companies from smaller industry segments. The revenue shares of products younger than five years exhibited an average level. Regarding company size, large enterprises made up the vast majority. The dominating corporate form was the stock company followed by the capital company.

The projects were primarily based on technology-push innovations and mainly represented new-to-the-market innovations. With respect to project organization, the matrix organization prevailed and approximately half of the projects were standardized according to the stage gate process.

7.3.3.2 Innovation Context

The organizational background was mainly beneficial for the realization of the innovation projects of cluster 3. The strategic direction and the organizational structure of the respective companies allowed a flexible and expedient project handling. The innovating organizations were characterized by a positive innovation culture and a high level of risk tolerance, as well as good internal communication. The management supported the projects and provided all required resources. No problems emerged when searching an adequate organizational home for the product innovations. Finally, the decision making processes were on an average lean level.

A great contribution to the subsequent success of the respective innovation projects of cluster 3 was the entrepreneurial team. The involved people were quite experienced at the realization of such innovation projects and had a high level of professional competence. Furthermore, the teams were multidisciplinary and had a great personal network. Moreover, the team members exhibited good social competences, worked together as a team, and were highly motivated to bring the innovation projects to success.

The technologies which underlay the innovations of cluster 3 fostered the project realization on an average level. This might be due to the high level of newness. The technologies had not been implemented in previous products but demonstrated good potential for further applications. Furthermore, the technologies were characterized by a great capability, relatively high cost advantages, and a good level of reliability and safety. However, the technical development was elaborate, associated with distinct difficulties, and high investments.

Finally, the target markets were quite advantageous for innovation implementation. Thus, the respective market size and the forthcoming market growth were beneficial for the corresponding innovations. Even in retrospect, the respondents assessed the market selection and the timing of market introduction to be good. The competitive situation and the external influences were on an average level while the market barriers were quite low.

7.3.3.3 Innovation Process

Relatively high priority was put on the establishment of strategic partnerships in the innovation projects of cluster 3. Correspondingly, suppliers and customers were perceived as strategic partners within the majority of the analyzed projects. Furthermore, in one third of all cases end users of the product innovations, distribution partners, or research institutes were strategically involved. Similar to the clusters 1 and 2, the open innovation approach was not of intense focus. Although there was little integration of lead users in idea generation, they were involved in the generation of requirements, during product development, and while subsequently testing the product innovations. Additionally, a regular gathering of customer feedback and consequent integration in the innovation process was stressed. This customer feedback was mainly generated through interviews at the project start, the presentation of the product concept and the prototype, as well as the practical testing of the prototype and the end product.

A lot of weight was attached to a solid quality and risk management. Furthermore, an intensive intellectual property strategy was followed. Particularly, the underlying technologies, the core products, and occasionally, complementing components were protected. The implementation of a platform strategy was also fostered.

Even though the innovation companies introduced their innovations primary as innovators, they stressed a deliberate timing strategy of market launch, and also focused on a deliberate promotion strategy. The companies of cluster 3 positioned their product innovations deliberately and distinguished themselves from their competitors by following the differentiation strategy.

7.3.3.4 Innovation Success

The innovation projects of cluster 3 were very successful. Correspondingly, the average satisfaction of the survey participants was very high. More than half of the respondents were satisfied, and several respondents were even very satisfied with the results of their innovation projects.

With respect to sales performance, the projects of cluster 3 indicated the highest overall value of all clusters. Both revenue and market share predominantly met the expectations. Approximately half of the projects had a market share of up to 5% at the moment of maximal market penetration. Four projects exhibited a market share of 6 to 10%, four of 11-30%, three of 31-50%, and two even more than 50%.

The product quality of the considered innovations was at a very high level. Moreover, the product performance met the initial requirements, and hence, the customers were mainly satisfied. Compared to the other clusters, the overall product performance of the innovation projects of cluster 3 achieved a level above average.

Regarding process efficiency, the projects of cluster 3 were very successful. The speed of innovation realization was relatively high and also the available resources were utilized quite efficiently. Regarding the initially set time schedule and calculated budget, there was no identifiable tendency among the analyzed projects.

7.3.4 Cluster 4: Mediocre Implementation Circumstances

The innovation context of the projects in cluster 4 had only a slight positive impact on the innovation process. While the organizational circumstances neither influenced the innovation realization positively nor negatively, the underlying technology and the addressed target market challenged the implementation of the innovation project. Correspondingly, the cluster was named me*diocre implementation circumstances*.

7.3.4.1 Cluster Description

20 cases were allocated to the fourth cluster which represents 14% of all cases in the sample. Once again, the projects were mainly conducted in enterprises with more than 10,000 employees. Corre-

spondingly, the corporate form of stock companies was clearly dominating compared to capital companies. The main industry in which the considered innovations were realized was the automotive industry followed by the mechanical engineering industry. Interestingly, these companies were, in general, quite innovative, as their revenue share of products younger than five years was high if compared to the other clusters.

The projects were rather based on technology-push than market-pull innovations but had the lowest level of newness within the whole sample. Mainly new-to-the-market and new-to-the-firm innovations were realized. The matrix organization was the major organizational form, followed by the autonomous project organization. Additionally, the projects of cluster 4 were characterized by a high level of standardization. Hence, a lot of projects were organized according to a stage gate process.

7.3.4.2 Innovation Context

The organizational circumstances for the projects in cluster 4 had an averagely positive influence on the innovation implementation. While the organizational structure and the strategic direction fostered a flexible project realization, the resource allocation and the management support ranged on a mediocre level. Additionally, the innovation culture, the risk acceptance, the decision making process, and the internal communication were also on average positive. However, in the search for an organizational home, problems occasionally occurred.

The entrepreneurial team had a quite positive impact on the innovation realization. While the team members had a distinct level of experience in the implementation of such projects, they interestingly had just mediocre professional competences. They overcompensated this by their great personal network and the multidisciplinarity within the team. Furthermore, the team members were characterized by a high level of social competence, very good teamwork, and a great attitude.

In contrast to the entrepreneurial team, the technologies which underlay the innovation projects of cluster 4 were mainly hampering the innovation implementation. The technologies exhibited just an average level of performance capability and low cost advantages compared to alternatives. Moreover, the future application potential of the technologies was quite low and their safety and reliability were below average. Although the technologies were implemented in previous products, the technological development was elaborate and associated with high costs.

The target markets were also unfavorable. In general, the market size was interesting but compared to other clusters, slightly below average. Moreover, the prospects of forthcoming market growth were relatively low. Additionally, the competitive situation was on an average level, the market barriers were quite high, and external forces, like political or macroeconomic impacts, negatively influenced the innovation implementation. Nevertheless, the survey participants mainly evaluated the moment for market launch in retrospective as right.

7.3.4.3 Innovation Process

Within the projects of cluster 4, no particular weight was attached to strategic partnerships. Occasionally, suppliers, and rarely, customers and research institutes, were recognized as strategic partners. Accordingly, open innovation was not stressed. The innovating companies of cluster 4 developed primarily autonomously. Thus, little emphasis was put on the integration of customer feedback or lead user. Occasionally, lead users were involved in product testing. Customer feedback was mainly obtained through the presentation of prototypes, sometimes through interviews at the project start or when the prototypes or respectively the end products were tested.

Much attention was attached to a solid quality and risk management, and additionally, the implementation of a platform strategy. Moreover, generated intellectual property was intensively protected. The companies especially filed for intellectual property rights with respect to the underlying technologies and occasionally the core products and complementary components.

In two thirds of all cases, the innovating companies implemented the product innovations as pioneers and in one third as early followers on the market. The companies set up a deliberate timing strategy for market launch. Furthermore, they stressed purposeful positioning strategies as well as corresponding promotion measures. To stand apart from their competitors, the companies primarily followed the differentiation strategy.

7.3.4.4 Innovation Success

The innovation projects of cluster 4 were mostly successful and hence, the average project satisfaction of the survey participants was relatively high. 13 respondents were satisfied and four even very satisfied. One participant was undecided and one was unsatisfied with the project results.

With respect to sales performance, the projects were successful. The expectations regarding revenue and market share were primarily achieved. The market share at the moment of maximal market penetration achieved the highest value compared to the other clusters. Half of the projects obtained a market share of up to 5% while a great part of the projects even obtained a market share of 30 to 50%.

The product success was above average. Both product quality and product performance were on a relatively high level. Thus, the customers were mainly satisfied.

Regarding process efficiency of the analyzed projects, a slightly above average level could be realized. The speed of innovation realization was high while the available resources were efficiently utilized. The time schedule and the calculated budget could not be retained.

7.3.5 Cluster 5: Fruitless Innovation Wasteland

The general context of the projects in cluster 5 influenced innovation implementation very negatively. Accordingly, the team, the organization, as well as the technology impinged on the innovation success in a negative way. For this reason, cluster 5 was named *fruitless innovation wasteland*.

7.3.5.1 Cluster Description

Cluster 5 includes 30 innovation projects corresponding to 20% of the total sample. Half of them were implemented in mechanical engineering companies. The remaining projects were realized either in the automotive industry, in companies producing electronic equipment, or in companies focusing on further vehicle construction. To a great extent, the innovation projects were implemented in larger concerns, although also in companies of medium size. Concerning the corporate form, the stock company prevailed followed by the capital company and the company constituted under public law. The companies of this cluster had the lowest overall innovation rate which corresponds to a revenue share of less than 5% regarding products younger than five years.

Once again, the projects were mostly based on technology-push innovations and mainly resulted in new-to-the-market innovations. The process standardization was quite below average, as nearly half of the projects neither was standardized nor were arranged according to a common procedure. Concerning project organization, the matrix organization highly dominated and was followed by the autonomous project organization.

7.3.5.2 Innovation Context

The organizational circumstances for the projects of cluster 5 extremely hampered innovation realization. Correspondingly, the strategic direction, as well as the rigid organizational structure, obstructed project implementation. Moreover, the innovating companies were characterized by a very low innovation culture, little risk acceptance, and a low level of internal communication. The management refused essential resource allocations and similarly their overall project commitment. Accordingly, the processes of decision making were not lean and the search for an organizational home within the organization was accompanied by huge difficulties.

Similar to the organizational circumstances, the entrepreneurial team composition of the projects in cluster 5 was detrimental to a successful project realization. The involved people had little experience in the implementation of such projects and relatively low professional competences. Moreover, the teams were not multidisciplinary and had quite limited access to a strong personal network. Therefore, it was not surprising that the motivation and the teamwork among the members were quite weak. At the same time, the survey participants assigned their team members a low level of social competence.

Compared to the other clusters, the technologies of cluster 5 displayed the lowest overall values. The technologies were neither beneficial in terms of performance capability, nor in terms of cost advantages towards existing alternatives. Moreover, these technologies were not reliable and safe, had only been applied in previous products in a few cases, and did not display good potential for further utilization. Nevertheless, their technological development was time-consuming and expensive.

The target markets of cluster 5 projects neither showed clear advantages nor clear disadvantages. On the one hand, the market sizes and the prospects of forthcoming market growth were relatively poor, but on the other hand, the market barriers were relatively low. With few exceptions, no external factors influenced the markets negatively and just a few competitors were active. In retrospective, the survey participants evaluated the market selection as appropriate, whereas the timing of the market launch was evaluated as unfavorable.

7.3.5.3 Innovation Process

Within the projects of cluster 5, a little weight was attached to the establishment of strategic partnerships. Primarily, suppliers, customers, and sometimes research institutes were perceived as strategic partners, but mainly in an operative and not strategic mode. Similarly, the concept of open innovation and the integration of lead users were not stressed during innovation implementation. Even customer feedback was rarely implied. In just approximately half of all projects, customer feedback was obtained by presentation and field test of prototypes. Interviews at the project start, presentation of the product concept, and field test of the final product were just performed in approximately one third of all projects.

Little emphasis was put on the implementation of structured quality and risk-management and the realization of a platform strategy. Concerning the protection of intellectual property, the innovating companies in cluster 5 were also not very active. In approximately one third of all cases, they protected the underlying technologies, the core products, and complementary components.

The timing of market introduction was not made consciously and was additionally not supported by deliberate promotion measures. Primarily, the innovating companies appeared as pioneers and tried to disassociate themselves from their competitors by following the differentiation strategy. However, they did not stress a conscious positioning of the product innovations in the markets.

7.3.5.4 Innovation Success

The projects in cluster 5 displayed the lowest level of innovation success. Accordingly, the survey participants indicated the least level of satisfaction with respect to their project results. Nevertheless, it was surprising that even half of the respondents of cluster 5 were satisfied.

In comparison with the other clusters, the projects of cluster 5 achieved the lowest level of commercial success. Predominantly, the revenue and the market share did not meet the expectations. At the same time, the market share at the time of maximal market penetration displayed the lowest level of all clusters. Thus, the market share of the outweighing majority accounted for less than 5% and just a few projects achieved a percentage between 5 and 10.

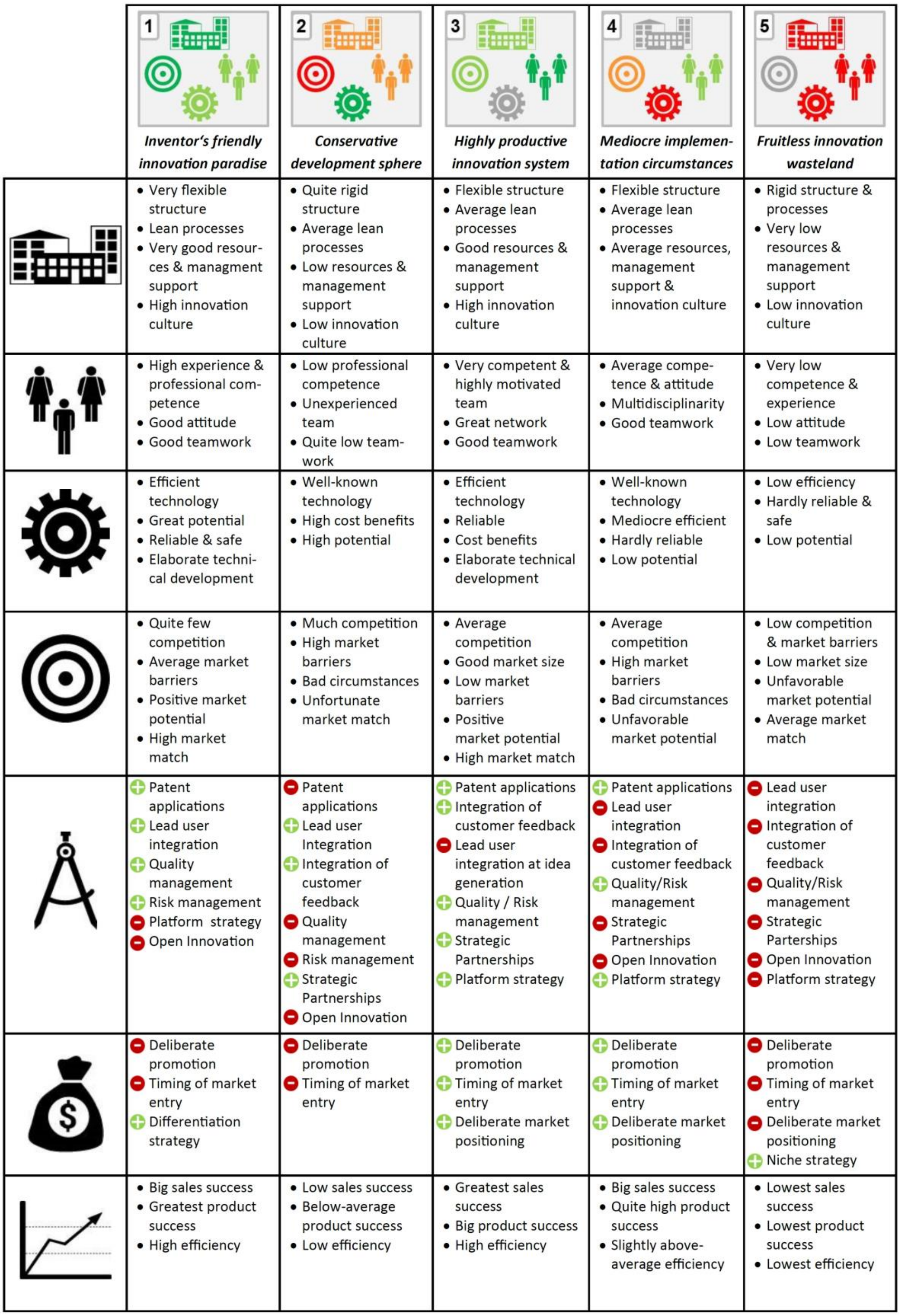
Overall, the product quality reached a high level and product performance mostly met the expectations. Nevertheless, it did not totally satisfy the customers. Accordingly, the product success of the innovation projects in cluster 5 displayed the lowest figure compared to the other clusters.

Regarding process implementation, the projects were sparsely efficient. The innovation realization progressed slowly and the available resources were deployed rarely efficiently. Moreover, the initial time schedule was not met and also the initially calculated budget was exceeded.

7.4 Summary and Cluster Overview

The conducted cluster analysis highlighted five clearly distinguishable clusters. These clusters were derived from the characteristics of the variables associated with the innovation context. As it was the goal to maximize homogeneity of objects within the clusters while maximizing heterogeneity between the clusters, the five detected clusters exhibited comparable preconditions for the subsequent innovation process (Hair, 2010, p. 505). The conducted Welch and ANOVA tests confirmed that the clusters could furthermore be distinguished with respect to the way the companies were realizing the innovation process. Additionally, the Cramer's V test indicated significant associations between each of the eleven process instruments and the cluster assignment. A comparison with the performer classification based on the three innovation success dimensions highlights the quality of the cluster solution. The way companies were realizing the innovation process could be better distinguished, when looking at the contextual circumstances than looking at the subsequent innovation success. Thus, the second central research question could be answered. The five clusters were clearly distinguishable based on the contextual circumstances and correspondingly could be perceived as innovation archetypes. The way the innovation processes were arranged within each cluster, could serve as orientation guideline for forthcoming innovation projects.

According to their characteristics, the clusters were named as archetypical project contexts. An overview of the main characteristics of the five clusters is presented in Figure 42. At the presentation of the innovation process instruments, the plus indicates that the companies within this cluster put above average weight on the implementation of the respective process instrument. A minus indicates below average emphasis for the particular process instrument.



	1 *Inventor's friendly innovation paradise*	2 *Conservative development sphere*	3 *Highly productive innovation system*	4 *Mediocre implementation circumstances*	5 *Fruitless innovation wasteland*
	• Very flexible structure • Lean processes • Very good resources & managment support • High innovation culture	• Quite rigid structure • Average lean processes • Low resources & management support • Low innovation culture	• Flexible structure • Average lean processes • Good resources & management support • High innovation culture	• Flexible structure • Average lean processes • Average resources, management support & innovation culture	• Rigid structure & processes • Very low resources & management support • Low innovation culture
	• High experience & professional competence • Good attitude • Good teamwork	• Low professional competence • Unexperienced team • Quite low teamwork	• Very competent & highly motivated team • Great network • Good teamwork	• Average competence & attitude • Multidisciplinarity • Good teamwork	• Very low competence & experience • Low attitude • Low teamwork
	• Efficient technology • Great potential • Reliable & safe • Elaborate technical development	• Well-known technology • High cost benefits • High potential	• Efficient technology • Reliable • Cost benefits • Elaborate technical development	• Well-known technology • Mediocre efficient • Hardly reliable • Low potential	• Low efficiency • Hardly reliable & safe • Low potential
	• Quite few competition • Average market barriers • Positive market potential • High market match	• Much competition • High market barriers • Bad circumstances • Unfortunate market match	• Average competition • Good market size • Low market barriers • Positive market potential • High market match	• Average competition • High market barriers • Bad circumstances • Unfavorable market potential	• Low competition & market barriers • Low market size • Unfavorable market potential • Average market match
	(+) Patent applications (+) Lead user integration (+) Quality management (+) Risk management (−) Platform strategy (−) Open Innovation	(−) Patent applications (+) Lead user Integration (+) Integration of customer feedback (−) Quality management (−) Risk management (+) Strategic Partnerships (−) Open Innovation	(+) Patent applications (+) Integration of customer feedback (−) Lead user integration at idea generation (+) Quality / Risk management (+) Strategic Partnerships (+) Platform strategy	(+) Patent applications (−) Lead user integration (−) Integration of customer feedback (+) Quality/Risk management (−) Strategic Partnerships (−) Open Innovation (+) Platform strategy	(−) Lead user integration (−) Integration of customer feedback (−) Quality/Risk management (−) Strategic Parterships (−) Open Innovation (−) Platform strategy
	(−) Deliberate promotion (−) Timing of market entry (+) Differentiation strategy	(−) Deliberate promotion (−) Timing of market entry	(+) Deliberate promotion (+) Timing of market entry (+) Deliberate market positioning	(+) Deliberate promotion (+) Timing of market entry (+) Deliberate market positioning	(−) Deliberate promotion (−) Timing of market entry (−) Deliberate market positioning (+) Niche strategy
	• Big sales success • Greatest product success • High efficiency	• Low sales success • Below-average product success • Low efficiency	• Greatest sales success • Big product success • High efficiency	• Big sales success • Quite high product success • Slightly above-average efficiency	• Lowest sales success • Lowest product success • Lowest efficiency

Figure 42: Cluster Overview

(+) Above average (−) Below average

7.5 Discussion and Limitations

The conducted cluster analysis did not at all address the question of whether there was an underlying cluster structure within the data. Therefore, it could not be neglected that the obtained cluster solution did not reflect the underlying cluster structure correctly or was even totally artificial. However, cluster analysis is an explorative approach of multivariate data analysis which is based on the raw data. The clusters were not known before and the identification of object groups within the sample was the result of this inductive data analysis technique (Backhaus *et al.*, 2016, p. 455; Schendera, 2008, p. 94).

Moreover, the hierarchical cluster analysis using Ward's method was applied in this research study. As the clustering of this method is based on the minimal increase in error sum of squares, it was a good approach to obtain very homogeneous clusters. Nevertheless, it tends to cluster solutions with approximately the same amount of cases in each cluster. Thus, it faces problems to detect small or stretched clusters and is furthermore vulnerable to outliers. Before statistical analysis, the data were scanned for potential outliers (cf. chapter 6.3.3). There were just a few slight outliers found in the data. Accordingly, this should not effect cluster analysis (Backhaus *et al.*, 2000, pp. 359–360, 2016, p. 484; Schendera, 2008, p. 24).

The applied clustering method started with each case in an individual cluster and agglomerated step-by-step these objects ending up with a single cluster. Hence, the appropriate cluster solution had to be determined (cf. chapter 7.1.1). This decision caused a trade-off between the cluster homogeneity on the one hand and the manageability of the cluster solution on the other hand. To resolve this conflict, content-related and research pragmatic arguments were considered. Nevertheless, this just addressed the number of clusters and did not affect the allocation of cases to particular clusters. Furthermore, the potential cluster solutions were verified with respect to interpretability, stability, and validity. Thus, Cramer's V and ANOVA tests were conducted and validated the appropriateness of the five cluster solution (Backhaus *et al.*, 2016, pp. 494–495; Schendera, 2008, p. 94).

In general, Cramer's V is suitable for nominal scales. As the process instruments were measured on a Likert scale, this association measure led to distinct information loss on behalf of these variables. However, the cluster assignment variable was nominal scaled and thus, no other appropriate association measure was available. Furthermore, the absolute values of Cramer's V were just of relative importance. Correspondingly, the particular coefficients of the process instruments were only considered relative to each other. For the comparison with the top performer classification, only the significance level of the associations was in the focus (Brosius, 2013, pp. 432–434).

Although the ANOVA and Welch tests indicated that the five clusters could be significantly distinguished, these tests did not pinpoint where the significant differences lay among the clusters. In principle, several a posterori tests were available for further investigating the cluster differences. However, these tests were not applied, as this issue was not of primary interest in this research study. The primary goal was to detect context-specific strategies for the innovation process and not to statistically distinguish these strategies from other contexts. Thus, the descriptive analysis of the different clusters was focused in the conducted study (Hair, 2010, p. 472).

The cluster analysis was based on the data of the quantitative survey. Hence, any limitations which are due to the study design of the survey, data collection, and data preparation are also relevant for the results of the cluster analysis. These limitations are profoundly outlined in chapter 6.4.5 and correspondingly not repeated in this chapter.

8 Operational Framework

As previously outlined (cf. 5.2.2), in the first stage of the innovation process it is decisive to identify if the innovation context represents an entrepreneurial opportunity. The innovation manager has to assess the circumstances of the innovation context and base the product development and commercialization strategy on this assessment. To support innovation managers of forthcoming projects, an operational framework was designed for the early stages of innovation projects, which target the realization of radical technological innovations within the mechanical engineering industry. Therewith, the third central research question was addressed and the second artifact generated.

The operational framework contains two fundamental parts. At first, the cluster has to be detected which most closely resembles the contextual circumstances of the specific innovation project. Therefore, the statistical method of discriminant analysis is utilized. The second part includes concrete recommendations for action, which are based on the cluster assignment of the new project and address the three stages of the innovation process *opportunity identification, product development,* and *commercialization*.

8.1 Assignment of New Projects to Clusters

8.1.1 Discriminant Analysis

The goal of the discriminant analysis is to explain the values of a dependent variable by the values of several independent variables. Therefore, cases that exhibit the characteristics of both types of variables have to be analyzed for statistical relationships. These relationships need to be expressed algebraically. This can subsequently be utilized to estimate the dependent variable for cases of which just the characteristics of the independent variables are known. For discriminant analysis, the dependent variable has to be nominal-scaled and the independent variables need to be parametric. Furthermore, this method measures the prediction accuracy of the generated prognosis model (Brosius, 2013, p. 649; Hair, 2010, p. 339; Schendera, 2008, pp. 299–300).

As the contextual circumstances for new innovation projects could be evaluated quite early within the innovation process, the independent variables are known, while the cluster classification (dependent variable) is unknown. Thus, discriminant analysis is the appropriate statistical technique to predict the cluster assignment of new projects. In general, discriminant analysis iteratively follows six steps: group definition, formulation of discriminant function, estimation of discriminant functions, assessment of independent variables, assessment of discriminant functions, and classification of new elements (Backhaus *et al.*, 2016, p. 219).

Due to the previously conducted cluster analysis, group definition was based on the cluster solution. In this context, the available data had to be taken into account. There were several recommendations regarding the appropriateness of data for discriminant analysis. The case numbers within the individual groups must not be too small. As a practical guideline, Hair suggests requesting at least 20 cases in each group. Furthermore, wide variations in the groups' size will impact the estimation of the discriminant function and the classification of observation. Additionally, the number of groups should not exceed the number of independent variables. For the minimum overall sample size, it is proposed to have five observations per independent variable (Backhaus *et al.*, 2016, p. 220; Hair, 2010, p. 353). With initially 23 independent variables, 147 cases as an overall sample size, 20 cases in cluster 4 as the smallest cluster, and 40 cases in cluster 3 as the largest cluster, these guidelines were fulfilled.

As a next step, the discriminant function had to be formulated as a linear combination of the independent variables. This was based on the selection of characteristic variables which would presumably help distinguish the respective groups. Similar to the conducted cluster analysis, the variables associated with the innovation context were selected for the discriminant analysis which exhibited significant positive correlations to at least one of the dependent success variables within the previously conducted correlation analyses. The actual discriminatory ability of these independent variables was assessed later on (Backhaus *et al.*, 2016, pp. 220–221; Hair, 2010, p. 353).

The estimation of the discriminant function was based on the discriminant criterion. This criterion measures group differences by calculating the ratio of distribution between the groups and distribution within the groups. Correspondingly, the estimation of the discriminant function was carried out in such a way that the discriminant criterion reached its maximum. If there are more than two groups, further discriminant functions can be established. Accordingly, four discriminant functions were estimated within the conducted study (Backhaus *et al.*, 2016, pp. 223–224; Hair, 2010, pp. 356–360).

At the assessment of independent variables regarding their discriminatory importance, two variables were deleted from the discriminant function. Wilk's lambda was utilized and a subsequent F-test indicated the significance of the respective variables (cf. Table 39, Appendix VI - 1). As the variables TEC_1 and TEC_5 did not significantly differ across the clusters, they were of little use for the discriminant analysis and hence, left out (Backhaus *et al.*, 2016, p. 243; Hair, 2010, p. 353).

For assessing the quality of the potential discriminant functions, the most utilized criterion is Wilk's lambda. It is calculated by dividing the non-defined distribution by the overall distribution and can be transformed into a probabilistic variable which is based on the chi-squared-value. Thus, a statistical significance test of the discriminant function is possible. Wilks' Lambda indicated for the first three discriminant functions highly significant values (cf. Table 41; Appendix VI – 1). Furthermore, the individual importance of the functions expressed by the respective eigenvalues generally declined quite steeply (cf. Table 40; Appendix VI – 1). Thus, just the first three discriminant functions were utilized. An overview of the discriminant functions coefficients is depicted in Table 43 (cf. Appendix VI – 1). A second way to assess the quality of the discriminant functions is to compare the ultimate classification based on the discriminant analysis with the actual cluster assignment. Table 45 gives an overview of the classification results. In sum, 76.9% of all cases were correctly classified which represents a solid accuracy (Backhaus *et al.*, 2016, pp. 236–241).

The probability concept was selected for the classification of new cases, as it offers the most flexibility of all potential techniques. Accordingly, the classification probabilities of new cases with respect to the five clusters could be calculated on the basis of the existing distances and a-priori-probabilities by utilizing the Bayes-theorem. The highly significant Box's M test indicated that the null hypothesis of equal distributions of the covariance matrices could not be retained (cf. Table 46; Appendix VI – 1). Thus, the unequal distributions of the covariance matrices had to be considered at classification (Backhaus *et al.*, 2016, pp. 249–253).

8.1.2 Instructions

For the classification of new projects, in which radical technological innovations are realized, four concrete steps have to be followed: assessment of the independent contextual variables, recoding of several variables, entering the data in SPSS, and execution of classification.

The questions of the survey instrument were originally designed for retrospective answering. However, in contrast to the conducted survey, the projects to be assessed within the operational framework are in an early phase of innovation realization. Therefore, the wording of the questions was adapted. The respondents are asked to relate their answers to the concrete project, in which they participate. The queried variables are posed as statements and the respondents should honestly indicate their consent on a five-point Likert scale. In Appendix VI – 2, the 21 questions addressing the independent contextual variables with corresponding answer options are listed.

As the variables TM_5, ORG_6, ORG_8, ET_4, and ET_7 are negatively-keyed, these items have to be recoded. Afterward, the complete data of the 21 variables need to be entered in SPSS. For this purpose, the original dataset containing the collected data of the quantitative survey has to be utilized. The 21 variables have to be inserted in a new data row in the data view window of SPSS. For classification, the discriminant analysis has to be conducted according to the syntax depicted in Figure 87 (cf. Appendix VI – 1). This syntax has to be inserted in the syntax editor of SPSS and executed. Finally, the ultimate cluster assignment with corresponding classification probability can be deduced from the output file of SPSS.

8.2 Cluster Specific Recommendations for Action

On the basis of the five detected clusters, concrete recommendations for action were derived with respect to the three stages of the innovation process: *opportunity identification*, *product development*, and *commercialization*. Depending on the classification of the new projects, the corresponding cluster specific recommendations should be considered when realizing these innovation projects. Figure 43 gives an overview of the cluster-specific recommendations for action.

The formulation of recommendations for the challenge of *opportunity identification* was based on the descriptive analyses of the contextual circumstances and the subsequent innovation success of each cluster. With respect to the realization of *product development* and *commercialization*, the correlation analyses regarding the innovation process in the overall sample (cf. Figure 39), as well as the descriptive analyses of the innovation process within each cluster were fundamental.

	1 Inventor`s friendly innovation paradise	2 Conservative development sphere	3 Highly productive innovation system	4 Mediocre implementation circumstances	5 Fruitless innovation wasteland
	The circumstances are very positive and represent a good opportunity → The innovation project could be started without any doubts	Bad circumstances for innovation project → A) Reject idea → B) Establish an independent organizational unit with a high level of freedom and an adequate new team	The circumstances are very positive and represent a good opportunity → The innovation project could be started without any doubts	Average/mediocre circumstances → for success probability maximization: search for alternative application areas & markets; foster technological development	Bad circumstances for innovation project → A) Reject idea → B) Establish an independent organizational unit with a high level of freedom and an adequate new team
	• Solid patent strategy • Solid quality & risk management • Focus on lead user integration • Integrate customer feedback	If option B: Derive strategy based on resulting circumstances → probably strategy approach like cluster 1	• Intense patent strategy • Solid quality & risk management • Integrate customer feedback & lead user • Strat. partnerships • Platform strategy	• Solid patent strategy • Solid quality & risk management • Integrate either lead user or customer feedback • Platform strategy	If option B: Derive strategy based on resulting circumstances → probably strategy approach like cluster 1
	• Deliberate market positioning • Differentiation strategy	Derive strategy based on resulting circumstances → cf. strategy for product development	• Deliberate market positioning • Purposeful promotion • Deliberate timing of market entry • Differentiation strategy	• Deliberate market positioning • Purposeful promotion • Deliberate timing of market entry • Differentiation strategy	Derive strategy based on resulting circumstances → cf. strategy for product development

Figure 43: Overview of the Cluster Specific Recommendations for Action

8.2.1 Recommendations for Cluster 1

8.2.1.1 Opportunity Identification

The contextual circumstances for the innovation projects allocated to the first cluster were in general, very positive. Accordingly, the critical success factors of the organizational context, the entrepreneurial team, the technology that underlies the innovation, and the target market were fostering the innovation realization. Moreover, these projects were very successful, as they achieved a high level of sales performance, the highest value of product performance compared to the other clusters, and high process efficiency. If the contextual circumstances of new innovation projects most closely resemble the innovation contexts of the projects allocated to cluster 1, these projects could be started doubtlessly as they represent a great business opportunity.

8.2.1.2 Product Development

The product development of these new projects should be realized quite autonomously within the company borders. Thus, strategic partnerships should only, if ever, be established with customers, suppliers, and/or research institutes. However, to not miss the market needs, lead users should be integrated especially at requirements analysis, product development, product test, and subsequent market introduction. In this context, it is furthermore decisive, to continuously gather and consequently integrate customer feedback in the innovation realization. In particular, the presentation of the product concept, as well as the presentation and subsequent testing of the prototype at the customer represent crucial occasions for feedback generation.

Additionally, great emphasis should be put on a solid quality and risk management as both measures are important for the subsequent sales and product performance. Moreover, the protection of intellectual property should be stressed. As far as possible the underlying technology, the core product, and complementary components should be protected.

8.2.1.3 Commercialization

For commercialization, the innovating companies should implement the respective innovations as pioneers in the market. The innovations should be deliberately positioned, in particular as a premium solution. To stand out from its competitors, the companies should follow the differentiation strategy instead of cost leadership or excessive niche strategy. To additionally increase sales performance, deliberate communication measures and a conscious timing strategy of market introduction is considered helpful. The latter two marketing measures are not obligatory for this kind of project, however, they exhibit a reinforcing effect.

8.2.2 Recommendations for Cluster 2

8.2.2.1 Opportunity Identification

The circumstances for a successful project realization were generally quite negative for the projects allocated to cluster 2. Similar to the organizational context, the entrepreneurial team and the target market were obstructive to project success. Although the technology had a positive effect on innovation realization, the hampering factors clearly dominated. This becomes especially obvious when looking at the poor innovation success. The sales performance, the product performance, and the process efficiency were on a low level.

Correspondingly, a natural recommendation for forthcoming projects which have a similar innovation context like the projects of cluster 2 is to reject the project ideas as fast as possible and focus on more promising initiatives. If the projects should be initiated despite the poor preconditions, it would be recommended to fundamentally change the circumstances for not starting a futile undertaking. One possibility would be to establish an independent and autonomous organizational unit. Within this unit, a specifically selected team which has been released from its operational duties should take over the full responsibility of the project. This team should be equipped with the essential resources and a great amount of freedom to autonomously realize the technological development and subsequent commercialization of the respective innovations. In this setting, the team must be free to identify the market which matches best to the advantages of the underlying technology.

8.2.2.2 Product Development and Commercialization

If these projects will not be stopped, and correspondingly an independent organizational unit for innovation realization will be formed, the strategy for product development has to be aligned with the newly generated circumstances. If this will be implemented as recommended in the previous chapter 8.2.2.1, the resulting innovation context probably resembles the ones of cluster 1 projects. Accordingly, the product development has to be aligned to the strategy recommendations for these projects. The same applies to the commercialization strategy of the respective innovations.

8.2.3 Recommendations for Cluster 3

8.2.3.1 Opportunity Identification

Similar to cluster 1, the contextual circumstances of the projects allocated to cluster 3 were very beneficial for innovation realization. Especially, the entrepreneurial team exhibited a particularly positive influence. Moreover, the organizational background and the target market were also fostering innovation success, while the technology which underlies the respective innovations was at least on an average level. With respect to the ultimate innovation success, the projects of cluster

3 achieved the highest level of sales performance compared to the other clusters as well as a high level of product performance and process efficiency. If a new project is classified to cluster 3, this corresponds to a great entrepreneurial opportunity. Thus, the project should be started.

8.2.3.2 Product Development

As a recommendation for product development, strategic partnerships should be established in any case with customers and suppliers. Depending on the situation, further partners like end users, sales partners, or research institutes should additionally be involved. Moreover, lead users should be integrated into requirements analysis, product development, and product testing. Furthermore, it is recommended to continuously generate and integrate customer feedback in product development. This feedback should be obtained by interviewing customers at the project start, presenting the product concept and the prototype to the customer, and by testing the prototype and the end product.

Additionally, the realization of a profound quality and risk management is decisive for sales and product performance. An intensive protection strategy for intellectual property rights is of vital importance. In particular, the underlying technology, the core product, and if possible, complementary components should be protected.

8.2.3.3 Commercialization

Regarding the commercialization strategy, the respective innovations should be deliberately positioned at the market ideally as a premium solution. The innovating company should distinguish itself from its competitors by following the differentiation strategy. Furthermore, significant weight should be attached to a deliberate timing strategy of market introduction and supporting communication measures.

8.2.4 Recommendations for Cluster 4

8.2.4.1 Opportunity Identification

The preconditions for successful innovation realization, for the projects allocated to cluster 4, were on a mediocre level. While the organizational circumstances were on an average level and the entrepreneurial team exhibited a positive influence on innovation implementation, the technology and the target market were not favorable. Nevertheless, the innovation projects of cluster 4 achieved a high level of sales performance, a quite high product performance, and a slightly above average process efficiency.

If the contextual circumstances of a forthcoming project resemble the innovation context of the projects of cluster 4, the project could be started. For maximizing the prospects of success, it is recommended to search for alternative target markets. Additionally, the technological development should be focused to increase the capability and reliability of the respective technology.

8.2.4.2 Product Development

For new innovation projects allocated to cluster 4, the product development ought to be realized quite autonomously within the innovating company. Strategic partnerships, if any, should be established with suppliers and depending on the situation with customers and research institutes. Within the analyzed projects of cluster 4, little weight was attached to the integration of lead users and customer feedback. Due to the relatively autonomous product development approach, this particularly seems critical as no external market impulses were integrated. For not totally missing the market needs, it is recommended to forthcoming projects to urgently integrate either, lead users at requirements analysis and product development, or obtain customer feedback through interviews at the project start as well as the presentation of the product concept and the prototype.

Furthermore, much emphasis ought to be put on a solid quality and risk management approach. Intellectual property which is generated during the project is supposed to be protected, in particular, regarding the technology, and if possible, regarding the core product and complementary components. Additionally, the implementation of a platform strategy should be considered and addressed.

8.2.4.3 Commercialization

To distinguish itself from its competitors, the innovating company should follow the differentiation strategy and deliberately plan the timing of market introduction. Moreover, the innovations ought to be consciously positioned in the market and promoted by purposeful communication measures.

8.2.5 Recommendations for Cluster 5

8.2.5.1 Opportunity Identification

The contextual circumstances of the innovation projects in cluster 5 were very obstructive for their realization. The team, the organization, and also the technology hampered the project. Only the target market was characterized by an average positive influence on innovation realization. Correspondingly, the innovation success was quite low. Compared to the other clusters, the projects allocated to cluster 5 achieved the lowest level of sales and product performance, as well as the lowest process efficiency.

If the contextual circumstances of a forthcoming project are similar to the preconditions of the projects within cluster 5, there are two options for action. The natural suggestion is to stop the project and reject the idea. The second, much more complex option requires fundamentally changing the present circumstances to generally enable a successful project implementation. Based on the current innovation context, the project would be doomed to fail in advance. As it was with the projects that resemble the projects of cluster 2, an autonomous organizational unit has to be established. Within this unit, a newly formed team has to be equipped with the essential resources and a great amount of freedom. This team is supposed to take over responsibility for technological development, market identification, and market approach.

8.2.5.2 Product Development and Commercialization

The same that applies to projects that resemble the projects of cluster 2, applies for projects which resemble the projects of cluster 5. If these projects will not be stopped and an autonomous organizational unit for innovation realization will be established, the strategies for product development and commercialization have to be aligned with the newly generated circumstances. If the resulting innovation context resembles the ones of cluster 1 projects, the respective articulated recommendations for action regarding the product development and commercialization strategy should be implemented.

8.3 Validation of the Operational Framework

For validation, the operational framework was retrospectively applied for the three conducted primary case studies detailed in chapter 5.3. At first, the instructions to assign the projects to one of the five clusters outlined in chapter 8.1.2 were followed. Afterward, the respective cluster specific recommendations regarding the innovation process were compared with the actual implementation of the innovation process within the three cases. It was aimed to figure out differences and similarities to assess the accuracy, relevance, and usefulness of the operational framework. Although the case of cryogenic machining by 5ME (process innovation and not within the power transmission industry) originally was not within the scope of the conducted quantitative survey (cf. chapter 6.2.1), it seemed beneficial for the evaluation of the operational framework to include this case as well. Each of the three cases specifies a successful implementation of a radical technological innovation within the mechanical engineering industry. Therefore, the cases were well suited for the purpose of validating the operational framework.

8.3.1 Cluster Assignment of the Cases of Pinion, SKF, and 5ME

As detailed in chapter 8.1.2, there are four concrete steps that have to be followed for the classification of new projects. These steps were conducted by the author of this thesis for the cases of Pinion, SKF, and 5ME. Table 47 gives an overview of the answers to the 21 questions addressing the independent contextual variables for each case filled in by the author (cf. Appendix VI – 3). In the following subchapters, the cluster specific assessment of the contextual variables will be explained.

After the contextual assessment of the three cases, the variables TM_5, ORG_6, ORG_8, ET_4, and ET_7 were recoded, and subsequently, the complete data was entered in the original dataset of the quantitative survey in SPSS. Finally, a discriminant analysis was conducted for cluster assignment of the three cases.

8.3.1.1 Contextual Assessment of the P1.18 Bicycle Transmission by Pinion

With respect to the market introduction of the P1.18 bicycle transmission, the market-related barriers were not high. The biggest obstacle Pinion had to face was the low level of reliability connoted to a young start-up. In general, the market perfectly matched to the innovation, as the high end sector of the German bicycle market in total was very big and quite absorptive for such product innovations. Furthermore, the timing was right, as the industry context was shaped by beneficial trends addressing sustainability and environment.

The innovation culture within Pinion was very good and the whole company was focused on the development and commercialization of its product innovation. Accordingly, the climate within the start-up was characterized by a high level of risk tolerance and failure acceptance. As it was the original goal of the company to bring the P1.18 to success, the start up's strategy was aligned with this goal. Naturally, the two founders totally supported their employees and allocated the needed resources. Therefore, they rose funding from their investors. After a natural setback when the first investor left, the second investor finally provided the necessary budget. The structures and processes of Pinion were established to provide the best possible organizational surrounding for a flexible and lean innovation realization. Moreover, the internal communication was open and honest due to the low hierarchical levels.

The general concept of a maintenance free gearbox utilizing a spur gear had already been implemented in cars and motorbikes. Nevertheless, the overall surrounding for bicycles was totally different, and thus, the technology had to be fundamentally adapted. However, Pinion managed to achieve a high maturity level when entering the market. Accordingly, the technology was reliable and safe.

Despite the fact that the team was quite inexperienced, the essential competences were present. As the team primarily developed autonomously, the average level of personal network did not hamper innovation realization. The team was diverse and worked very well together. The involved people had a good social competence and really wanted to bring the P1.18 to market success (cf. chapter 5.3.2).

8.3.1.2 Contextual Assessment of the Friction Disc by SKF

The fundamental prerequisite for entering the wind energy market was the certification process. Besides this, SKF had no further market barriers to overcome, as the company and its customer

Senvion assured mutual exclusivity. The wind industry in general perfectly matched to the Friction Disc, as the market was shaped by massively increased power ranges and the challenge to keep the weights of the individual components controllable. Moreover, the timing of market introduction was right, because SKF's customer just started the development of its new wind turbine, and thus, both development processes could be aligned.

SKF's overall strategy was clearly addressing the wind market. Hence, the Friction Disc was absolutely in this focus. Accordingly, the management supported the team and allocated any and all resources needed for the realization of the respective innovation. Due to the quite low hierarchical level within the company, the internal communication was open and honest. On the other hand, the company was not very innovation oriented, and correspondingly, risk tolerance and failure acceptance were not very high. Understandably, the structures and processes of a big enterprise did not particularly foster innovation realization and lean decision making. However, the stage gate process provided a measure to canalize these processes.

Before SKF utilized the coating technology for the Friction Disc, the technology was just applied for very small surfaces and low power transmission tasks. Therefore, field tests had to prove its performance. These tests and the certified friction coefficient confirmed the safety and reliability of the Friction Disc.

For implementing the innovation project, the team was extremely beneficial. The involved people were quite experienced with the realization of such projects and had the right competences. Furthermore, the team was diverse and the members had a great personal network. Additionally, the involved people were socially competent, worked together as a team, and desperately wanted to bring the innovation to success (cf. chapter 5.3.3).

8.3.1.3 Contextual Assessment of Cryogenic Machining by 5ME

In the case of cryogenic machining, the market barriers contained a certification, as well as changing the classical machining approach and infrastructure of the customer. The high end sector of the American metalworking machinery seemed to represent very good matching, as the benefits of the technology were clearly obvious within this market. Furthermore, the timing of market introduction seemed right, because a lot of machinery spending and production ramp ups were expected.

5ME was spun out from the global machine tool builder MAG to develop and commercialize cryogenic machining. Accordingly, the strategic direction was aligned to this objective. Moreover, the structures and processes of the company were set up to provide a supportive organizational environment for a flexible and lean innovation realization. Nevertheless, the owner and investor of 5ME had to be involved in certain decisions. The team had access to any needed resources and the management totally supported project realization. In general, 5ME was characterized by a strong innovation focus, a high level of risk tolerance, and failure acceptance. The internal communication was open and honest among the team.

The technology of cryogenic machining had not been implemented in different industries or companies before. However, 5ME managed to achieve industrial maturity and proved its applicability through several field tests and certification approvals.

Regarding the entrepreneurial team, the involved people had exactly the right competences. Many team members were working previously for MAG, and correspondingly, knew the requirements of 5ME's customers and machining processes in general. Nevertheless, hardly any of them was involved in the realization of such a radical innovation. The involved people worked together as a team and were socially competent. Despite any obstacles, they wanted to implement cryogenic machining in the market and make it a success. The team was principally quite diverse and the team members furthermore had a great personal network (cf. chapter 5.3.4).

8.3.1.4 Cluster Classification

After the data was entered in the dataset of SPSS, the discriminant analysis was conducted. Table 48 gives an overview of the cluster assignment of the three cases (cf. Appendix VI – 3). With a probability of 72.5%, the case of the P1.18 bicycle transmission by Pinion was assigned to cluster 1. Similarly, the case of cryogenic machining by 5ME was allocated to cluster 1 with a probability of 72.7%. In contrast, the case of the Friction Disc by SKF was assigned to cluster 3 with a probability of 79.1%.

8.3.2 Comparison of the Cluster Specific Recommendations with the Actual Implementation of the Innovation Process

8.3.2.1 P1.18 Bicycle Transmission by Pinion

Similar to the projects of cluster 1, the contextual circumstances for Pinion were very positive. In accordance with the cluster specific recommendation to start the project, the two founders of Pinion trusted their personal gut feeling and realized their vision to develop a gearbox as competitive shifting solution for bicycles. With more than 1,000 gearboxes sold in 2014, a mature product with clear advantages, compared to its alternatives, and a highly efficient project realization, the subsequent innovation success also corresponds to the results of the projects allocated to cluster 1.

In line with the cluster specific recommendations, Pinion primarily developed autonomously. Customers and suppliers were involved relatively late. However, their involvement was realized strategically and deliberately. Accordingly, particular feedback was generated based on the presentation of their prototype at a trade fair and conscious product tests. As recommended for projects assigned to cluster 1, Pinion attached much weight to the integration of lead users. Nevertheless, the company did not follow a structured risk and quality management contrary to the cluster specific advice. However, they were aware of these issues and tried to address them as far as possible within the loose structures of a newly founded start-up. Furthermore, the protection of intellectual property was deliberately and strategically realized. Correspondingly, the product development strategy of Pinion complied with the cluster specific recommendations.

Like most of the companies in cluster 1, Pinion introduced their product innovation as a pioneer to the market. The P1.18 was positioned as a premium product for the high-end sector of the German mountain, trekking, and touring bike market. In the short-term, this corresponded to a niche market. However, Pinion was planning to cover the entire bicycle market little by little. Therefore, the company aimed to distinguish themselves from their customers by following a clear differentiation strategy. According to their timing strategy for market introduction, Pinion deliberately chose their first trade fair attendance. Additionally, the start-up consciously utilized particular promotion measures to support the market implementation of the P1.18. To sum up, Pinion's overall commercialization approach was in close conformity with the expressed recommendations for the projects classified to cluster 1.

8.3.2.2 Friction Disc by SKF

Generally, the innovation context for SKF was quite positive, like it was with the projects allocated to cluster 3. However, the organizational background within SKF exhibited positive and negative impacts on innovation realization which differed slightly to the average of the projects in cluster 3. Based on the personal gut feeling of SKF's key account manager for Senvion, SKF initiated the project. This was in line with the cluster specific recommendations. By 2014, a medium three-digit sales number was achieved, what makes the Friction Disc a very profitable business for SKF. Furthermore, product performance and process efficiency were on a very high level. As it was with the results of the projects in cluster 3, the overall innovation success of the Friction Disc was particularly high.

Within the Friction Disc project, SKF's customer was similarly the lead user of the product. Product development was realized in close cooperation between both companies from project start until market introduction. As recommended for projects allocated to cluster 3, customer and similarly lead user feedback was continuously integrated. Furthermore, the supplier, responsible for the coating process, and a technical university were strategically involved. Moreover, SKF followed a detailed risk and quality management. Due to the intense cooperation, SKF and its customer shared and protected the generated intellectual property. Accordingly, the product development approach of SKF corresponded to the recommendations for cluster 3 projects.

In accordance with the cluster specific advice, SKF consciously positioned the Friction Disc as a premium product at the market. The company followed the differentiation strategy and deliberately chose its timing strategy. Due to the exclusivity contract with its customer and the respective intellectual property situation, SKF put little emphasis on marketing. Regarding the latter issue, this differed from the recommendations for projects of cluster 3.

8.3.2.3 Cryogenic Machining by 5ME

At the moment of assessment, the innovation context for 5ME was just as positive as it was for the majority of the cluster 1 projects. However, this was not the case right from the start of technology development. The organizational circumstances within the cumbersome structures of the former company MAG IAS hampered innovation realization and the market was small due to the focus on MAG IAS machines. An assessment of the innovation context at this point in time probably would have led to an allocation to cluster 2 (good technology prospects, weak market opportunity, hampering organizational context, mediocre team). As the MAG IAS management team realized the opportunity of cryogenic machining, they did not want to reject the idea. Thus, they ultimately spun-out 5ME for establishing better contextual circumstances to commercialize cryogenic machining. Based on the significant private investment of 5ME's owner, the newly founded company took over the full responsibility for technological development, market identification, and market approach. This totally corresponds to the recommendations given to projects allocated to cluster 2.

The resulting innovation context based on the newly founded company resembles the ones of cluster 1 projects. The structures and strategy of the company was set-up for a successful innovation realization. Customer interest was high and the first machine was equipped by the end of 2014. The reliability and maturity of technology performance could be proofed in 5ME's tech center and thus, their customers were quite excited. However, market introduction just started in 2014. Therefore, ultimate innovation success seemed promising but had not been achieved by the end of 2014. Nevertheless, project realization within the newly founded company was very efficient up to this point in time.

5ME strategically integrated particular customers, certain universities, and lead users for realizing product development. These partners were especially involved in requirements analysis, product development, and product testing for the generation of specific feedback. Like Pinion, 5ME did not have a detailed risk and quality management system, although they utilized certain measures to deal with these tasks. The protection of intellectual property played an important role for 5ME, as they wanted to secure their development efforts. Accordingly, the product development approach of 5ME was in line with the cluster specific recommendations for cluster 1 projects.

In accordance with the companies of cluster 1, 5ME consciously chose its timing strategy and implemented cryogenic machining as a pioneer in the market. The company positioned the technology as a premium solution for niche applications of tough materials in the short-term. In the long-term, 5ME wanted to address any metal machining operations and distinguish cryogenic machining through a clear differentiation approach. To communicate the benefits of cryogenic machining, 5ME was intensively engaged in marketing. In summary, the commercialization strategy of 5ME predominantly resembled the recommendations posed for cluster 1 projects.

8.3.3 Summary

The operational framework was retrospectively applied to the three cases of Pinion, SKF, and 5ME. Based on the conducted discriminant analysis, the cases of the P1.18 bicycle transmission by Pinion, and of cryogenic machining by 5ME, were assigned to cluster 1, while the Friction Disc case was allocated to cluster 3. The probabilities for these classifications ranged between 72% and 80% which represents a solid accuracy. Furthermore, the cluster specific recommendations of the operational framework addressing the innovation process were in close conformity with the actual implementation of the innovation process. As each of the three cases exhibited a particular level of innovation success, this reflects the relevance of the expressed recommendations for action.

Nevertheless, several differences were detected in the actual realization of the innovation process compared to the posed recommendations. Neither Pinion nor 5ME followed a structured risk and quality management, although this was recommended for the realization of product development for projects assigned to cluster 1. A potential explanation of this could be the fact that both companies were newly founded for the realization of their respective innovations in contrast to the vast majority of companies allocated to cluster 1. Correspondingly, these processes were not previously established. However, both companies cared for these issues, but not highly structured.

Contrary to the recommendations stated for the commercialization strategy of projects classified to cluster 3, SKF attached little weight to marketing. Maybe this was due to the Friction Disc project being based on market-pull, in contrast to the mainly technology-push induced innovation projects of cluster 3. As SKF's commercialization within the wind industry was limited to Senvion, further marketing efforts probably would not have increased sales success.

In summary, the operational framework could be qualitatively validated by applying it to the three primary case studies of Pinion, SKF, and 5ME. As the individual contextual circumstances slightly differed with respect to the average cluster median, isolated recommendations varied regarding their overall importance. However, the expressed cluster specific recommendations for action predominantly corresponded to the actual realization of the three respective innovation projects.

8.4 Discussion and Limitations

For the cluster assignment within the operational framework, the statistical method of discriminant analysis was utilized. One limitation regarding the conducted discriminant analysis is the sample size of cluster 4. This cluster has just 20 cases which represents 14% of the overall sample. Tabachnick recommends that the sample size of the smallest group should exceed the number of predictor variables. As 21 variables were used as predictor variables, this recommendation was narrowly missed (Tabachnick and Fidell, 2007, p. 381). Any other recommendations regarding the appropriateness of data for discriminant analysis were fulfilled (cf. chapter 8.1.1).

According to Table 45, 76.9% of all cases were correctly classified by the discriminant analysis. As outlined in chapter 8.1.1, this classification result represents the quality of the utilized discriminant functions. However, the accuracy rate of the discriminant analysis is generally excessive if it is calculated on the basis of the same sample on which the estimation of the discriminant function was based. This is the common way of calculation and was also applied within the conducted study. This sample effect is due to the fact that the discriminant functions are estimated to achieve the optimal accuracy rate within the particular sample. Nevertheless, this effect diminishes with increasing sample size. As the underlying sample of the study accounts to 147 cases, this effect becomes less important (Backhaus *et al.*, 2016, pp. 239–241).

For assigning new cases to the clusters, the classification probabilities with respect to the five clusters are calculated on the basis of the existing distances and a-priori-probabilities by utilizing the Bayes-theorem. However, the application of the Bayes-theorem excludes the possibility that a new case may not belong to any of the predefined clusters. Thus, the classification probabilities do not admit a statement regarding the probability of a particular case belonging to none of the clusters. Therefore, a qualitative plausibility check of the cluster assignment of new cases is recommended. This was done for the cases of Pinion, SKF, and 5ME (Backhaus *et al.*, 2016, pp. 249–253).

The derivation of cluster specific recommendations was based on descriptive and statistical analyses of the quantitative survey. Similarly, the discriminant analysis for cluster assignment was also based on the data of the conducted survey. Any limitations that are due to the study design of the survey, data collection, and data preparation are once again relevant for both analyses. These limitations are outlined in chapter 6.4.5 and will not be repeated in this chapter. Hence, the generalizability of the operational framework is limited, as the survey was explicitly focused on radical technological product innovations within the German power transmission industry. However, for this branch, the operational framework represents a sound tool to guide the context specific realization of radical technological innovations. Nevertheless, the operational framework is meant to serve as indication for the creation of a realization strategy. In practice, further qualitative analyses have to be conducted to find the appropriate project specific implementation approach. Moreover, the question of whether the operational framework also applies to the overall mechanical engineering industry has to be confirmed by further research.

9 Conclusion and Outlook

9.1 Summary

The trends and characteristics of the mechanical engineering industry determine the increasing need for companies from developed countries to realize radical technological innovations. Many factors, led by the pace of technological change, globalization in general, and of particular emphasis, the strong position of Chinese manufacturers, cause this situation. These factors combine to form the current opportunity of radical technological innovations which open up huge differentiation potential. However, the realization of radical technological innovations is accompanied by a high level of risk, costs, and uncertainty. Hence, it is sensible to consider the parameters influencing the success of these innovations. On the search for these parameters, the analysis of previous scientific and practical studies indicated a gap in research, as several questions remained open. These questions were condensed to three concrete research questions and associated sub-problems:

RQ 1: What are the Critical Success Factors for the realization of a radical technological innovation within the mechanical engineering industry?

RQ 2: Is it possible to distinguish distinct innovation archetypes and corresponding strategies for the realization of radical technological innovations within the mechanical engineering industry that depend on the project-specific contextual circumstances?

RQ 3: How can an operational framework be designed for the realization of radical technological innovations within the mechanical engineering industry which is based on the project-specific contextual circumstances and contains concrete recommendations for action?

These research questions were addressed with the thesis at hand. Correspondingly, two fundamental artifacts were designed: the CSF framework derived by answering the first research question and the operational framework generated by answering the third research question. As overarching research methodology, the design science approach was followed.

For answering the first research question RQ 1, a secondary case study analysis was conducted to create an initial framework of CSFs for radical technological innovations within the mechanical engineering industry. This framework was qualitatively validated. It was compared to existing literature, evaluated and modified based on expert interviews, and finally, validated by conducting three primary case studies (P1.18 bicycle transmission by Pinion, Friction Disc by SKF, and cryogenic machining by 5ME). In order to quantitatively analyze the framework, the CSFs were transferred into measurable variables and testable hypotheses. Subsequently, a quantitative survey was conducted and the results were statistically analyzed in the context of the proposed hypotheses.

The resulting CSF framework is depicted in Figure 40 and contains 24 factors. These factors were arranged in the two dimensions: *innovation context* and *innovation process.* All 24 factors correlate significantly with at least one of the three variables of the ultimate *innovation success*. Accordingly, the framework was named *Innovation-Context-Process-Success (ICPS) framework*. The innovation context is shaped by its four main categories *technology, target market, organization,* and *entrepreneurial team* while the innovation process consists of its three iterative fields of action *opportunity identification, product development*, and *commercialization*. The innovation success as a key target figure of each innovation project contains three dimensions: *sales performance, product performance,* and *efficiency.* From the innovation manager's point of view, the CSFs assigned to the innovation context are uncontrollable and constitute the sphere of concern. In contrast, the factors associated with the innovation process are directly controllable by the innovation manager and form his sphere of influence. The finally adapted ICPS framework contains the qualitatively and quantitatively validated CSFs for the realization of a radical technological innovation within the mechanical engineering industry and serves, therefore, as an answer to the first research question.

The second research question RQ2 was addressed by utilizing the results of the conducted quantitative survey. Based on the set of context specific CSFs detected by answering RQ 1, a statistical cluster analysis was conducted to search for distinct innovation archetypes. Indeed, five clearly distinguishable clusters could be detected which represent typical contextual project circumstances. According to their characteristics, the clusters were named as archetypical project contexts: cluster 1 as *inventor`s friendly innovation paradise*, cluster 2 as *conservative development sphere*, cluster 3 as *highly productive innovation system*, cluster 4 as *mediocre implementation circumstances*, and cluster 5 as *fruitless innovation wasteland*. Further statistical analyses indicated that the five clusters could furthermore be distinguished with respect to the way the companies were realizing the innovation process. A comparison with the performer classification, based on the three innovation success dimensions, highlights the quality of the cluster solution. Thus, the manner in which companies were realizing the innovation process could be better distinguished, especially, when looking at the contextual circumstances than looking at the innovation success. As the five clusters were clearly distinguishable, based on the contextual circumstances, they could be perceived as innovation archetypes. Therefore, the second research question could be answered.

The development of an operational framework serves as an answer to the third research question RQ3. The term, operational framework, is meant to describe a strategy model which supports innovation managers of forthcoming projects with the generation of an overall plan to "operationalize" their respective innovation process. It is meant to represent a method to derive concrete recommendations for action that are based on the project-specific contextual circumstances. Thus, the detected innovation archetypes (RQ2) form the underlying basis for the operational framework. First, a cluster has to be detected which most closely resembles the contextual circumstances of the specific innovation project. Therefore, the statistical method of discriminant analysis is utilized. Based on the cluster assignment of the new project, concrete recommendations for action are given that address the three stages of the innovation process: *opportunity identification, product development,* and *commercialization*. These recommendations are based on the descriptive analysis of the five innovation archetypes (RQ2) and the ICPS framework (RQ1). The operational framework was qualitatively validated by applying it to the three conducted primary case studies (P1.18 bicycle transmission by Pinion, Friction Disc by SKF, and cryogenic machining by 5ME). Thereby, the third research question could be answered.

In summary, all three research questions have been answered by this study. Therewith, this thesis helps to reduce the complexity and uncertainty associated with the realization of a radical technological innovation within the mechanical engineering industry. Most importantly, it serves as a hands-on guidance for the actual implementation of forthcoming projects of this kind.

9.2 Relevance

This thesis has both scientific, as well as highly practical relevance. As outlined in chapter 2, the critical review of the state of the art highlights several open questions forming the lack in research that could then be addressed by this thesis. Correspondingly, the thesis fosters the understanding of radical technological innovations within the mechanical engineering industry and thus, contributes to the scientific community by providing new knowledge in the field of technology and innovation management. Therefore, the challenge of realizing radical technological innovations is illustrated and potential strategies to deal with this task are presented. Accordingly, the results of this thesis constitute a substantial contribution to the field of innovation research, and particularly, provide new insights for the implementation of innovation processes of this kind.

From a practical perspective, this thesis is of great benefit for technology driven companies within the mechanical engineering industry since growth and survival of these firms could be fostered by radical technological innovations. The successful realization of radical technological innovations creates sustainable competitive capacity and enhances a firm's potential to succeed in their respective market (Dahl, 2015, p. 5). In particular, this thesis provides support for the strategic management of this kind of innovation. The knowledge and awareness of the concrete CSFs depicted in the ICPS framework which impacts the ultimate innovation success reduces the complexity and uncertainty for the realization of these risky and cost-intensive innovations. Moreover, the operational framework assists innovation managers in forthcoming innovation projects with the establishment of concrete recommendations for action. These recommendations are based on the specific contextual circumstances of the distinct innovation project and therefore directly match the present environment.

Beside incumbent firms, the results of this thesis can help startups and entrepreneurs in this domain as well. As outlined in the ICPS framework, the innovation context for radical technological innovations is shaped by four categories. Three out of four categories are similarly important for entrepreneurs. Correspondingly, the CSFs listed in the categories technology, target market, and entrepreneurial team are highly relevant for entrepreneurs and startups which try to implement a radical technological innovation within the mechanical engineering industry. Nevertheless, the organizational circumstances, the structures, and processes of these entities are not that rigid and fixed like they are for incumbent companies. Instead of the organizational parameters of incumbents, the investor quality and relation as well as potential incubator or accelerator programs may be important for this kind of innovators. However, the innovation culture and strategy are crucial for both types of entity. Moreover, the CSFs of the innovation process are equally decisive, while the concrete realization may differ in its details. Therefore, the operational framework as well as the detected innovation archetypes may serve as orientation for entrepreneurs and startups due to the sample of the survey.

Another target group of the thesis at hand is business consultants who work on strategy projects in technology driven companies. Once a radical technological idea has been generated, the operational framework can be used as an easily applicable tool for any project and business environment without greater efforts. However, the thesis cannot serve for the generation of new radical ideas. To utilize the takeaways of this thesis, it is a precondition that a radical technological idea within the mechanical engineering industry is already available.

Furthermore, technological progress and innovation activity have a positive impact that exceeds the company-based value. Correspondingly, technological innovations within the mechanical engineering industry positively influence the society, when considering the improvements in the quality of life. For example, distinct medical treatments, eco-friendly electricity supply, transportation, and specific production methods became feasible, more efficient, or affordable through radical technological innovations. Additionally, innovation activity is a decisive growth factor for entire economies. It fosters company foundation, job and knowledge generation, tax revenues, and ultimately increasing prosperity. By the gross domestic product (GDP), this could be eventually measured (Dahl, 2015, p. 7; Schilling, 2010, p. 2; Vahs and Brem, 2012, pp. 4–5).

In summary, the thesis has high relevance from a scientific, macro-, and micro-economical perspective. During the course of conducting the study, the author regularly came across high interest of innovation scholars and representatives of the mechanical engineering industry. This fact, and frequent positive feedback regarding the importance of radical technological innovations, and their successful management, further emphasizes the relevance of this thesis (Hilgers, 2015, p. 11).

9.3 Limitations and Outlook

The conducted research study outlined in the thesis at hand, however, includes several limitations which though normal in research should be documented. The method-specific limitations have been described in the respective subchapters (cf. chapter 4.3, chapter 5.1.3, chapter 5.2.3, chapter 5.3.6, chapter 6.4.5, chapter 7.5, and chapter 8.4). Nevertheless, the consideration of the main limitations of the overall study design from an overarching perspective is reasonable and, as noted, simultaneously forms the basis for potential future research endeavors.

First of all, the quantitative study was conducted addressing the German power transmission industry as target industry (cf. chapter 6.3.1). As outlined, the power transmission industry is a sub-sector of the mechanical engineering industry which is quite diverse. Accordingly, the survey results cannot be doubtlessly generalized to the mechanical engineering industry as overall target industry of the thesis (Dahl, 2015, p. 65; VDMA and McKinsey, 2014c, p. 12). This represents a major limitation, as the central results of this study (the finally adapted ICPS framework, the innovation archetypes, and the operational framework) are based on the findings of the quantitative survey. Although the potential transferability of these results to further sub-sectors of the mechanical engineering industry seems to be a natural progression, it currently lacks empirical validation. To enlarge the generalizability of the achieved results, the conducted survey may be replicated in different sub-sectors of the mechanical engineering industry by future research endeavors (Sekaran and Bougie, 2010, p. 22). Any limitations that are due to the survey design, the data collection, and the data preparation of the quantitative study are detailed in chapter 6.4.5.

A central aim of the quantitative study was to statistically test whether or not the data support the hypotheses outlined in chapter 6.1 which were based on a sound qualitative pre-study. Therefore, correlation analyses were applied. On a probability level of 95%, the detected correlations indicated that the respective CSFs are associated with the ultimate innovation success. This has been manifested in the adapted ICPS framework. However, the chronological and factual contribution of each CSF to the overall innovation success has not been analyzed. Correspondingly, future research approaches could target the concrete impacts of the detected CSFs on the subsequent innovation success. Furthermore, due to the holistic survey design of the quantitative study, the CSFs have not been analyzed in depth and remain on a general level. Further studies could focus on the distinct CSF categories outlined in the ICPS framework (e.g. organization or entrepreneurial team) and delve deeper into the concrete characteristics of the associated CSFs.

Although the conducted cluster analysis for the detection of innovation archetypes was inductive, and based completely on the collected data, the limitation exists that it could not be neglected that the ultimate cluster solution did not reflect the underlying cluster structure correctly, or was even artificial. This limitation has been detailed in chapter 7.5. To verify the conclusive five clusters, Cramer's V and ANOVA tests were applied. These statistical tests indicated that the five clusters could be significantly distinguished regarding the realization of the innovation process and serve as a much better classification scheme than the performer differentiation. However, a qualitative analysis of the five clusters could enhance the validity of this cluster solution. Therefore, expert interviews or primary case studies could be conducted as further research endeavors.

The operational framework is meant to be a sound tool to guide the context specific realization of radical technological innovations in forthcoming projects. As previously outlined, one limitation of the framework is that the assignment of new cases to the five detected clusters excludes the possibility that a new case may not belong to any of these clusters (Backhaus *et al.*, 2016, pp. 249–253). In light of this, a qualitative plausibility check of the cluster assignment was conducted by applying the operational framework to the cases of Pinion, SKF, and 5ME. Additionally, the cluster specific recommendations derived from the operational framework were tested. However, this qualitative validation approach was just based on this small sample of three cases, and furthermore, the application was done retrospectively. A natural suggestion for further research is to increase this sample of case studies. Another potential way to qualitatively test the operational framework is to set up an action research endeavor. Therefore, the operational framework should be applied to forthcoming projects of radical technological innovations in an early realization stage. The actual implementation in practice of the generated recommendations could be scientifically tracked within a simultaneous research project.

9.4 Concluding Remarks

While risky, costly, and uncertain, radical technological innovations open up tremendous opportunities for technology driven companies in the mechanical engineering industry. The thesis at hand aims to contribute to closing the existent research gap and to provide assistance in a successful realization of these innovations. This capability has to be interpreted as a complex concept, as it is influenced by a variety of factors, internal and external, to the organization (Terziovski, 2007, p. 19). This thesis, however, should help to reduce the complexity and uncertainty associated with radical technological innovations. As not each factor and process instrument is equally relevant for all companies, the project specific contextual circumstances have to be considered (sphere of concern) at the generation of the realization strategy for the innovation process (sphere of influence). To support innovation managers in forthcoming projects with this challenge, the operational framework in this thesis provides a hands-on tool to derive concrete and project specific recommendations for action. However, the operational framework should be thoroughly questioned and continuously refined, due to the inherent limitations of this thesis. The great potential of radical technological innovations for the mechanical engineering industry is worth such an effort.

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Appendix I – Secondary Case Study Analysis

Indications for CSFs with Page Numbers – Part 1

Critical Success Factors	**Apple** - Gable et al. (1988)	**Biodel** - Crowe and Maidique (1988)	**CDC** - Poel and Burgelman (1988)	**Data Net** - Frevola and Maidique (1988)	**IBM** - Cohen et al. (1988)	**PC&D** - Christiansen et al. (1988)	**TI** - Jakimo and Bupp (1988)	Herstatt and Hippel (1992)	**Sony** - Sanderson and Uzumeri (1995)	**HP** - Christensen and Rogers (1997)	**3 M** - Hippel et al. (1999)
Relative Advantageousness	267	174		389-404	461		123		769	1	
Feasibility & Maturity		174			461-462			219			
Market Match	267		588							6-8	
Opportunity	260	181	588	397					761	5-6	51-54
Market Barriers			588	407			116-118		780		
Environmental Context											
Competition	260			397	462-464	536-537			778	2-3; 7	
Company Culture	262-265	178	581								
Internal Communication					459				775		
People		177-178	591		462-463	526-537				4-18	
Size, Flexibility & Autonomy					459	525-530	120-121		770-780	2-4	
Finance & Funding		173-181	591-592	389-414		526-528	120-121			4	
Management & Owner Commitment		178	581		465	526-527	122			2	
Organizational Home			592		461-462		120-121		770-780		
Intellectual Property		179-180						218			
Lead User Integration	260							213-215			48-49
Risk Management		184							780	8-10	
Speed & Costs				404-408	461		122; 127	213; 220	762; 777	4	
Value Proposition	257-259	175-176		404			114; 123		762-763	1	
Cope with Uncertainty		184								1-8	
Sensitiveness to Market Needs				397-407				218-219	775-777	7	51-54
Timing				404	464				762	8	
Marketing	266-267			408-409	459		122-123		772-773	8	
Platform Strategy & Product Family	267								769-771		
Partnerships / Strategic Alliances	261		585-588								

Indications for CSFs with Page Numbers – Part 2

Critical Success Factors	**3M** - Figueroa and Conceição (2000)	**ARM** - O'Keeffe (2002)	**3M** - Conceição et al. (2002)	**TechCo** - Pavia and Dodson (2008)	**Donnelley** - March (2009)	**Elio** - Sankara and Winkmann (2009)	**Intel** - Burgelman et al. (2009)	**Matrix** - Denend et al. (2009)	**Pixim** - McVie et al. (2009)	**Pitney Bowes** - Christensen and Yu (2009)	**SMal** - Christensen and Anthony (2009)	**Vitreon** - Shapiro (2009)
Relative Advantageousness		9; 17		152		14-16	1140-1141	108	78-81	878	351; 359	1017-1018
Feasibility & Maturity		5				14; 30		108				1018
Market Match				128-151	912	18		108-119	86-90	882; 887	352	
Opportunity		6-7; 17	34-37		904-906	15		114-119		884		1014
Market Barriers		11				28-29	1155				352	1018
Environmental Context	99		29				1155			878-885		
Competition		4		152		19-28				887	359	1018
Company Culture	101	15	31-33									1013
Internal Communication	94-102	15	33									
People			33	127-128			1148			883		1020-1021
Size, Flexibility & Autonomy	94-103		27-29	131-137	910			120				
Finance & Funding				128								
Management & Owner Commitment			30-31	151			1156-1157					
Organizational Home										883		1014
Intellectual Property		4-5	31			16		111; 119-120				
Lead User Integration			32							883-884		
Risk Management		4-6				29-30			86			
Speed & Costs					903-905	30	1156-1157				357	
Value Proposition		1		134-135	905-910	14-18	1153	119	86	886	350-360	1017-1018
Cope with Uncertainty				148				114	86	884		
Sensitiveness to Market Needs			32	136	906		1140; 1156			883-884		
Timing							1155-1157					
Marketing		1-4		127-128	910		1155-1157	119		883	357	
Platform Strategy & Product Family		13		136-139								
Partnerships / Strategic Alliances		5-10				29	1155	120	85		357	

Appendix II – Expert Interviews

1) Interview Guide Round 1

I. Einleitung
- Erläuterung der Ziele des Gesprächs → Vorhaben der Dissertation
- Aufzeichnung/Datenschutz
- Zeitrahmen für das Gespräch

II. Fragen zur Person und dem Unternehmen
- Bitte stellen Sie sich kurz vor. Gehen Sie hierbei kurz auf Ihren akademischen und beruflichen Werdegang ein?
- Welche Position / Rolle nehmen Sie in Ihrem Unternehmen ein?
- Welche Rolle spielen Innovationen ganz allgemein für Ihr Unternehmen?
- Welche Innovationsstrategie verfolgt Ihr Unternehmen?
- Wie sieht der Prozess der Innovationsumsetzung in Ihrem Unternehmen aus?
- Wie hoch liegt in etwa der Umsatzanteil von Produkten die jünger als 5 Jahre sind in Ihrem Unternehmen? Wie erreichen Sie das? (Im Hinblick auf Anreizsysteme, Organisation, Technologien, Markt)

III. Erfolgsfaktoren für die Innovationsumsetzung
- Was sind Erfolgsfaktoren bei der Realisierung von radikalen technischen Innovationen?
- Worauf kommt es beim Prozess der Innovationsumsetzung ganz allgemein an?
- Welche Einflussparameter bestimmen den Erfolg der Produktentwicklung?
  (IP-Management, Effizienz, Lead User, Risikomanagement)
- Welche Faktoren bestimmen den Erfolg der Kommerzialisierung?
  (Timing, Umgang mit Marktbedürfnissen und damit verbundener Unsicherheit, Plattformstrategie → Produktfamilie, Marketing, strategische Partnerschaften)
- Welche Rolle spielt das Umfeld für eine erfolgreiche Innovationsumsetzung?
- Welche Rolle spielt der Zielmarkt? (z.B. im Hinblick auf Markteintrittsbarrieren, Umwelteinflüsse, vorherrschenden Wettbewerb, Market Match, Opportunity)
- Welche Rolle spielt die beteiligte Organisation - Ihr Unternehmen?
  (→ Unternehmensentwicklung, Flexibilität, Finanzierung, Organizational Home, Management bzw. Owner Commitment, Unternehmenskultur, interne Kommunikation)
- Welche Rolle spielen die beteiligten Menschen bei der Innovationsumsetzung?
- Inwiefern spielt die Technologie, welche der Innovation zugrunde liegt, eine Rolle für den Innovationserfolg? (Vorteile im Vergleich zu Technologiealternativen, Reifegrad)

IV. Prozess der Innovationsumsetzung
- Aus Ihrer Erfahrung heraus: Wie würden Sie vorgehen bei der Innovationsumsetzung?
- In welche Phasen würden Sie das Vorgehen unterteilen? (Schritte)
- Gibt es ein erkennbares Muster im Ablauf bei den Ihnen bekannten Innovationsprojekten?
- Weshalb scheitern Innovationsprojekte?
- Wo treten die meisten Schwierigkeiten bei der Umsetzung auf?
- Welche Rolle spielen die Erfinder, das Unternehmen für die Erfolgswahrscheinlichkeit von Innovationen?
- Wie kommt man von einer Idee zur potentiellen Anwendungen?
- Welche Kriterien bzw. Eigenschaften der Technologie, die der Innovation zugrunde liegt, bestimmen die Relevanz für eine bestimmte Anwendung?
- Inwiefern sollte man die Technologie gegenüber Technologiealternativen abgrenzen?
- Welche Kriterien bestimmen die Marktauswahl?
- Welche Rolle spielen die Vorteile einer Innovation im Vergleich zu ihren Alternativen?

2) Interview Guide Round 2

I. Einleitung
- Erläuterung der Ziele des Gesprächs → Vorhaben der Dissertation
- Aufzeichnung/Datenschutz
- Zeitrahmen für das Gespräch

II. Fragen zur Person und dem Unternehmen
- Bitte stellen Sie sich kurz vor. Gehen Sie hierbei kurz auf Ihren akademischen und beruflichen Werdegang ein?
- Welche Position / Rolle nehmen Sie in Ihrem Unternehmen ein?
- Welche Rolle spielen Innovationen ganz allgemein für Ihr Unternehmen?
- Welche Innovationsstrategie verfolgt Ihr Unternehmen?
- Wie sieht der Prozess der Innovationsumsetzung in Ihrem Unternehmen aus?
- Wie hoch liegt in etwa der Umsatzanteil von Produkten die jünger als 5 Jahre sind in Ihrem Unternehmen? Wie erreichen Sie das? (Im Hinblick auf Anreizsysteme, Organisation, Technologien, Markt)

III. Erfolgsverständnis:
- Was macht nach Ihrer Auffassung den Erfolg von technischen Innovationen aus?
- Welche Kriterien / Parameter bestimmen den Erfolg? (→ Umsatz, Marktanteil, Kundenzufriedenheit, Produktperformance)
- Können Sie eine Definition für den Erfolg von technischen Innovationen formulieren?

IV. Kontext für technische Innovationen:
- Was beeinflusst Ihrer Meinung nach die Rahmenbedingungen für radikale technische Innovationen?

Organisation:
- Welche Rolle spielt die innovierende Organisation für den Erfolg von technischen Innovationen?
- Welche Faktoren der Organisation beeinflussen den Erfolg?
- Wie sollte eine Organisation aussehen, damit die Voraussetzungen möglichst gut sind, um erfolgreich zu innovieren?
- Welche Rolle spielt die Kultur für erfolgreiche Innovationen?
- Welchen Einfluss hat die interne Kommunikation?
- Welche Rolle kommt den durchführenden Personen zu?
- Wie wichtig ist eine flexible Organisationsstruktur für den Erfolg?
- Welche Rolle spielt die Finanzierung? Wie kann eine optimale Innovations-Finanzierung im Sinne der strategischen Organisationsziele erreicht werden?
- Welche Rolle spielt das Management Commitment?
- Zum Teil können radikale Innovationen in bestehende Unternehmensstrukturen schlecht eingebettet werden und finden keine Produktheimat? Was spielt das für eine Rolle für den Erfolg? Wie geht man damit um?

Zielmarkt:
- Welchen Einfluss hat der Zielmarkt für den Erfolg einer Innovation?
- Welche Faktoren / Kriterien bestimmen die Erfolgsaussichten einer Innovation auf einem bestimmten Markt?
- Welche Rolle spielt der Market Match?
- Welche Rolle spielen Umwelteinflüsse für den Erfolg einer Innovation (→ Subventionen, Regularien, Wirtschaftskrisen etc.)
- Welche Rolle kommt dem Wettbewerb zu?
- Wie beeinflussen die Markteintrittsbarrieren die Erfolgsaussichten einer Innovation?
- Wovon hängt es ab, dass ein bestimmter Markt große Chancen für die Innovation bietet?

Technologie:
- Welche Rolle kommt der Technologie zu, die der Innovation zugrunde liegt?
- Welche Rolle spielen in diesem Zusammenhang Alternativtechnologien und die Eigenschaften der verwendeten?
- Welchen Einfluss hat der Reifegrad einer Technologie auf den Erfolg der Innovation?

Allgemeine Fragen zum Kontext:
- Beeinflussen die Rahmenbedingungen den Prozess der Innovationsumsetzung? Und wenn dann in welcher Form?
- Bei welchen Rahmenbedingungen sollte man die Innovationsumsetzung gar nicht erst angehen?
- Welche Faktoren der Rahmenbedingungen korrelieren? Welche Faktoren sind gegenläufig?

V. Prozess der Innovationsentwicklung:
- Welche Phasen / Schritte bestimmen den Prozess der Innovationsentstehung?

Produktentwicklung:
- Worauf kommt es bei der Produktentwicklung an?
- Welche Rolle spielt die Prozesseffizienz für den Erfolg? Denken Sie hierbei an Entwicklungskosten und Entwicklungsdauer.
- Wie wichtig ist Risikomanagement? In welchen Phasen wird das relevant?
- Welche Bedeutung kommt dem Schutz von geistigem Eigentum bei?
- Sollte man Lead User in die Produktentwicklung einbeziehen? Wenn ja, warum und wann?

Markteinführung:
- Worauf kommt es bei der Markteinführung einer Innovation an?
- Was bestimmt den Wert, den eine Innovation für einen Kunden hat?
- Bei der Entwicklung von radikalen technischen Innovationen bewegt man sich in einem Umfeld großer Unsicherheit. Wie sollte man damit umgehen? Sind hier besondere Strategien wichtig?
- Wovon hängt das Timing bei der Markteinführung ab? Sollte man den Zeitpunkt strategisch wählen? Wann ist das wichtig?
- Gibt es auch Situationen, in denen der Zeitpunkt egal ist, weil andere Dinge dominieren?
- Wie schafft man es die Bedürfnisse des Kunden stets zu bedienen und zu berücksichtigen? Gibt es Situationen in welchen man diese ignorieren sollte?

Diffusion:
- Was wird in der Diffusionsphase eines Produktes wichtig?
- Welche Bedeutung kommt hier dem Marketing zu?
- Inwiefern sind strategische Partnerschaften bei der Innovationsumsetzung wichtig? In welcher Phase des Innovationsprozesses werden diese wichtig?
- Welche Rolle spielt eine geeignete Plattformstrategie für den Erfolg? Wann sollte man diese Strategie verfolgen?

Allgemeine Fragen zum Prozess:
- Wo treten Schwierigkeiten beim Innovationsprozess auf?
- Woran scheitern Innovationsprojekte?
- Wie kann man das verhindern?
- Welche Faktoren des Prozesses korrelieren? Welche Faktoren sind gegenläufig?

VI. Feedback zum TOMP-Modell
- Vorstellung des TOMP-Modells → Haben Sie Feedback, offene Fragen oder Kritik?

3) Expert Profiles Round 1

The expert E1a is working as a business developer at the technology transfer service unit of a big technical university in Southern Germany. This expert was chosen as she is responsible for identifying potential innovations based on scientific results, the search for cooperation partners in the industry, and the initiating of commercial exploitation.

The expert E1b is an independent scientist and consultant for various areas of innovation and research. He has been working in academic research, applied research, and industrial research for several years. Major thrusts of his industrial career have been the topics competitive intelligence, intellectual asset management, new business development, and technology intelligence.

The expert E1c is an entrepreneur and CEO of a start-up based on a new technology from the organic chemistry sector. Based on his PhD-research, he set up a business together with two partners. He was selected as an interview partner as he has personally experienced the challenges of technology exploitation.

The expert E1d is a manager of Application Engineering in an established company from the power transmission branch with globally more than 40,000 employees. Moreover, he has been responsible for a team of innovation and project managers for several years.

The expert E1e is an entrepreneur and CEO of a technology-based start-up in the mechanical engineering industry. After completing his PhD-project, he has been working for several years in the industry. Together with his partner he founded a company based on a radical new welding technology. They continually developed this technology and finally reached market maturity.

The expert E1f is temporary managing director of an application-oriented research institute from the information and communication sector. This institute is implementing the latest research results in ready-to-use solutions for the industry and clients from the public sector. For gaining insights into the perspective of a research institute on the topic of radical technological innovation, E1f was selected as an interview partner.

The expert E1g is head of new technologies in an established company from the mechanical engineering sector with globally almost 40,000 employees. This expert was chosen as his task is to identify and evaluate innovative technologies from science for his company and to initiate exploitation projects.

The expert E1h is an entrepreneur and CEO of a technology-based start-up in the industrial robotics segment. He has done his Ph.D. within this field and consecutively started the company with two colleagues. With his practical experience of technology entrepreneurship, he serves as appropriate interview partner.

The expert E1i is innovation manager in a medium-sized company in the power transmission industry with globally almost 2,000 employees. In this function, he supports and fosters the innovation creation, development, and commercialization.

4) Expert Profiles Round 2

The expert E2a is an entrepreneur and CEO of a start-up based on a new technology for additive manufacturing. The company serves scientific and industrial customers and develops customized solutions and processes for specific industrial applications based on their innovative technology. Due to his personal experience, he is well suited to contribute to our research.

The expert E2b is managing director of an application-oriented research institute for innovation research and professor of innovation management. She has broad experience in the field of innovation and technology management and is thus, highly appropriate as an interview partner.

The expert E2c is head of the technology transfer service unit of a big technical university in Southern Germany. The services of this department range from the protection of intellectual property rights based on scientific results to technology marketing, to the initiation of industry cooperation, and to the support of spinoffs and shareholdings.

The expert E2d is head of the innovation department in an established company from the power transmission branch with globally more than 40,000 employees. The tasks of this department are to initiate, guide, support, and partly manage innovation projects within the company.

The expert E2e is an innovation manager in an established company from the power transmission branch with globally more than 70,000 employees. She was part of the team that has established the central innovation department within the corporate R&D. Within her function, she fosters ideation, trend research, and innovation management.

The expert E2f is a business consultant, who has many years of work experience. He primarily works in the fields of strategy consulting, technology-based entrepreneurship, innovation, and idea management. His clients are small and medium-sized companies as well as large concerns.

The expert E2g is a business developer in a business incubator of an established company from the automotive supplier industry with globally more than 250,000 employees. This incubator has been set up with the aim to generate new businesses for the parent group. Internal start-up teams should be challenged and promoted to exploit their ideas.

The expert E2h is head of business development at a technology based, medium-sized company from the mechanical engineering industry with more than 500 employees. He is responsible for the strategic direction of the company and potential application fields for their technology.

The expert E2i is head of the advanced development department of an established company from the mechanical engineering industry with globally more than 10,000 employees. Detached from daily business, the aim of his department is to develop strategically interesting product ideas to generate the company's innovations of the future.

The expert E2j is head of the innovation department of a medium-sized company. The company he is working at has more than 6,000 employees and is producing semi-finished products made of carbon. Therewith the company enables their customers to generate radical technological innovations based on their material. E2j is responsible for the topics of innovation, networking, and cooperation. He was chosen as interview partner to get insights into the perspective on the innovation process from a supplier of semi-finished goods.

5) Transcription Rules

- Transcription is done literally, not summarizing. Dialects are not transcribed but standard German was used.
- Language and punctuation are flattened.
- Long pauses will be marked by (…).
- Interrupted or not completed sentences will be separated by "/".
- Approving statements (mhm, aha, mh) from the interviewer will only be transcribed if they interrupt the course of the speech.
- Paragraphs of the interviewers are marked with their name initials "FW:", "LH:", and "KY:". The paragraphs of the experts are marked with the abbreviation described in Table 5.
- Each contribution to the interview has its own paragraph.
- If the interview is disrupted, the reason will be noted in brackets.
- Other vocalizations such as laughter will be noted in brackets.

The transcription rules have been derived from Kuckartz (Kuckartz, 2012).

6) Initial Category System

The initial category system had three levels. The first level distinguishes two dimensions – the context and the process of innovation. The second layer defines the main categories within the three dimensions (C1-C3 and P1-P3). On the third level, the subcategories of the associated main categories are specified by applying the concrete CSFs. Thus, two basic sub-systems have been established for subsequent text analysis (cf. Figure 44 and Figure 45).

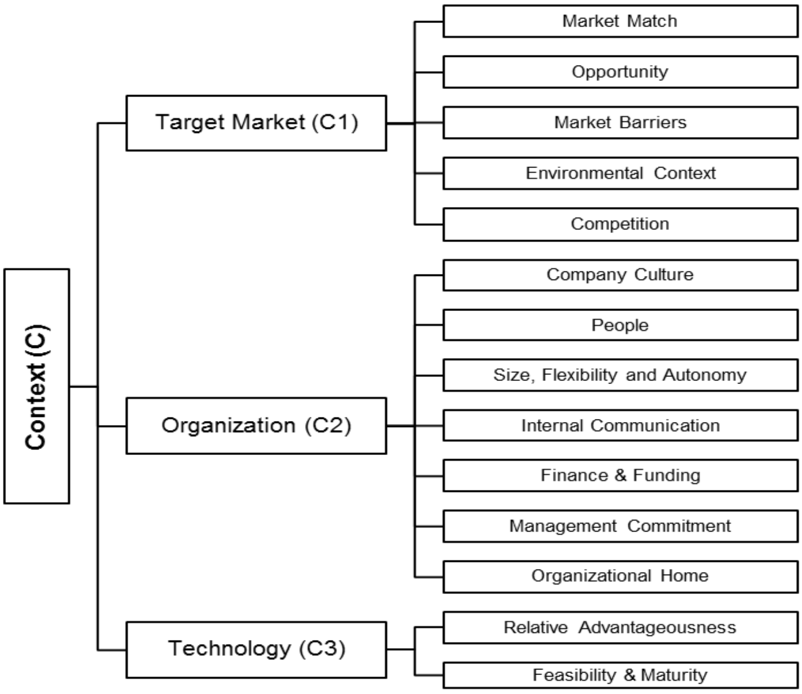

Figure 44: Initial Sub-System for the Context Dimension (Hellmann, 2014, p. 82)

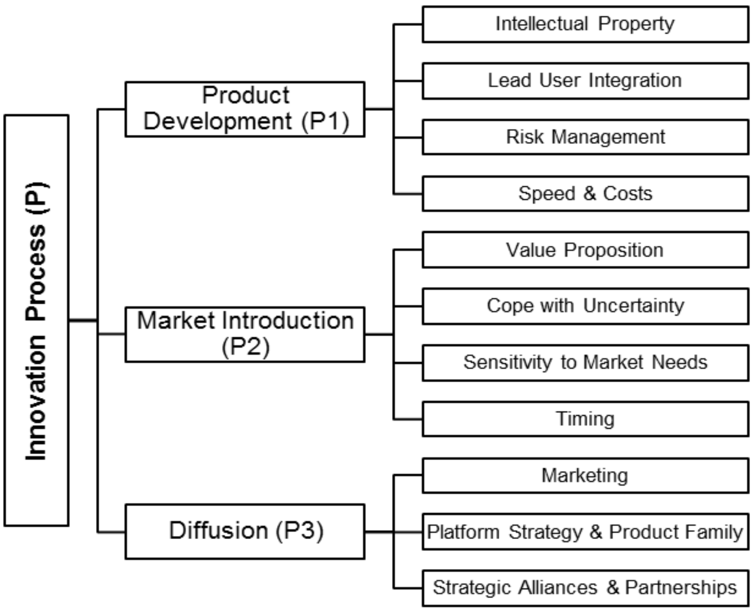

Figure 45: Initial Sub-System for the Process Dimension (Hellmann, 2014, p. 91)

7) Larger Version of the ICPS framework

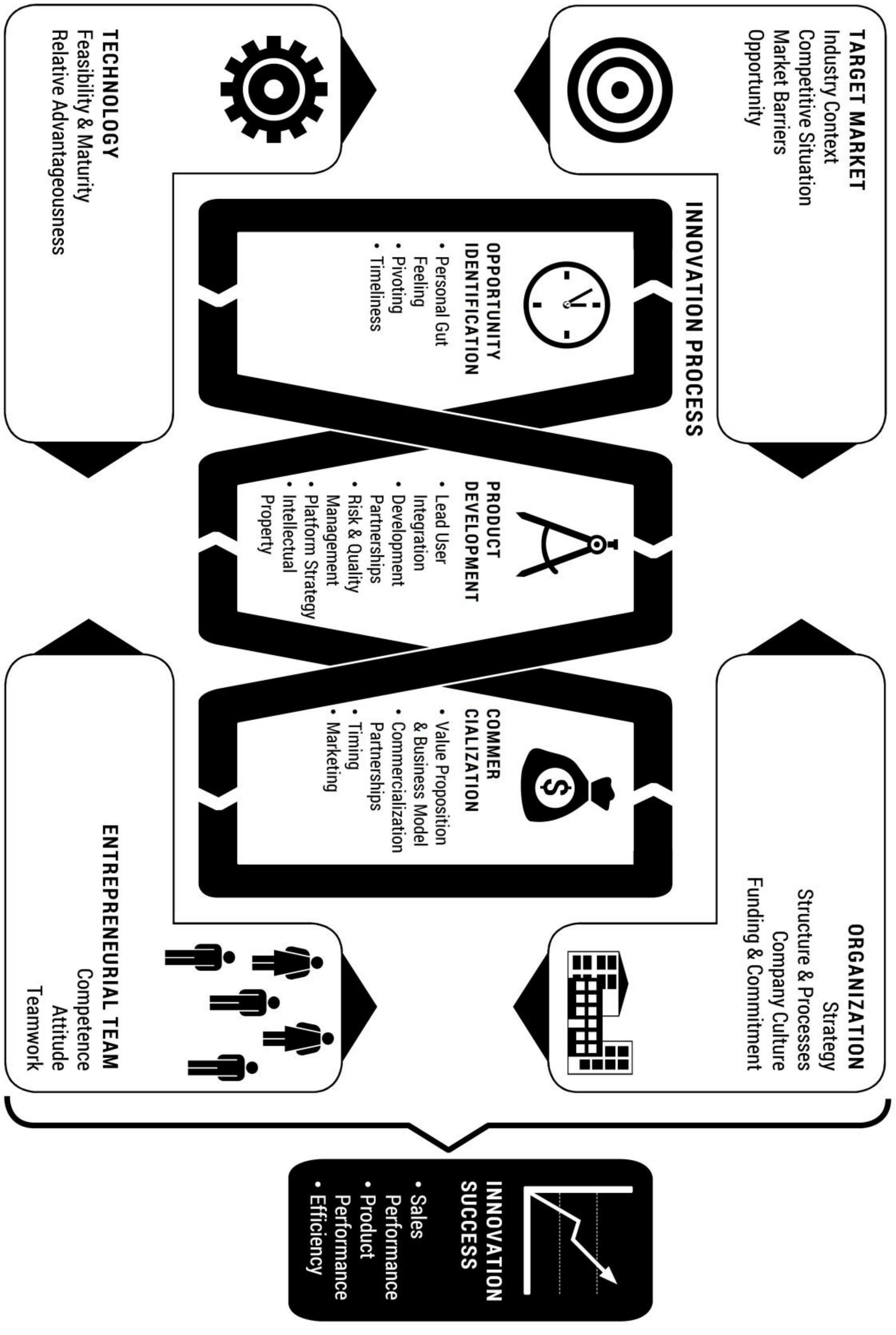

Figure 46: Larger Version of the ICPS Framework

8) Initial Version of the ICPS Framework

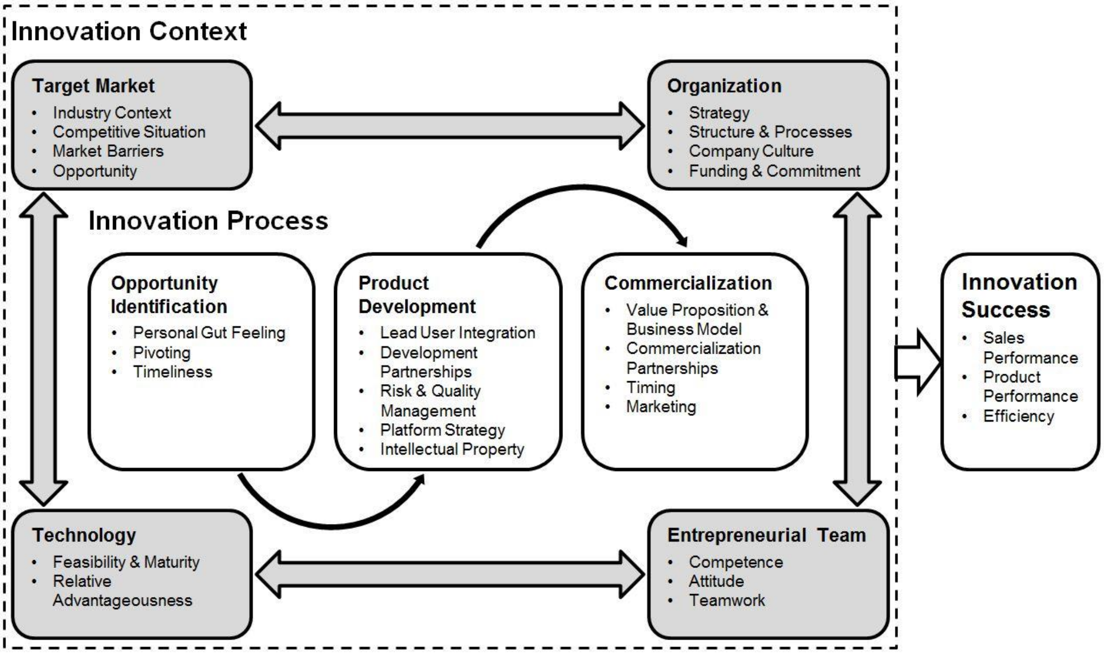

Figure 47: Initial Version of the ICPS Framework

Appendix III – Primary Case Studies

1) Aggregated Case Study Protocol

According to Yin a case study protocol should have the following sections (Yin, 2009, p. 81):

- The overview of the case study project includes the main project objectives and auspices, the case study issues, and relevant readings about the topic being investigated.
- The field procedures include the presentation of credentials, a description of the access to the case study sites, a section dealing with the protection of human subjects, and a schedule of the planned steps within the case study.
- The case study questions addressing the specific questions that the case study investigator must keep in mind in collecting data and the potential sources of information for answering each question.
- The guide for the case study report includes instructions regarding the format and structure of the final report and the way the collected evidence are documented.

1. Overview

Technology driven companies are forced to be innovative, to not just gain advantage in the market but to stay competitive. This is increasingly a question of an adequate employment of innovative technologies. The knowledge of the Critical Success Factors (CSFs) for the strategic management of radical technological innovations helps to reduce complexity and to focus on the main aspects of the planning, development, and employment process.

Previous work has detected a comprehensive set of 28 CSFs that influence the innovation context on the one hand, and the innovation process on the other (cf. Figure 20). Based on these factors, three real life cases (Pinion, SKF, 5ME) addressing radical technological innovations should be studied. Case studies are multi-perspectival analyses that serve as an instrument to analyze and to understand complex issues. Especially if an in-depth investigation is required, case studies serve as a robust research method. The central tasks of the research endeavor are conducting a cross case analysis and comparing the emerging concepts. The correlation of the different parameters should be analyzed in deep and certain patterns of success should be derived. In a multiple-case study, the central goal is to build a general explanation that fits each individual case, even though the cases will vary in their details. This should be done within the research endeavor by following the rules of the qualitative method of case study research.

2. Field Procedures

According to Yin, the following points need to be reflected in data collection (Yin, 2009, p. 85):

Gaining access to key organizations or interviewees:

<u>Pinion:</u>

One of Pinion's founders will serve as key informant and contact person. As he is difficult to reach and has less time, mainly telephone interviews will be conducted.

<u>SKF:</u>

In the case of SKF, the key informants are an innovation manager that has been involved in the Friction Disc project and the responsible project manager of the Friction Disc project. As the researcher has worked with both of them during his former industrial career in SKF there is still a good relationship with them. Thus, they will be directly contacted by telephone and asked for their willingness to be interviewed.

5ME:

There is a close relationship from EnTechnon and 5ME. From the 2nd until the 30th of November the researcher will carry out a research project and spend one month at the facilities of 5ME. This time period will be split up into two main parts. In the first two weeks, the researcher will be at the Tech Center of 5ME in Warren, Michigan to analyze the technological development of the cryogenic machining. During the second two weeks, the researcher will be at the 5ME headquarters in Cincinnati, Ohio to investigate the marketing approach, the company foundation, and it's funding. During the time in the US, the researcher will conduct several interviews with the following key informants of the case study to collect data: 5ME's Cryogenic Engineering & Product Manager, 5ME's Cryogenic Business Development Manager, 5ME's Marketing & Product Manager, and 5ME's President.

To document the interviews in each of the three case studies the voice recorder Olympus Digital Voice Recorder VN-712PC will be used. Later on, the interviews will be transcribed with the software F4.

Having sufficient resources in the field:

The main research will be done via an Internet search and several personal interviews. For the Internet research, a computer of the EnTechnon can be used. The expert interviews will be conducted personally or via telephone. There are two voice recorders available at the EnTechnon. During the whole research project, one of these two voice recorders is permanently available.

Developing a procedure for calling for assistance and guidance, if needed, from other case study investigators or colleagues:

The researcher is in close contact with two of his institute colleagues Dr. Jeanette Siegele and Dr. André Presse. They have conducted several case studies in their research project "Baden Stories" which addresses the founding story of Start-Ups from the KIT-environment. This serves as valuable advice and guideline for the current research endeavor. Furthermore, Abilio Avila a Ph.D.-peer is conducting case studies as well. Correspondingly, there is a good possibility of sharing information.

Making a clear schedule of the data collection activities that are expected to be completed within specified periods of time:

Pinion:

- Selection of appropriate Case Study Design → week 47/48 in 2013
- Getting familiar with the company Pinion and its technology → week 49 in 2013
- Preparation of a guideline for the telephone interview with the founder of Pinion → week 50 in 2013
- Telephone interview with the founder → 12/17/2013
- Write down interview transcript → week 51 in 2013
- Further data collection → week 2-10 in 2014
- Additional telephone interview with the Pinion's founder to clarify open questions → 04/03/2014
- Analyzing data → week 5-12 in 2014
- Wrap up and write down a draft report → week 5-12 in 2014
- Send the draft report to Pinion's founder → 04/17/2014
- Review of the draft report by the founder → until week 19 in 2014
- Include hints and comments, work out, and publish the final report → week 22 in 2014

SKF:

- Selection of appropriate Case Study Design → week 21/22 in 2014
- Getting familiar with the technology of the Friction Disc → week 23 in 2014
- Collection of data → week 24-32 in 2014
- Preparation of a guideline for the personal interview with the project manager of the Friction Disc project → week 27 in 2013

- Additional personal interview with the project manager → 07/11/2014
- Personal interview with innovation manager → 07/21/2014
- Write down interview transcripts → week 30/31 in 2014
- Analyzing data and wrap up → week 42 in 2014
- Write down the report → week 36 in 2014
- Send the draft report to project manager → week 37 in 2014
- Review of the draft report by the project manager → until week 39 in 2014
- Include hints and comments, work out, and publish the final report → week 42 in 2014

5ME:

- Selection of appropriate Case Study Design → week 44 in 2014
- Getting familiar with the technology of Cryogenic Machining → week 44 in 2014
- Collection of data → week 44-48 in 2014
- Preparation of a guideline for the personal interviews with key interviewees → week 44 in 2014
- Data Collection with respect to the technological development → week 45-46 in 2014
- Data Collection with respect to the marketing approach, company funding and foundation → week 47-48 in 2014
- Write down interview transcripts → week 49 in 2014
- Analyzing data → week 49-50 in 2014
- Wrap up and write down the single case study report → week 2 in 2015
- Send the draft report to 5ME's president → week 3 in 2015
- Review of the draft report by 5ME's president → until week 6 in 2015
- Include hints and comments, work out, and publish the final report → week 8 in 2015

Providing for unanticipated events, including changes in the availability of interviewees as well as changes in the mood and motivation of the case study investigator:

The plan is to end up in week 20 of 2014 with the Pinion case study, in week 41 with the SKF case study, and in week 8 of 2015 with the 5ME case study. These are not external deadlines as they were set by the case study investigator himself. But to keep on track it is useful to communicate the dates of the planned draft review to the interview partners for generating external pressure on the investigator to conclude the research.

Describe the procedures for protecting human subjects:

In the beginning of each interview the interviewee will be asked if it is ok to record the call and furthermore, the purpose of this recording will be explained. A draft of the case study report will be sent to the key informants, to check if on the one hand all events are historically correct and on the other, the publication of the report will not hurt personal human subjects or business internal information. As there is no further involved case study investigator, there is no need for further sensitization.

3. Case Study Questions

According to Yin, there are five levels of questions. Within the protocol, the focus should lay on Level 2 questions.

- Level 1: questions addressing specific interviewees
- Level 2: questions addressing the individual case
- Level 3: questions addressing findings across multiple cases
- Level 4: questions addressing the entire study
- Level 5: questions going beyond the narrow scope of the study (Yin, 2009, p. 87).

Level 1: these questions are detailed in the concrete guidelines for the personal interviews. These questions have been derived from the level 2 questions.

Level 2:

Questions:

- What was the history of the innovation?
- How was the project financed during its deployment?
- How does the technology work?
- What are the advantages/disadvantages of the technology (relative advantageousness, feasibility, maturity)?
- What are competitive alternatives?
- What is the target market?
- What are the properties of the target market (opportunity, market barriers, industry context, and competitive situation)?
- How does the innovation match to the market?
- What are the organizational circumstances for the innovation realization (strategy, structure & processes, company culture, funding, and commitment)?
- What are the properties of the entrepreneurial team (teamwork, competence, and attitude)?
- How did the innovation process look like?
- What was decisive for the opportunity identification (personal gut feeling, pivoting, and timeliness)?
- How has product development been organized (lead user integration, development partnerships, risk & quality management, platform strategy, IP-protection)?
- What was important for the commercialization of the innovation (value proposition & business model, commercialization partnerships, timing, and marketing)?
- Which level of innovation success was achieved with the central innovation regarding sales performance, product performance, and efficiency (costs & time)?

Main Sources:

- Interviews with key informants
- Documents: presentations, data sheets, success stories, press releases, brochures etc.
- Diverse test and press reports
- Scientific and academic papers

Level 3-5: These questions have not been composed for this protocol in accordance with Yin's recommendation (see section above).

4. Guide for the Case Study Report and Documentation

To reach reliability, the way of organizing and documenting the data collected for case studies is essential. Yin differentiated between two main data collections: the compilation of evidence and the final case study report (Yin, 2009, pp. 118–119).

As the raw data need to be available for independent inspection, a database should be established. For the current research the Software "Citavi 4 Pro" will be used to create a database for collecting case study evidence. Written texts, Pdfs, graphs, and links to websites are inserted. Interviews get transcribed and stored as text files. Quotations will be tagged and subsequently categorized.

The final case study report should be written in Word 2010 and will be structured in a linear analytical way with chronological elements within the section reflecting the business evolution of the different cases. In the beginning, the text will have a methodological part, reflecting the chosen research design. Furthermore, it will contain multiple narratives, covering each of the cases singly and presented as separate chapters. Additionally, the report will contain a chapter covering the cross-case analysis and results. The overall case study report was written in past tense while the more detailed individual case studies have been prepared in the present tense (Yin, 2009, p. 171).

2) Quality Tactics for Case Study Research

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

Figure 48: Quality Tactics (Yin, 2009, p. 41)

3) Case Study Report – P1.18 Bicycle Transmission by Pinion

Technology

The main goal of the two Pinion founders was to develop a competitive shifting system for bicycles to overcome the existent disadvantages of traditional derailleur systems and internal gear hubs (Steinke, 2013).

After years of development the team ended up in July 2012 with a compact, totally enclosed, and maintenance free gearbox solution ready for series production. The P1.18 is a spur gear consisting of two transmission structures that are connected in series (Pinion, 2013a, p. 3). Via pedal the first of the two parallel partial shaft transmissions, equipped with three pairs of gears, will be driven. The second shaft transmits the power on six pairs of gears. The multiplication of six by three ratios gives 18 real ratios. Contrary to overlapping gears of conventional derailleur systems, the gears of the P1.18 are evenly spaced in steps of 11.5%.

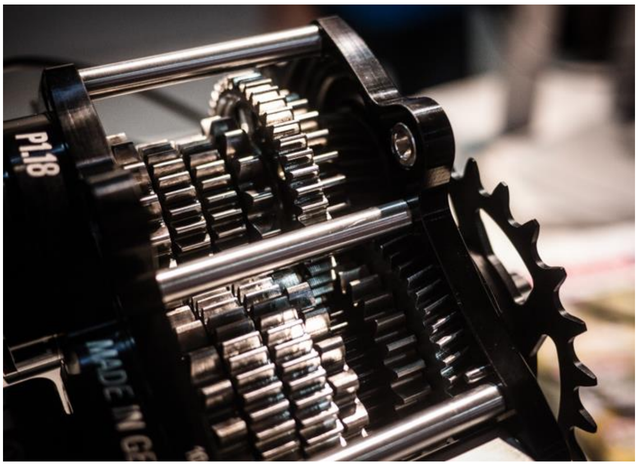

Figure 49: Exposed P1.18 Gearbox (Steinke, 2013)

In sum, the Pinion transmission achieves a total gear ratio of 636% what is higher than the maximum transmission ratios of currently available derailleur systems (~620%) and internal gear hubs (~530%) (Birkhofer, 2013; Pinion, 2013a, p. 6; Schäfer, 2013).

Unlike any current bicycle shifting system, the Pinion transmission needs two cables to operate its rotary shifting mechanism (Wragg, 2012). This mechanism inside the gearbox is actuated with a turning handle. Within the shaft of the upper cluster gear (not the drive shaft) the intended ratio is engaged (Birkhofer, 2013). This shaft is constructed as a continuous hollow shaft in which a camshaft and switchable pawl free-wheels are integrated (Lermen, 2011). When you call for a shift, the camshaft activates the pawls inside the hollow shaft. These pop up underneath the selected gears and subsequently lock them in place. Thus, the P1.18 engages only two pairs of spur gears in each gear to transmit the power (Lermen, 2011; Pinion, 2013a, p. 6; Wragg, 2012).

Figure 50: Hollow Shafts with Camshaft and Pawl Freewheels (Staudt, 2011)

The reason for a turning handle as a shifting actuator is the required movement radius of the cam-shaft. As the shaft reaches a maximum angle of 1020° between the lowest and highest gear, the shift cable has to be pulled quite far although there is a planetary transmission to reduce this distance (Stahl, 2011). This is the explanation why a conventional thumb shifter would not work (Wragg, 2012). Even when loaded, the gearbox is switchable: It is possible to upshift at full load and down-shift at part load. Additionally, the P1.18 can be shifted in standby mode without any problems (Lermen, 2010).

The use of the Pinion P1.18 bicycle transmission is only possible on frames that are specially de-signed by the manufacturers for the use with Pinion. By using six mounting points on a bridge assembly, the gearbox is attached that it forms an integral part of the bicycle frame (Pinion, 2013a, p. 21).

The Pinion transmission is placed at the bottom bracket and has thus, an optimal position within the two-wheeled vehicle bicycle. At this position, the gearbox is in the center of all three dimensions what leads to a deeper lying center of gravity and an evenly distributed rotating mass. The transmission includes all the elements that traditionally have been in or at the rear wheel: shift cable, shifting mechanism, cartridge, and gear hub. Consequently, the rear wheel can be designed simpler and lighter (Donner, 2012, p. 24). Contrary to a derailleur system, the chain runs just on two gearwheels of the same size and is guided by the chain tensioner that sits directly behind the gearbox (Schäfer, 2013; Wragg, 2012).

Figure 51: P1.18 Gearbox (Reidl, 2012)

Alternatively, it is possible to assemble a belt pulley directly at the gearbox to transmit the driving force via tooth belt (Stahl, 2013).

Table 13: Technical Data of the P1.18 Gearbox (Pinion, 2013a, p. 26)

Number of Gears	18
Overall Ratio	636%
Gear Steps	11.5%
Gain Ratio in 1st Gear	1.59
Gain Ratio in 18th Gear	0.25
Maximum Input Torque	250 Nm
Overall Weight	2700 g
Lubrication	Splash Lubrication
Oil Type	Synthetic Pinion Oil
Oil Capacity	60 ml (2.0 oz)
Oil Change Interval	every 6,200 miles / once a year
Temperature Range	-15°C to +40°C / 5°F to 104°F

Feasibility and Maturity

The Pinion P1.18 entered series production in July 2012. By 2014, more than 1,000 gearboxes have been sold. Thus, the deployed technology is now feasible and mature. Additionally, the Pinion team develops the product continually further (Pinion, 2013a, p. 3; Schäfer, 2013; Steinke, 2013).

This was not obvious in the beginning, as the two founders received relative negative feedback by automotive R&D personnel regarding the feasibility of the initial idea. The two engineers derived their transmission design from automotive gearboxes and tried to adapt automobile technologies to bicycles. The aim to reach less than 3 kg for the bicycle gearbox compared to more than 30 kg for automobile gearboxes was a great technological challenge. Less speed and a comparable torque of 250 Nm was indeed not easy to handle. Furthermore, the standardized calculation methods could not be applied as they were designed for automobile gearboxes. Consequently, a test rig has to be constructed to display the actual load spectrum for bicycles. In sum, it was a long way to go that lasted seven years to gain a mature product (Pinion, 2013b, 2013a, p. 3).

Technological Alternatives

There are two basic alternatives to the Pinion transmission: internal gear hubs and derailleur systems. In the following section, three of the most competitive internal gear hub concepts and one representative and widespread derailleur concept will be presented.

Rohloff SPEEDHUB 500/14

The Rohloff SPEEDHUB 500/14 (cf. Figure 52) gearbox consists of three in line interconnected planetary gear assemblies. It is a fully encapsulated maintenance free gear mechanism that runs within an oil bath. The engagement of the 14 evenly spaced (13.6%) real gears is controlled within the hub itself. In sum, the hub achieves an overall range of 526%, weights approx. 1800 grams and its price is starting from 750 € (Rohloff, 2011; Warentest, 2013).

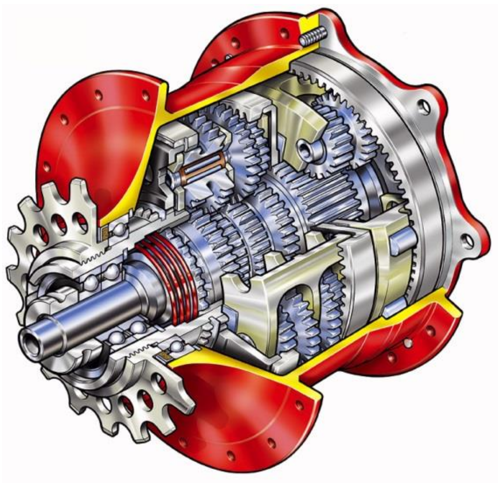

Figure 52: Rohloff Speedhub (Rohloff, 2011)

Shimano ALFINE 11

The Shimano ALFINE 11 offers 11 gears and an overall ratio range of 409% (cf. Figure 53). The gear steps are nine times 13% and twice 17%. The hub transmission is realized by a helical-cut planetary gear system in an oil bath. It is completely enclosed and nearly maintenance free. The gear hub weights approx. 1600 grams and costs approx. 350 € (Simpel-ch, 2014; Warentest, 2013).

Figure 53: Shimano Alfine (Shimano, 2011)

NuVinci N360

The NuVinci N360 (cf. Figure 54) transmits mechanical power with spheres instead of gears. It changes the ratio by tilting the axes of the spheres with respect to internal input and output traction rings. The nominal ratio range is 360%, with an underdrive of 0.5 and an overdrive of 1.8 (Fallbrook, 2012, pp. 1–2). The N360 is provided with permanent lubrication for life and completely sealed. The hub weighs approx. 2450 grams and costs approx. 360 € (Fallbrook, 2014).

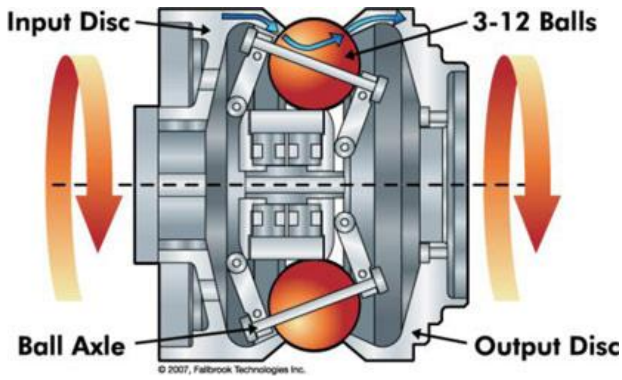

Figure 54: Nuvinci N360 (Velomobile, 2013)

Shimano DEORE XT

By combining three front chainrings (with 22-32-44 pinions) and nine rear chainrings (between 11 and 34 pinions), the Shimano Deore XT derailleur system (cf. Figure 55) has 27 theoretical and 16 practical gear steps, due to overlapping. The shifting procedure will be realized by moving the chain from one sprocket to another. In total, the ratio range is 618%. The price for the complete system differs extremely depending on the single components. A standard version within a complete bike costs roughly 400 € (Pro Activ GmbH, 2014; Warentest, 2013).

Figure 55: Shimano Deore XT (Bergleben, 2014)

Relative Advantageousness

To gain the relative advantageousness of the Pinion P1.18 with respect to the existent shifting alternatives, eight evaluation criteria have been derived from diverse bicycle test reports: overall ratio range, number of real gears, system weight, center of gravity, shifting performance, service and maintenance effort, requirements for construction change, and price.

Overall Ratio Range

With 634%, the P1.18 has a higher overall ratio than all available alternatives (cf. Figure 56). It has a greater range than the Shimano Deore XT derailleur drivetrain (618%) and moreover, has no overlapping or duplicate ratios (Wragg, 2012). The internal gear hub concepts possess an even lower ratio range: Rohloff Speedhub - 526%, Shimano Alfine 11 - 409%, NuVinci N360 - 360%.

Figure 56: Ratio Range Comparison (Pinion, 2013a, p. 6)

Number of Real Gears

In respect to its 18 real gears evenly spaced in steps of 11.5%, the P1.18 has great advantages. Due to its overlapping gears, the Shimano Deore XT only has 16 real gears. The Shimano Alfine has 11 almost evenly (2x17% and 9x13%) and the Rohloff Speedhub 14 evenly (13.6%) spaced gears. In this regard, the NuVinci N360 prevails, as its ratio can be chosen optionally (Fallbrook, 2012, pp. 1–2; Pinion, 2013a, p. 26; Pro Activ GmbH, 2014; Rohloff, 2011; Simpel-ch, 2014).

The great range and the finely stepped ratios of the P1.18 enable to choose the appropriate ratio for each potential driving situation at any time (Lermen, 2010). On the other hand, the fine steps of the gearbox can increase the need to shift. Even though gears could be skipped, there may be riders that dislike these small steps (Stiener, 2012). In summary, the evenly spaced 18 real gears combined with the great overall ratio form the outstanding benefit of the P1.18.

System Weight

Particularly because manufacturers of high-end bikes generally struggle for each gram, the question of weight is an important one. However, not the weight of the single component but the collected system weight is decisive. The single P1.18 gearbox weighs 2700 grams. Assembled on the bicycle, a Pinion equipped bike weighs roughly 400-700 grams more than a comparable bike equipped with the Rohloff Speedhub, 600-900 gram more than one with a Shimano Alfine 11, and approx. 2000 grams more than one with a Shimano Deore XT derailleur system. However, a Pinion bike is roughly 200 grams lighter than a bike equipped with the N360 (Donner, 2012, p. 26; Steinke, 2013; Warentest, 2013).

Center of Gravity

As mentioned before, the P1.18 bicycle transmission is positioned at the bottom bracket and is thus, in the center of all three dimensions what leads to a deeper lying center of gravity. Furthermore, the rear wheel can be designed simpler and lighter causing an evenly distributed rotating mass of this wheel. In contrast, the center of gravity of both alternative shifting systems is clearly situated nearby the rear wheel (Donner, 2012, pp. 24–26). The fewer rotating mass of the freed rear wheel of the Pinion bike leads to more agility and dynamics while driving. While being heavier is a clear disadvantage regarding high-end bike designs, the central position of the gearbox and its substantial better center of gravity overcompensates this disadvantage (Donner, 2012, p. 26).

Shifting Performance

Familiar with a traditional derailleur system, it takes some time to get used to the turning handle to activate the Pinion shifting mechanism. Both the necessary turning movement of nearly 20° for each gear change and the augmented shifting demand due to the fine gear steps (11.5%) can lead to initial difficulties (Steinke, 2013). However, the Rohloff Speedhub and the NuVinci N360 operate with a similar shifting mechanism. A traditional derailleur system like the Shimano Deore XT needs two shift levers, one for each chainring. Thus, using just a single shifter to move through every gear is an obvious advantage (Wragg, 2012).

With the P1.18, the rider has to take into account that downshifting will only be possible at part load (Lermen, 2010). If this is considered, the gear change follows fluently, properly, and exactly in either single or multiple gear steps (Donner, 2012, p. 26; Pinion, 2013a, p. 6). When switching gears, the shifter gives direct feedback to the rider that the gear has changed (Pinion, 2013a, p. 19). Unlike the Rohloff Speedhub and the Shimano Alfine which are composed of a large number of components transmitting the driving force, the P1.18 engages only two pairs of spur gears in each gear to transmit the power. This fosters the efficiency and leads to minimal drive noise, high smoothness, and nearly lossless power transmission of the Pinion concept (Donner, 2012, p. 26; Pinion, 2013a, p. 6). To sum up, after a training period with the P1.18, the advantages of fast and reliable shifting become apparent.

Service and Maintenance Effort

The Pinion P1.18 has minimal service and maintenance requirements as all components of the gearbox are safely protected in an enclosed, sealed housing and suspended in an oil bath. Once a year (or respectively every 10,000 km) an oil change should be performed. The gearbox is rated for a durability of 60,000 km. However, due to wear, after a while a few components of the system (like chainrings and shift cables) potentially need to be replaced (Pinion, 2013a, p. 22, 2013a, p. 6).

As all three internal gear hub concepts are encapsulated, sealed, and do not require maintenance, this feature of the P1.18 is not a unique selling proposition. Nevertheless, the maintenance freedom of internal gear hubs, in general, is definitely an advantage compared to traditional derailleur systems. Furthermore, none of the defect-susceptible parts of a derailleur system like rear and front derailleur, chain guide, and a set of chainrings are existent. This avoids damages and additionally, increases the ground clearance and therewith the capabilities of the bicycle in rough terrain (Pinion, 2013a, p. 5; Steinke, 2013).

Requirements for Construction Change

The use of the P1.18 is only possible on frames that are specially designed by the bicycle-OEMs for the use with Pinion. Together with the frame the gearbox forms a unified ensemble. On the one hand, this causes a relatively high level of system integration, but offers no alternatives to the P1.18, on the other hand, in the case of disfavor or breakdown. The bicycle manufacturers find themselves in a similar situation. They face a higher entrepreneurial risk as well as additional expenditures regarding development efforts and costs (Donner, 2012, p. 26; Pinion, 2013a, p. 21; Stiener, 2012).

In this regard, the alternative internal gear hub concepts gain advantages, as all of them are placed within the rear wheel. Thus, they are easy to adapt and do not need construction changes of the frame or the rear wheel design. As the derailleur system is the standard mechanism and correspondingly widespread, the current frame designs are specified for this system.

Price

Besides the technological advantages, the price is an essential criterion for evaluating the chances of mainstream market success. Until now, the Pinion P1.18 is not available as a single component as it is merely sold as an integral part of a fully equipped bicycle of certain partner OEMs. According to industry experts, the price for the gearbox ranges up to approx. 2,000 €. Depending on the utilized components, the price for a complete Shimano Deore XT derailleur system differs extremely. All single components can be ordered separately. Altogether a standard version within a complete bike costs roughly 400 €. The price for a Rohloff Speedhub is starting at 750 €, the Shimano Alfine costs approx. 350 € and the NuVinci N360 costs 360 € (Warentest, 2013).

It is obvious, that the P1.18 is the most expensive shifting system. This is due to the fact that the series production just started and the gearbox has exclusively been integrated into only a few high-end premium bikes with moderate market distribution. To become a real competitive alternative on the mainstream bicycle market, the total price for the P1.18 gearbox must be significantly reduced. In view of potential leverage effects by economies of scale, this should be possible in the long term.

Overview of the Relative Advantages of the P1.18

To get a better overview of the relative advantages of the P1.18 bicycle transmission, the different shifting systems have been evaluated with respect to the degree to which they meet the eight evaluation criteria on a ten-stage scale (cf. Figure 57).

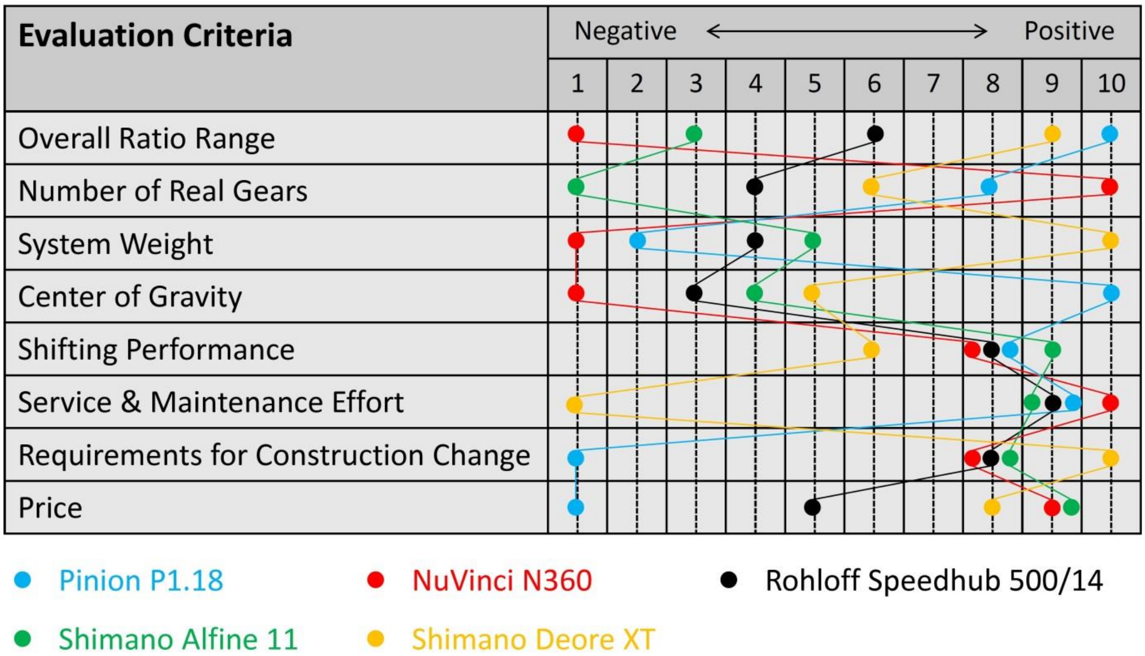

Figure 57: Overview of Relative Advantages of the P1.18

Ultimately, the unique advantages of the P1.18 gearbox compared to the existent alternatives are the great overall ratio range, the number of real gears, and the position of the center of gravity. In contrast, the high system weight, the obligatory need for frame construction change, and the currently high price are the disadvantages of the Pinion P1.18.

It becomes apparent that all shifting systems have their specific advantages and disadvantages. The ultimate highflyer fulfilling all potential requirements and needs of a bicycle shifting system is still not available. Due to subjective customer preferences, an evaluative comparison from an overall perspective is difficult and almost impossible. Decisive for the general success of a single shifting system are the individual requirements and needs of the targeted customer groups. Therefore, it is essential to know and meet the requirements of the distinct target market. Consequently, in the following chapter the target market will be analyzed (Stiener, 2012).

Target Market

Naturally, Pinion initially addresses the German bicycle market. Both founders are German and additionally enthusiastic cyclists. Thus, they are used to the characteristics of the local market.

Looking at the market share (cf. Figure 58) of the different models on the German bike market, it becomes obvious that the trekking bikes dominate with roughly 33% followed by the city- & urban bikes with approx. 24%. Mountain bikes, all terrain bikes, and e-bikes are nearly on the same level with about 10% (ZIV, 2013b, p. 68). Pinion is initially focusing on mountain bikes as well as the trekking and touring sector. In both segments, the advantages of the gearbox are highly transparent (Pinion, 2013b). The enclosed system of the P1.18 has no exposed shifting elements that could be damaged.

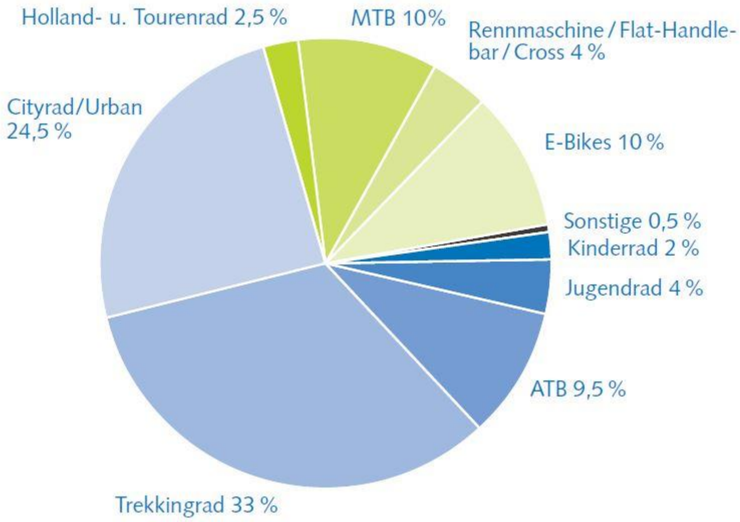

Figure 58: German Market Share of Bike Models by 2012 (ZIV, 2013b, p. 68)

This additionally increases the ground clearance and therewith the possibilities in rough terrain. Furthermore, the advantageous position of the center of gravity fosters bike handling and favors the usage of mountain bikes. Especially the maintenance freedom and the steady shifting comfort in various situations, forms the benefits of using the P1.18 at trekking and touring bikes (Donner, 2012, p. 26; Pinion, 2013a, p. 5).

The P1.18 is meant to be a premium product. As it is relatively expensive, the high-end segment is addressed. Furthermore, an expansion of the initial product portfolio seems obvious. The application of the gearbox for a recumbent, tandem, and e-bikes is currently under conception. With the German niche market for high-end mountain, trekking, and touring bikes Pinion has a regional, model segment, and quality level focus. However, the company is planning to cover the entire bicycle market little by little in Europe and subsequently, globally later on (Pinion, 2013b; Schäfer, 2013).

Industry Context

The industry context for the Pinion GmbH was predominantly positive. Environment and sustainability have become important topics in society and politics. Different laws and regulations already reflect this growing environmental awareness. Thus, strict emissions directives for commercial vehicles, clear zones in inner-city areas and environmental certificates have been introduced inter alia. Correspondingly, a trend towards new and energy-efficient mobility concepts in particular for urban spaces is observable. For these reasons, the bicycle gains in importance as an urban transport tool. Thus, a maintenance free bicycle gearbox seems to match the spirit of the time and to be a product with good prospects (Pinion, 2013a, p. 16; Reidl, 2012).

Furthermore, the German government supports the creation of technology and knowledge based business start-ups with their EXST program. To cover expenses, the entrepreneurs receive a grant of 800 to 2,500 € per month, depending on their academic degree, for a maximum period of 12 months (BWMi). The Pinion team received this grant in 2008 (Pinion, 2013b).

However, Pinion has to suffer from the economic upturn of the automotive industry. Pinion mainly trusts in suppliers of the automobile industry. As these suppliers had full order books, the start-up immediately slipped to the end of the order list (Reidl, 2012).

Competitive Situation

By now, Pinion is the only company to distribute this specific gearbox technology. Thus, it only has to compete with its technological alternatives. Those have been introduced and compared previously. However, Pinion needs to be aware of emerging and established market rivals. If the Pinion technology proves to be valuable, it is just a question of time until capable competitors will develop cannibalizing innovations and possibly enter the market (Schilling, 1998, p. 277).

Market Barriers

Initially, the Pinion team expected that the biggest obstacle to the market entrance would be the necessity to persuade frame-builders to design and produce a modified frame to integrate the gearbox. Therefore, a forged part needs to be welded at the bottom of the frame. The gearbox will be screwed to this forged part. In retrospective, the frame-building process was not a problem. Nearly all frames are produced in Asia and these manufacturers nearly do not care if they have to weld the bottom bracket tube to the frame or a forged part for the gearbox (Pinion, 2013b).

The de facto biggest barrier to market entry was the challenge to persuade the bicycle manufacturers to apply the Pinion technology. The main point that hampered the market introduction was the skepticism towards the new technology and even more towards the young company. This was the same with all bicycle manufacturers. They questioned the reliability of the young start-up and it took some time to trust Pinion. The way to become a serious partner within the bicycle industry is a long and tough one (Pinion, 2013b).

Additionally, there are several mountain bike manufacturers that have some issues with the P1.18 performance, mainly regarding loaded shifting and system weight. However, the major barrier is the existing question towards the reliability of a young start-up (Pinion, 2013b).

Opportunity

The global market for bicycles is tremendous. Every year over 130 million bikes are sold worldwide (GloboMeter). Understandably, Pinion initially started to address their German home market. With sales numbers of roughly 4 million bikes per year Germany accounts for 20% of the European market with approx. 19.7 million items in 2012 (Colibi, 2013, p. 19). The total value of the accumulated bike sales in Germany was about 2.03 billion € (ZIV, 2013a, p. 13). In Europe, the German average price for a bicycle of 513 € was solely outreached by the Netherlands with 724 € (Colibi, 2013, p. 21). With 260 million € Germany is responsible for 16% of the total 1.65 billion € for the

European production of bicycle parts and accessories (Colibi, 2013, p. 15). In sum, in2012 the approx. 50,000 employees of the German bicycle branch generated revenue of 4 billion €. With 71 million bikes in Germany, there are 80% cyclists among the population (ZIV, 2013b, pp. 62–63).

The average price per bike (513 €) in Germany is the second highest in Europe. This indicates that the quality requirements are accordingly high which is good for Pinion. The total revenue of 4 billion € within the German bicycle branch displays its potential (ZIV, 2013b, p. 62). Correspondingly, the total German bicycle market is very big and even the high-end sector of a submarket is very attractive with regard to the absolute numbers for a start-up like Pinion. There is still the option to potentially sell several thousand gearboxes (Pinion, 2013b).

It seemed logic for the two founders to start at the high-end market with high prices and low volumes. Not before the brand name has been shaped and an image of technological reliability has been developed, the mainstream market could successfully be addressed. Beyond that, it would not be possible for a start-up like Pinion to immediately purchase a large number of gearboxes due to their company infrastructure. Similarly, the bicycle manufacturers need to prepare their production as the P1.18 requires a design change of the frame (Pinion, 2013b). To sum up, choosing a market niche, like Pinion, seems to be the right way to commercialize a radical technological innovation like the P1.18 transmission.

Organization

The Pinion GmbH has officially been founded at the 29th of October 2008 in Stuttgart-Feuerbach. As the former company site gradually became too small, Pinion moved in April 2012 to larger production facilities to Denkendorf, near Stuttgart (Pinion, 2013a, p. 3). The two founders are entered in the commercial register as executive directors (Creditreform Deutsche Firmenprofile, 2014). By 2014, the two founders hold 23.24% of the company's shares each and the Pomian GbR (probably Pinion's main investor) 53.52% of the shares (Hoppenstedt Firmenprofile, 2014). Since the beginning of 2014, Pinion has nine employees, besides the two founders (Pinion, 2013b).

Strategy

It is Pinion's vision to develop and commercialize a competitive bicycle transmission in accordance with automotive standards. This bicycle transmission should become a natural alternative to the traditional bicycle shifting systems. Therefore, the two engineers have founded Pinion. Thus, it is the genuine purpose of the company to realize this vision. To reach this goal, Pinion developed primarily autonomously and waited a long time before presenting their gearbox to the public (Pinion, 2013b). At first, Pinion addresses the premium segment of the German mountain, trekking, and touring bikes market to get established. Later on, the company is targeting to cover the entire bicycle market in Germany, Europe, and finally, worldwide (Pinion, 2013b; Schäfer, 2013).

Structure and Processes

With nine employees and the two founders, the Pinion GmbH is a relatively small company. Hence, the structure and processes are relatively informal. There is a low power distance and little predefined processes with a low level of bureaucracy (Pinion, 2013b, 2014b). Thus, by 2014, the company had no organigram. In addition, the company is quite autonomous. Due to the fact, that the company was founded to commercialize the P 1.18 technology, it is not integrated into a coherent whole of an established concern structure. The total structure was established to foster the technology commercialization process. Furthermore, the investor does not force the team to follow strict milestone-plans but leaves the operational management to the two founders (Pinion, 2013b).

For the evolution of the highly innovative gearbox, this was beneficial as innovations could not evolve within tight structures and hierarchies (Holzschuher and Pechlaner, 2007, p. 45). Since 2012, Pinion has reached series production and therewith reduced uncertainty. The need to become more efficient with respect to its processes is obligatory. Therefore, Pinion hires experienced employees, such as a new assembly and quality assurance manager, in 2014, to establish clear structures for processes like purchasing and quality management. Additionally, Pinion thinks about getting certified according to the DIN EN ISO 9001. For the bicycle-branch, this is not a prerequisite. Thus, Pinion does not strive for it just for the sake of the certificate, but for being forced to establish certain structures and processes (Pinion, 2014b).

Company Culture

An innovation-friendly company culture is essential to successfully realize technological innovations. According to the interviewed founder, the company atmosphere is very good (Pinion, 2013b). The employees have a lot of ideas that are appreciated. In general, Pinion is quite open with respect to new ideas. Nevertheless, since the start of series production, the company has left its creative startup-phase. Now, Pinion has to prioritize the emerging ideas regarding the feasibility and rapid realizability due to certain obligations like concrete delivery dates. Being aware that this would hamper creativity, even more, the two founders are trying to hire experienced employees within the next recruiting round for establishing a solid company. With an eye to the future, they think of an independent advanced development division as a sort of creative pool for the development and realization of new ideas (Pinion, 2014b).

The commercialization of technological innovations is a highly uncertain endeavor and thus, the need for an intensive information exchange is great (OECD, 1971, p. 13). At the moment, Pinion's internal communication is primarily issue-specific and on an ad hoc basis. There are no regular meetings. In the case of an emerging topic or problem, the employees spontaneously walk and talk to the responsible colleagues. This leads to a rapid solution, but sometimes interrupts working processes and leads to a certain kind of inefficiency (Pinion, 2014b).

In addition, the team is growing and to keep everybody informed, team- and topic-specific meetings need to be implemented. Previously, such continuous meetings have been unnecessary as the team was small and worked together in the same office (Pinion, 2014b). A central knowledge management is not existent within Pinion. For archiving CAD-files, the company uses the integrated product data management system of SolidWorks, Pinion's CAD-system. The remaining data like Microsoft-Office-files is stored on a server solution (Pinion, 2014b).

Funding and Commitment

Gear manufacturing, in particular, the creation of prototypes, is expensive. Thus, the two founders decided to search for an investor even before they founded the company. Pinion had an advantage in their search since their product innovation was quite tangible. The majority of potential investors had a more or less close connection to the field of bicycles and furthermore, the advantages and disadvantages of traditional derailleur systems and internal hubs were easy to explain. Hence, it was not a big challenge for the team to get access to potential investors. The team carefully selected its partners and even neglected the cooperation with one investor due to bad gut feeling. Finally, the two engineers got to know their future investor at an event organized by the Technologie-Transfer-Initiative GmbH (TTI) (Pinion, 2013b). The TTI at the University Stuttgart is the central place to go for people, who need advice and support on all issues concerning company foundation (TTI, 2014). At this event, several founders had the chance to introduce themselves and their business concept to a group of investors. On this occasion, the Pinion team met an investor, who was a supplier of the automotive industry from Pfullingen and showed great interest in the project. After several discussions and tough negotiations, the team officially founded the company together with this investor in October 2008 (Pinion, 2013b).

In 2008, the team additionally received the EXIST-grant. This is a German government funding for the creation of start-ups. Repeatedly, the two founders applied for this sponsorship. Two times the application has been refused, during a period in which the two would have needed it most. When they finally obtained the grant, it was not absolutely necessary as they already found an investor (Pinion, 2013b).

By the end of 2008, the automobile crisis emerged quite fast and heavy. As the investor was active in the automotive industry, he informed the Pinion team in the beginning of 2009, that he was not able to further fund the company. He could not take the responsibility to invest risk capital into a start-up on the one hand, and send his employees into short-term work or even lay them off on the other (Pinion, 2013b). As a result, the Pinion team was left without an investor just a few months after contract signing (Reidl, 2012).

The involved people from the company of the first investor regretted their exit and tried to support building and establishing contacts. Consequently, the two founders got in contact with a person from Munich, who was originally meant to provide contacts to potential investors within his broad network. Educated as a physicist, he worked in science and was part of the management board of several German industrial concerns. Furthermore, he founded and sold his own venture. Now in his advanced age of about 70 years, he is investing in miscellaneous projects and start-ups (Pinion, 2013b). In the spring of 2009, the Pinion team arranged a meeting with him and presented their new gearbox design. Instead of exclusively discussing target markets and potential sales figures, the three were analyzing technical challenges and the details of the new design (Reidl, 2012). Beyond that, the future investor conducted a due-diligence investigation to work out in deep the main risks, strengths, and weaknesses of Pinion's business. Due to this intensive evaluation period, the three got to know each other very well and were on good terms. Subsequently, the future investor left rather acquire another investor for the Pinion team. One week later, he called and told the team that he would like to participate on an equity basis himself. The Pinion team signed a cooperation contract with him in October 2009 (Pinion, 2013b, 2013a, p. 2). The new investor enjoyed full voting right but left the operative management to the two Pinion-founders, who maintained their position as main associates and executive directors of Pinion (Pinion, 2013b).

With their new investor, the two founders were lucky, as he is enthusiastic about the product and provides not just money, but additionally technical and personal interest (Donner, 2012). Hence, he is not just an investor but mentor and consultant as well (Reidl, 2012). In the face of high uncertainties and long-time horizons, technological innovations pose specific challenges not only to the founders but also to the investor. Deep support, cautiousness, and goodwill of the investor are required to reach market maturity and commercial success (Meier, 2007, p. 282). In the case of Pinion, this becomes apparent, as the team developed over a period of seven years without selling a single product and generating revenue (Donner, 2012).

According to the interviewed founder, among the investor's motives have been the joy and the ambition to participate and shape the future of this promising project. Thus, he does not follow strict rules of general institutional investors regarding return expectations and exit strategies (Pinion, 2013b).

Since the conclusion of the contract, the partnership has been undisturbed. Once every six to eight weeks, both parties meet to discuss open issues and the current status. The investor is totally informed and the relationship bases on absolute mutual trust. Without this trust, it could have become pretty troublesome for Pinion, as there have been various challenges during initial production phases. In general, new developments take time in the mechanical engineering sector. This is what happened to Pinion. When the two engineers destroyed several prototypes on the test rig and the spare parts frequently had a delivery time of three to four months, the progress stagnated. As Pinion mainly trusts on suppliers of the automobile branch, its bookings steadily slip to the end of the order list in times of high capacity utilization. Especially in these situations, true investor commitment is crucial (Pinion, 2013b; Reidl, 2012).

Entrepreneurial Team

Since the beginning of 2014, Pinion has nine employees besides the two founders. The whole team is quite young with an age distribution of 26 to 36 years and is thus, very homogenous. The two founders are jointly responsible for managing the businesses of the company like financial affairs and negotiations with suppliers and customers. Additionally, they are working in the design engineering. By 2010, the first employee, a design engineer, was hired and is still on board by 2014. Furthermore, there are two sales representatives, two additional design engineers, an assembly worker, an assembly manager, a part-time accounting employee, and an office worker (Pinion, 2013b, 2014b).

According to the interviewed founder, the management and the team pull together and are highly motivated. They share a relaxed relationship among each other with a good atmosphere. The young, enthusiastic employees are very creative and have a lot of ideas. On the other hand, Pinion lacks experienced personnel that possesses serenity, sovereignty, and know-how to deal with challenging situations. The Pinion staff mainly consists of university graduates and first-time employees, who need to learn and expect guidelines from the management. The two founders are only able to make a limited contribution to providing the desired assistance, as they are equally doing it for the first time. Both are aware of this and are therefore planning to hire preferentially senior professionals within the next recruiting round (Pinion, 2013b, 2014b).

Innovation Process

Opportunity Identification

In 2006, the two founders got to know each other when they were working students at the engine and transmission design department within the Porsche R&D-center in Weissach, Germany (Pinion, 2013b). Soon, both detected that they shared enthusiasm not just for motorsport, but for mountain biking as well (Donner, 2012, p. 24). It was within this context that the initial idea for the foundation of a company emerged. However, it was not entrepreneurship for its own sake that was the focus of the Pinion team. Rather it was the ambition to solve the central technological challenge that drove them to start their own business (Pinion, 2013b). The two founders were unsatisfied with traditional derailleur systems with their typical problems of stuck chains, bent derailleurs, and the need for time-consuming care and maintenance after each ride. Internal hubs did not provide a real alternative since they are less efficient in certain gears, did not meet high standards regarding bicycle handling and dynamics, and have an unfavorable weight distribution (Pinion, 2013a, p. 3). The two founders asked themselves why there should be maintenance free gearboxes in cars and motorbikes but not in bicycles (Pinion, 2013b). Having found no satisfactory answer to this question, they decided to realize their vision of developing a competitive gearbox for bicycles in accordance with automotive standards in order to offer a real alternative to the traditional derailleur system. However, to get from mind to market, the team had to go a long way (Donner, 2012, p. 24).

Product Development

After idea generation in 2006, the two founders developed the initial concept further in parallel with their university education and their employment as working students at the Porsche AG, activities that naturally limited their available time. Starting with rough paper sketches, the team refined their ideas to gain first CAD-drafts (Pinion, 2013b). During 2006 and 2007, various transmission concepts were developed, discarded, and revised (Pinion, 2013a, p. 2). Ultimately, the team settled on one concept and elaborated it to such an extent that the main components were specified – practical realization seemed feasible (Pinion, 2013b).

In order to test their gearbox-prototypes, the two engineers installed a test rig and subsequently examined their first prototype in November 2008 (Pinion, 2013a, p. 2). When Pinion lost its first investor in the beginning of 2009, the team used the arising unoccupied time to thoroughly revise their design concept (Pinion, 2013b). The initial gearbox design contained three intermediate shafts (Pinion, 2013a, p. 2). During the manufacturing and testing of the prototype, the team discovered huge technical weaknesses of this initial design concept. According to the interviewed founder, in retrospect, this concept could not have been manufactured in serial production. As the former investor drove them by milestones and deadlines, the team probably would have been caught within this initial concept and forced to retain and refine it (Pinion, 2013b). Due to their obligations towards their investor, they just had no time to fundamentally optimize and question their invention (Reidl, 2012). Thus, the interviewed founder summarized, that the exit of the investor at precisely this point in time, has been a stroke of good fortune (Pinion, 2013b). Within the subsequent unoccupied time of the first half of 2009, the team developed a design concept with two transmitting shafts which was brought to serial production later on and which is equivalent to the current design of the gearbox (Pinion, 2013a, p. 2).

In December 2009, a newly developed test rig was commissioned (Pinion, 2013a, p. 3). On this test rig, the Pinion team tested primarily the load capacity and performance of the gearbox. Endurance and long-time tests have been conducted by experienced bikers on the track (Pinion, 2013b). The gearbox went through its baptism of fire when a friend of the two Pinion founders and extreme cyclist crossed the Himalaya riding a Pinion bicycle transmission prototype in the summer of 2010 (Pinion, 2013a, p. 2). The team felt slightly uncomfortable, but their friend knew the risk and dared the adventure carrying a replacement gearbox in his luggage. The prototype overcame the strains of the tour and this has led to a huge media attention (Reidl, 2012).

On the trade fair Eurobike 2010, the Pinion team exhibited an advanced prototype under the name Pinion P1 for the first time to the public (Pinion, 2013a, p. 3). Heretofore, the team has developed their innovation over four years without considerable contact to bicycle manufacturers. The reaction and response to the product were overwhelming and strongly motivated the team (Reidl, 2012). In the spring of the following year 2011, the first bicycle manufacturers began to develop a framework for the gearbox which bore the official name P 1.18 from then on. As a result, the first bikes equipped with a P 1.18 pre-series model were presented on the bicycle trade show Eurobike 2011. By the end of 2011, the team finally revised the design and lifted the P 1.18 from pre-series state to production standard. After that, general production began (Pinion, 2013a, p. 3).

Lead User Integration

It is decisive during the development process to ensure that the end product will match the market needs. Therefore, Pinion has conducted a market analysis in an early development phase and derived a requirements list together with a small bicycle manufacturer. Furthermore, the two founders themselves were passionate cyclists and had a broad network in the biking scene. Thus, they tested a lot on their own and discussed with friendly bikers. In due course, they involved lead users at testing gearbox prototypes to gain feedback. Primarily, these were skilled amateur cyclists that contributed to the product development by serving detailed feedback regarding performance and existing problems of the gearbox (Pinion, 2013b). Additionally, they provided concrete advice for modification, when they highlighted the potentials for improvement of the chain guide, a chain tensioner, or a gear indicator at the twist grip for instance (Donner, 2012, p. 25; Stahl, 2011). Besides this, several of these cyclists documented their trials in test reports that were published in diverse bike magazines. This generated publicity and increased the awareness for the new shifting alternative. Accordingly, the breakthrough of the P1.18 was accomplished when in 2010 their friend crossed the Himalaya. Therefore, he made an important contribution to the commercialization of the P1.18 (Reidl, 2012).

Development Partnerships

Within the mechanical engineering branch, reaching the minimal viable product to gain suitable market feedback is not easy. It takes quite long to develop a mature technological innovation and half-baked products can easily lead to negative market feedback. Especially for technological innovations negative market feedback during early development stages is commonly unfavorable as bad attitude towards an innovation is generally difficult to transform later on. Accordingly, Pinion developed primarily autonomously roughly over four years (Pinion, 2013b).

Within the early stages and test phase, the two bicycle manufacturers Endorfin and Hot Chili participated in Pinion's development process. Furthermore, Pinion involved some additional manufacturers until series production of the gearbox. Furthermore, Pinion had to cooperate with frame-builders as well that designed and produced the modified frames for the gearbox later on (Pinion, 2013b; Lermen, 2010).

Risk and Quality Management

Pinion had no structured risk and quality management system but used some methods to deal with risks and quality issues. In contrast to having a detailed risk analysis and evaluation procedure, the two founders mainly trusted their personal gut feeling and intuition. The interviewed founder assumed, that Pinion has only come this far not because, both founders did so many things the right way, but due to the fact that both refused to do certain things. In retrospect, they are happy that they have not accepted several offers or did not cooperate with certain firms. Mainly intuition and collective decision making after a short conversation were the base for their risk evaluation (Pinion, 2014b).

Another risk to deal with was the great technological challenge. As written above, the gearbox has to withstand a torque of 250 Nm. Due to the fact that the standardized calculation methods could not be applied for the P1.18 as they were designed for automobile gearboxes, a test rig was created. To simulate the effects of many years of use under realistic conditions in a short time frame, initially, a load spectrum of real-world peak forces was captured. By an iterative and empirical approach, the decisive parameters for designing a bicycle gearbox have been laboriously derived. Subsequently, the complete gearbox and each individual component were tested under repetitive use at extreme load to ensure durability and performance (Pinion, 2013b, 2013a, pp. 14–15, 2013a, p. 3).

In times of series production, Pinion receives roughly 100 elements of the gearbox from approximately ten suppliers from the Stuttgart region. Not all of them delivered the expected quality right from the start. Accordingly, the incoming goods inspection and the subsequent product test on the test rig played an important role in quality assurance (Schäfer, 2013).

One of the biggest risks Pinion still has to handle is the fact that its suppliers originate from the automobile industry. In times of economic upturn, Pinion will be the last to receive their products due to their lower purchase quantity. Pinion already suffered this condition when they had to postpone their launch of the first series gearboxes (Donner, 2012, pp. 25–26).

Platform Strategy

As far as possible, Pinion is trying to establish a common part and platform strategy. During the development of the 18-speed gearbox, the company has developed a modularized system with different components and mechanisms. At the conception of new products, these can be transferred with little modification as the basic development has been done. Accordingly, the fundamental shifting mechanism with its camshaft, pawls, and gearwheels is transferrable to any further product version. Equally, the sprocket geometry or the gearwheel design is versatile. At the establishment of a product family, this strategy approach could help Pinion (Pinion, 2014b).

Pinion's next product should be a gearbox with a reduced number of gears at a lower price level. The current P1.18 has a huge performance range with respect to the number of real shifts and its transmission ratio. According to the interviewed founder, average cyclists do not need this wide range of performance (Pinion, 2014b). Furthermore, Pinion has conducted a design study of an electric motor-gear unit for bicycles (Pinion, 2013a, p. 3). Nevertheless, in the medium term the company initially focuses on the classic gearbox transmissions (Pinion, 2014b).

Intellectual Property

It has not been possible to obtain a patent for the fundamental gearbox concept. The idea of a bottom bracket gearbox or a spur gear in the center of the bike was not new. Correspondingly, Pinion strives for protecting individual aspects of the principle concept. Primarily, several minor innovations for solving the technological challenge of the P1.18 form the main subjects of Pinion's patent applications. Recently, the company is trying to protect complementing parts like the shifting mechanism of the system. The team handed in their first patent application in October 2007. By 2014, Pinion had filed for eight to nine patent applications. Several of these have already been granted (Pinion, 2014b, 2013a, p. 2).

Pinion's scope of protection contains Europe, USA, and several Asian countries. Causally for this are market-relevant data and partly also the competitors' approach. In Europe, Germany, and the Benelux states are most important. As the European Patent Law admits an overall protection at reasonable costs, Pinion opts for this option. Furthermore, the company assesses the U.S. and Japan market to become critical for the future (Pinion, 2014b).

The IP-strategy of the company is also dependent on its financial situation. In general, Pinion strives for a patent protection with respect to inventions that are decisive for the consolidation and expansion of its market position from their point of view. According to the interviewed founder, Pinion could apply for more patents but due to the company's financial situation, it has to be selective. Using their patent portfolio as a strategic lever is correspondingly not focused (Pinion, 2014b).

The elaboration of Pinion's patent applications is done by a patent attorney from Stuttgart. Due to the intense cooperation, he is used to the mechanisms of the gearbox. Based on a brief invention description and some additional drawings, he is able to independently elaborate the applications. After an iterative process the patent applications are submitted (Pinion, 2014b).

Commercialization

Value Proposition and Business Model

Pinion does not directly sell their gearboxes to the end-user. The P1.18 transmission is solely available as an OEM component for volume bicycle manufacturers. Thus, they cooperate with several bicycle manufacturers, who are Pinion's customers and the de facto technology disseminators. Finally, the bicycle dealers sell Pinion equipped bicycles to the end-users (Pinion, 2013b, 2013a, p. 21).

Besides the technical and economic benefits (cf. relative advantageousness), the value proposition of a company is shaped by its service and social benefits (Wouters, 2009, p. 1028). Pinion tries to ease and support the use of its gearbox for its customers. As the P1.18 is not completely maintenance free, the company has uploaded several video guides to its homepage for each of the maintenance tasks to be carried out. Additionally, Pinion offers a complete spare parts program, a continually expanding range of accessories, and specialist tools through its conventional distribution channels (Pinion, 2013a, p. 27, 2013a, p. 22).

Furthermore, the company fosters the reputation of a high tech quality product that is able to give a signal towards urban mobility. Therewith, Pinion tries to shape the image of setting a social statement by choosing the P1.18 (Pinion, 2013a, p. 16).

Commercialization Partnerships

The bicycle manufacturers, in general, played a very important role. It was the biggest barrier to market entry to persuade them to apply the Pinion technology. At the start of series production in 2012, there have been 15 and by the end of 2013, 40 bicycle manufacturers offering Pinion equipped bikes with a steadily rising number (Pinion, 2013b, 2013a, p. 21).

All parts of the gearbox were completely developed and designed by Pinion and subsequently, fabricated in contract production by ISO certified suppliers. Like Porsche in the automobile industry, Pinion is a pure assembly-firm. Roughly 95% of Pinion's suppliers originate from the automotive supplier industry around the city of Stuttgart (Pinion, 2013b). On the one hand, this leads to a high level of product quality, but on the other hand, causes supplier shortages in times of economic upturn of the automotive industry (Donner, 2012, pp. 25–26).

With growing quantities of sales, Pinion is planning to build up new supplier relationships even for common parts to share the risk and reduce the dependency on individual suppliers (Pinion, 2014b). Further important alliances for the company exist with the dealers offering Pinion equipped bicycles. Looking at the dealer network in Europe (cf. Figure 59), it becomes obvious that Pinion's current sales focus is clearly situated on the German market with strategically selected distributors in foreign neighboring countries (Pinion, 2014a).

Figure 59: Pinion Dealer Network in Europe (Pinion, 2014a)

Timing

The optimal timing of entry is a crucial decision. Pinion has prepared their market introduction strategically. In 2010, the company exhibited at the trade fair Eurobike an advanced prototype (Pinion, 2013a, p. 3). According to the interviewed founder, the Eurobike which takes place every September in Friedrichshafen, is the most important bicycle trade fair in Europe and was correspondingly adequate for presenting their innovation to a broader publicity. The team deliberately chose their first trade fair attendance to be early and before reaching series maturity. As Pinion's customers need one to two years for preparing bicycle models for the usage with the P1.18 gearbox, Pinion had to assume the specific moment in time when the series maturity of the gearbox could be reached within the next one to two years. If the development would last longer, potential earnings could be lost. However, presenting the bicycle transmission too early would be unfavorable just the same. The emerging hype when showing the innovation to the public and the corresponding interest for the product could fade away if Pinion could not deliver for a longer period. Thus, not an easy decision, but all in all Pinion's assumptions were good as the company reached series maturity in 2012 (Pinion, 2014b).

Additionally, a fortunate coincidence pushed Pinion's prototype presentation at the Eurobike 2010. The Spiegel magazine reported in their Eurobike-article about Pinion just before the trade fair starts. Correspondingly, the attention of the visitors and media representatives at the trade fair was high (Pinion, 2014b).

Marketing

Pinion clearly addresses the premium market segment. Thus, the company is trying to position its gearbox as a high-quality, reliable, and long lasting bicycle component contrary to the putative disposable culture of the recent past (Pinion, 2013a, p. 8). Therewith, the company wants to emphasize its contribution to the modern urban mobility (Pinion, 2013a, p. 16). Pinion chose its sales strategy accordingly. To ensure the targeted quality and safety standards of the final bicycle, the company just sells its P1.18 transmission as an OEM component for volume bicycle manufacturers working to a high industrial quality standard. Thus, the gearbox is currently not available to the public via wholesale and retail (Pinion, 2013a, p. 21).

The company strategically plans its marketing efforts. In 2010, Pinion eventually exhibited for the first time on the Eurobike. The interest and enthusiasm were great and surprised the team as they had nearly no contact with the public before. Hence, it pushed the team and strongly motivated them for their further development and market introduction (Reidl, 2012). Since then, Pinion steadily exhibits at the Eurobike and presents its innovations to the public. After the first P1.18 series products were produced, bike manufacturers were equipped with sample gearboxes to attract them (Pinion, 2013a, p. 3). At consciously chosen times, the team involves journalists to highlight its products. Additionally, Pinion provides links to certain test reports of the gearbox via its homepage (Pinion). Furthermore, Pinion cooperates with an external marketing agency regarding issues like the external presentation of the company, corporate design, creation of the homepage, and generation of its image brochure (Pinion, 2013b).

Innovation Success

Sales Performance

With the start of series production in 2012, Pinion cooperated with 15 bicycle manufacturers and ended up with three-digit sales figures. 2013 Pinion generated with 40 manufacturers a low four-digit sales figures and roughly 1.1 million € revenue. The number of collaborations with bicycle manufacturers is rising on and on. Pinion expects to reach sales figures of a mid-four-digit range within the next years (Pinion, 2013b).

According to the interviewed founder, on a scale from great skepticism, if Pinion will still have a product on the market in the future until the P1.18 is a natural alternative to the established shifting components, Pinion is positioned right in the middle. By the end of 2013, he stated, most of the bicycle manufacturer have realized that the Pinion transmission is not just a flash in the pan, but will be a long-time business (Pinion, 2013b).

Product Performance

Since the Pinion P1.18 entered series production, more than 1,000 gearboxes have been sold by 2014. The gearbox is a mature product that meets its high requirements with respect to load, durability, and performance (Pinion, 2013a, p. 3). Several benchmark tests have been conducted and the reaction and response to the gearbox were predominantly positive (Reidl, 2012).

In comparison with the alternative shifting systems, the Pinion P1.18 has concrete advantages as well as concrete disadvantages (cf. relative advantageousness). Therefore, it is essential to hit the customer preferences of the chosen target group, mountain bikes and trekking and touring bikes. In both markets the P1.18 is beneficial (Pinion, 2013b, 2013a, p. 5).

For the creation of the P1.18, Pinion was awarded the BIKE Milestone Award for the best bicycle component of 2011 (Pinion, 2013a, p. 3).

Efficiency

According to the interviewed founder, one of the decisive factors at commercializing technology is to possess an immense power of perseverance. He estimates that it takes seven to ten years from idea emergence of a technological innovation to its full establishment in the market. Since the idea generation of the Pinion gearbox, it has been seven years and risk of failure still exists. Therefore, it is important to take the time that is needed to develop a technological mature product and not to bring half-baked development results to the market. Being efficient is important, but just being fast is not the preferred method to take when it comes to the development and commercialization of radical technological innovations (Pinion, 2013b; Reidl, 2012).

However, for the sake of efficiency, the development costs need to be kept down. The founders did not take high salaries and firstly worked with student licensees of their CAD-software SolidWorks. Not before company foundation, they finally bought a full license (Pinion, 2014b). As gearbox manufacturing is expensive and prototypes, in particular, the team tries to save costs as far as possible. Initially, the prototypes have been tested externally on an automobile gearbox test rig. Since this was very expensive, Pinion decided early to develop and build its own test-rig (Pinion, 2013b).

Interestingly, the interviewed founder stated that the time at the Porsche R&D-center has not helped them to develop the P1.18 gearbox. According to him, the influence of Porsche with respect to the fundamental technique has been marginal and is mainly limited to inspiration. The team has not transferred any concept of Porsche gearboxes to their bicycle gearbox. Furthermore, no employee of Porsche helped them with their development and their engagement as working students did not enable them to gain deep insights into Porsche's process structures (Pinion, 2014b).

4) Case Study Report – Friction Disc by SKF

Technology

The requirements for power transmission within the industrial drive branch increased over the recent years. To satisfy this demand SKF engineers developed an innovative coating system for highly loaded flange couplings to increase the friction coefficient between the contact surfaces. Consequently, the frictional locking and correspondingly the power transmission could be significantly enhanced. In general, there are two influencing variables of the frictional locking: the friction coefficient and the normal force ($F_R = \mu \cdot F_N$). SKF addressed the frictional coefficient with the Friction Disc (Gläntz, 2011).

A defined sum of sector shaped elements each with three holes forms a ring-type device (cf. Figure 60). This device with an optimized friction coefficient is inserted in a bend-proof flange coupling and fastened with screws. The two flanges match up with the ring-type device. They are designed with through holes and threaded blind holes for mounting (Baumann, 2009, p. 35; Gläntz, 2011).

The contact surfaces of the two flanges are required to have a certain degree of Ra-roughness. The sector shaped elements of the ring-type device are coated with a galvanic hard-dispersion layer (cf. Figure 2) on both sides (Baumann, 2009, p. 36; Horling *et al.*, 2009, pp. 2–3).
This hard-dispersion layer is galvanically applied in two layers on the surface of the ring-type device which serves as a coating substrate (cf. Figure 3). The first nickel layer has a wetting purpose (Baumann, 2009, p. 36).

Figure 60: Friction Disc (Gläntz, 2011)

Thus, the second nickel layer has a much better basis for adhesion. This coating layer contains hard particles. The thickness of the two layers corresponds to approximately half of the average grain size of the particles. As the coating layer consists of galvanically applied nickel, the coating substrate is simultaneously protected against corrosion. The adhesive force of the nickel causes a solid embedding of the hard particles within the layer (Baumann, 2009, pp. 36–37; Horling *et al.*, 2009, pp. 2–3).

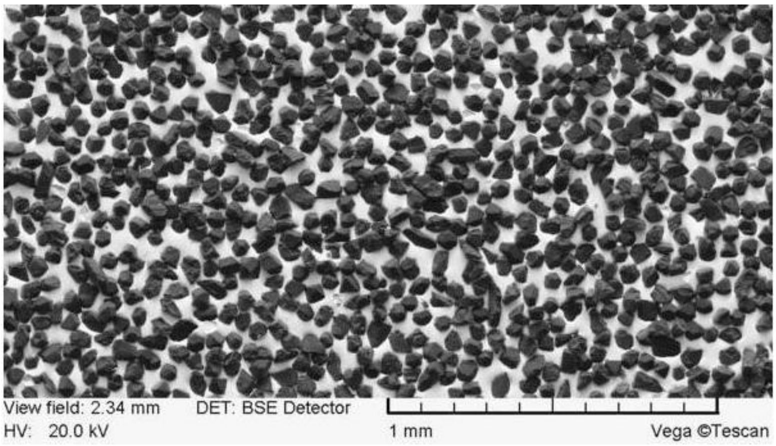

Figure 61: SEM Picture of the Coating with Integrated Hard Particles (Gläntz, 2011)

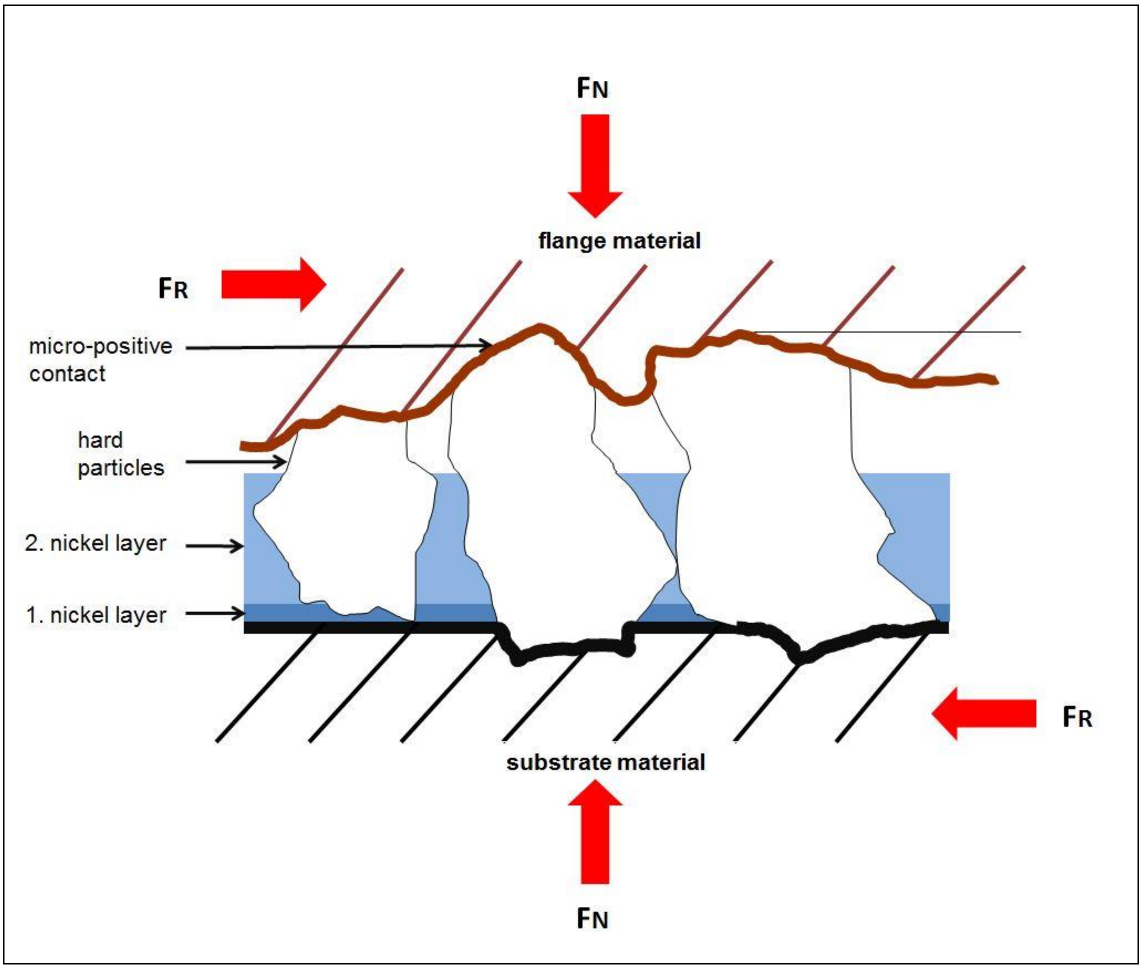

Figure 62: Schematic Diagram of the Coating (Baumann, 2009, p. 37)

It is advantageous to use a substrate material that is harder or at least equally hard or has a higher tensile strength than the material of the flanges. Thus, the particles rising up out of the coating layer would primarily press into the flanges and not into the substrate material. As the flange material of spheroidal-graphite cast iron has been defined by SKF's customer, SKF took a high-strength cold forming steel as a substrate material. If the coated ring-type device gets screw-fastened with the flange coupling, the hard particles will be pressed into the flange material. Thus, a mechanical interlock – a micro-positive contact – will be attained between the device and the two shaft ends (Baumann, 2009, p. 43, 2009, p. 38; Horling *et al.*, 2009, pp. 2–3).

Based on a conservative approach, the friction coefficient μ of the Friction Disc is 0.65. Further tests revealed even higher results showing that the SKF solution offers a high level of performance reserves and security against slipping. Furthermore, the long-time behavior and variation of the friction coefficient after several assembly and disassembly procedures was tested. It was found that the friction coefficient differs just slightly and the first prototypes withstood the practical test of two years without notable damages (Gläntz, 2011).

Table 14: Technical Data of the Friction Disc (Baumann, 2009)

Friction Coefficient	$\mu \geq 0.65$
Contact Pressure	80 – 150 MPa
Coating Layer Material	Nickel
Substrate Material	Cold Forming Steel
Flange/Shaft Material	Spheroidal-Graphite Cast Iron

Feasibility and Maturity

The Friction Disc is a mature product that was introduced to the market in 2009. By 2014, every wind turbine of SKF's customer in the 3.3-MW-class was equipped with the discs and a middling three-digit number of pieces have been sold. This is the result of a cooperative and intense development of SKF and its customer. The performance of the Friction Disc meets the customer requirements in all aspects and this was proven by field tests. By 2014, the Friction Disc was a certified product and the friction coefficient of 0.65 has been certified by an accredited certification organization (SKF, 2014b, 2014d).

Technological Alternatives

The Friction Disc is meant to increase the friction coefficient and thereby the power transmission capacity of the flange coupling. Investigations show there is just one other alternative in the market that is based on the same technological principle – 3M Friction Shims. Of course, another possibility is to just use the blank flange coupling instead on any intermediate objects. By 2014, this became the de facto standard in the market. Another credible technological alternative is the application of shrink discs. In this technology comparison, the focus will be on hydraulically adjustable shrink discs, especially as the ease of assembly has great advantages for the current application. Furthermore, some original equipment manufacturers utilize friction increasing pastes or coatings on the face side of the flanges. However, this is a complex process and is not considered to be a robust method. Consequently, the latter alternative will not be taken into account within the paper at hand (Baumann, 2009, p. 1; Gläntz, 2011).

3M Friction Shim

The functional principle of 3M Friction Shims is very comparable to the Friction Disc technology of SKF. It is based on diamond particles embedded in a Nickel matrix. The coating is applied on thin steel foils. 3M serves three shims versions. For the application of flange couplings, the largest foil version is more suited. Thereby, the Nickel matrix has a thickness of 14 to 22 μm and the particles have a mean size of 35 μm. The complete thickness of the shim corresponds to 0.185 mm. At mounting, the diamonds are pressed into the counter surface and micro-positive contact is generated. According to 3M, static friction coefficients μ of up to 0.6 are possible. This creates the possibility for lightweight compact designs while the potential load and peak torque in bolt connections could be increased (3M, 2015a, 2015b, p. 2, 2015c).

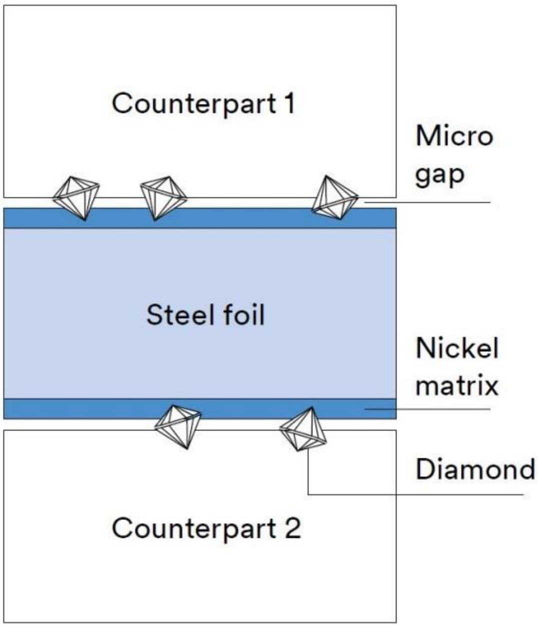

Figure 63: 3M Friction Shim (3M, 2015a, p. 1)

Blank Flange Coupling

Flange couplings, in particular, rigid non-shiftable types, are used to transmit the operating torque in industrial drive trains by frictional connections. A defined amount of screw connections generate a preloading and thereby a strong joint between the two flanges that ultimately transmits the power. Most common is the material combination of steel-steel or steel-cast iron. In the case of blank flange couplings, according to technical literature, the friction coefficient for these material combinations range from μ = 0.12 to 0.2 (Baumann, 2009, p. 1; Gläntz, 2011).

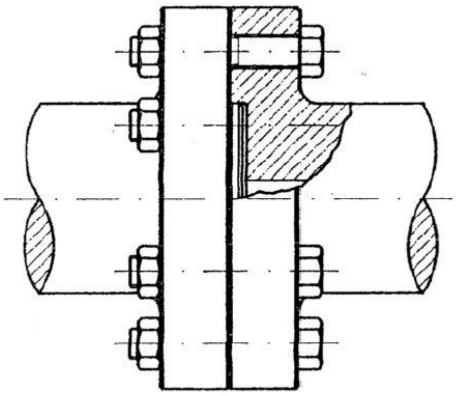

Figure 64: Blank Flange Coupling (Kurzawa, 1993)

Shrink Disc

Shrink discs produce force-fit shaft-hub connections. In the case of linking the rotor with the generator shaft within the drive train of a wind turbine, the shrink disc has to be integrated into the generator shaft. Due to the tapered surfaces of the exterior components the inner diameter of the shrink disc will be reduced by axial displacement. A corresponding interference fit between the shaft and the hub is generated. Thus, the shrink disc is not within the power flux as the torques and forces are transmitted at the joining surfaces of the shaft and the hub by force fit (Ringfeder, 2015).

Figure 65: Shrink Disc (Michel, 2011)

The required preload will be applied hydraulically. It is possible to use a hydraulic hand pump, as only a small amount of oil is needed to generate the required pressure (Michel, 2011).

Relative Advantages

To gain the relative advantages of the SKF Friction Disc compared with the alternatives, eight evaluation criteria have been established in consultation with a team member of the Friction Disc project at SKF: power transmission, robustness of solution, downsizing potential, cost saving potential, assembly/disassembly process, resistance to environmental impacts, design leeway, and price. The analysis is carried out with respect to the blank flange coupling as this is the de facto standard joint in the field.

Power Transmission

Power transmission is dependent on the strength of the joint between the shaft and the hub. The working principle of the joints of the Friction Disc, the Friction Shim, and the blank flange coupling is the same as all are based on the use of flange couplings and correspondingly frictional connections. As mentioned before, the two influencing variables of frictional locking are the friction coefficient and the normal force. The friction coefficient of the Friction Disc equates to a value of at least $\mu = 0.65$. In comparison, 3M Friction Shims may have a maximum static friction coefficient of 0.6 and the friction coefficient of blank flange couplings ranges from $\mu = 0.12$ to 0.2. If a comparable normal force is assumed for these three options, the Friction Disc has the highest value, followed by Friction Shims and the blank flange couplings. The shrink disc, on the other hand, is generating an interference fit which results in the transmission of a very high level of torque (3M, 2015b, p. 2; Gläntz, 2011; Michel, 2011).

Robustness of Solution

Especially in the case of highly loaded drive trains of wind turbines the robustness and reliability of the applied solution is vital. Based on a conservative approach, the friction coefficient of the Friction Disc equates to $\mu = 0.65$ with this value having been certified by an accredited certification organization. Further tests showed even higher results with the conclusion being that the SKF solution offers a high level of performance reserves and security against slipping. Furthermore, the long-term behavior and variation of the friction coefficient after several assembly and disassembly procedures was tested in a demanding application of wind turbines. It was found that the friction coefficient just differs slightly and the first prototypes withstood the practical test of two years without notable damages (Gläntz, 2011). 3M Friction Shims have been applied, tested, and certified by an accredited certification organization within the automotive industry. However, this solution has not been approved yet for the more demanding application of wind turbines that is characterized by a completely different load distribution (3M, 2015b, p. 2). Blank flange couplings are the conventional standard approach and are thus reliable. But in the case of increasing the power range of the turbine, the main dimensions and particularly the screw connections have to be redesigned. This is partly due to higher specific loads which may lead to a critical level on individual components (Gläntz, 2011). However, shrink discs provide a robust solution in the given power range and do not require any maintenance (Ringfeder, 2015).

Downsizing Potential

As the power class of wind turbines has increased massively over recent years, keeping the weight of individual items within the nacelle under control has become an important issue. Higher power transmission requirements lead to the need for more bolted joints and thus, bigger dimensions of the flange coupling. The SKF Friction Disc could help to solve this challenge. For the wind turbine of SKF's customer, it was possible to significantly reduce the number of bolted joints at the same power transmission capacity. Thus, the main dimensions of the flange, the gearbox housing, and the neighboring bearings could be reduced resulting in a significant weight reduction (Gläntz, 2011). Equally, the usage of 3M Friction Shims enables a reduction of the component sizes and weights and hence the weight of the complete drive train. Compared to the Friction Disc, this reduction is less due to the lower power transmission capacity (3M, 2015b, p. 1). Concerning the high component weight of shrink discs, there is no overall weight reduction potential. Instead, the overall drive train becomes heavier when using shrink discs (SKF, 2014d).

Cost Saving Potential

Due to the reduction in dimensions resulting from the Friction Disc and the Friction Shim, a considerable amount of costs for the individual components could be saved. Furthermore, shrink discs and the Friction Disc have lower requirements regarding the surface tolerances. Thus, certain cost savings during the production process of the shaft and the flanges could be realized (SKF, 2014b; 3M, 2015b, p. 1; Ringfeder, 2015).

Assembly/Disassembly Process

One key customer requirement is multiple usages, at least five to six times, of the utilized components. Consequently both, the assembly and disassembly processes are important factors for the reusability of a potential solution. When using conventional flange couplings, the assembly process requires specialized tools to generate the required preload. In the case of disassembly, specialized tools are also needed, as the joints have often experienced severe wear or even massive seizure. The Friction Disc allows comparatively easy, cost effective assembly and disassembly procedures. For hydraulic shrink discs, both processes are even easier as the use of hydraulic hand pumps allows straight forward easy handling. Friction Shims, on the other hand, are not as simple to handle. In particular, fixing during assembly is more difficult. In general, multiple usages are possible, but sometimes the foils stick at the flange surfaces and are not easily removable (SKF, 2014b, 2014d; 3M, 2015b, p. 1; Gläntz, 2011; Ringfeder, 2015).

Resistance to Environmental Impacts

The joint fit has to resist environmental effects like moisture, contamination or salty air. Correspondingly, blank flange couplings face some problems as these influences could ultimately lead to a seizure. Friction Discs and Friction Shims are comparatively insensitive against contamination and even friction-reducing media. In the case of shrink discs, the fitting surfaces have to be cleaned before mounting. However, at the run time no dust, contamination or moisture should reach the functional surfaces (3M, 2015b, p. 1; Gläntz, 2011; Ringfeder, 2015).

Design Leeway

The required safety factors for wind turbines with given external forces and torques give just little leeway for designers to create innovative solutions. Thus, the blank flange coupling concept and equally the shrink disc concept dictate the corresponding embodiment design. In contrast, the higher power transmission capacity of the Friction Disc and the Friction Shim allow new opportunities to be realized within the design process. As the Friction Disc is able to transmit higher forces and torques than the Friction Shim, the Friction Disc reached the highest level of the four alternatives regarding design leeway (SKF, 2014d; 3M, 2015b, p. 1; Gläntz, 2011).

Price

With regard to the price level, the whole technical system has to be considered in the evaluation. Therefore, the price for a standard flange coupling has to be added to the prices of the individual components of Friction Shims and Friction Discs. Thus, the lowest price is generated by blank flange couplings as no additional components are required. Compared with the Friction Disc, 3M Friction Shims are cheaper. Shrink Discs exhibit the highest overall price (SKF, 2014b, 2014d; Baumann, 2009, p. 1).

Overview of the relative Advantages of the Friction Disc

To gain a better overview of the relative advantages of the Friction Disc, the different technological alternatives have been evaluated with respect to the degree to which they meet the eight evaluation criteria on a ten-point scale (cf. Figure 7).

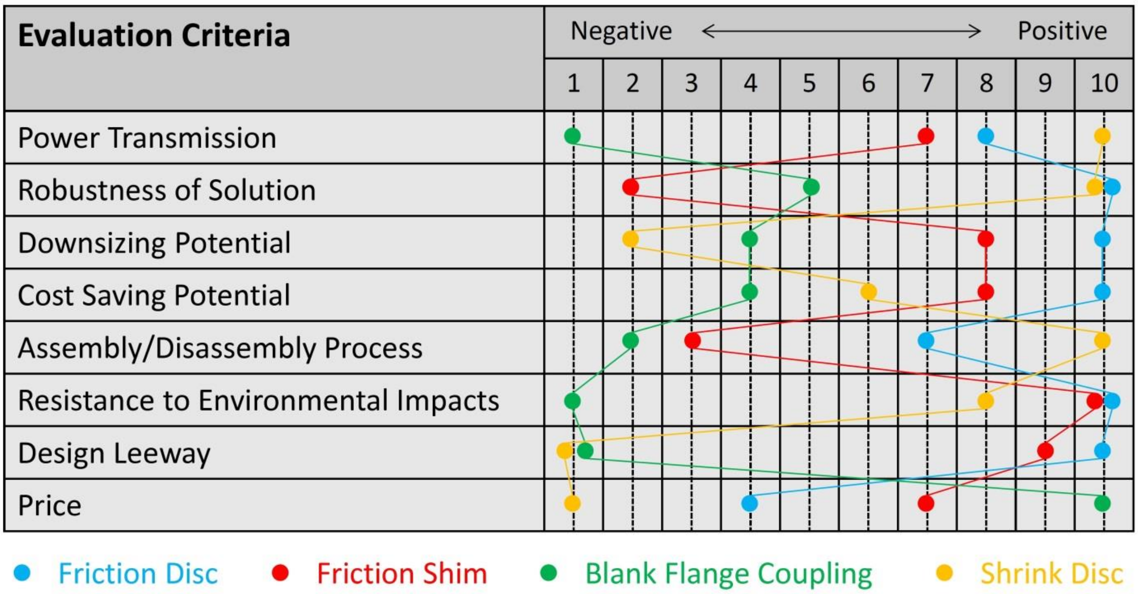

Figure 66: Overview of Relative Advantages of the Friction Disc

The unique advantage of the Friction Disc compared to its alternatives is the great downsizing potential for the wind turbine that ultimately can lead to a huge cost saving. The Friction Disc offers much leeway for the designer and opens up great opportunities to create new and innovative solutions. However, the corresponding price of the Friction Disc has to be considered. Regarding the global trend of massively increasing power classes for wind turbines, particularly offshore, the Friction Disc offers a great opportunity for keeping the overall weight within the nacelle to a minimum. In general, it is essential for the ultimate success of a radical technological innovation to clearly address the key requirements and needs of the target market. Therefore, the specific target market of the Friction Disc will be assessed in the following chapter.

Target Market

The field of application for the Friction Disc is heavy mechanical engineering. Initially, the wind industry was addressed as a first target market. In 2006, the development was started for Senvion's 3.3-megawatt onshore turbine. SKF and its customer established a development contract and assured mutual exclusivity within the wind industry. Thus, SKF became single supplier (SKF, 2014b, 2014d; Law, 2012, p. 5; Senvion, 2014, p. 1).

Senvion is a global manufacturer of onshore and offshore wind turbines. Its product portfolio comprises wind turbines with nominal powers of 2.0 to 6.15 megawatts. The company's core expertise lies in the production and installation of wind turbines. SKF's customer develops, manufactures, sells and erects. With more than 3,700 employees it has installed more than 6,100 wind turbines globally. By 2014, the company has in Germany a market share of 9% in terms of installed wind turbines (IWES, 2015, p. 40, Senvion, 2015a, p. 10, 2015b).

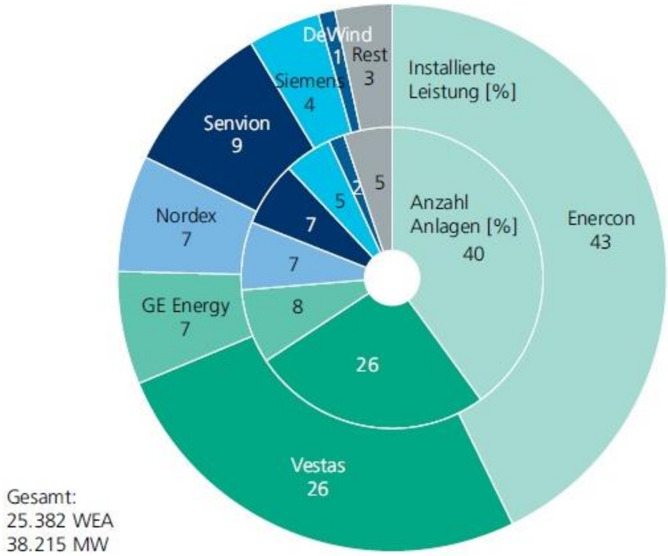

Figure 67: German Market Share of Onshore Wind Turbines by 2014 (IWES, 2015, p. 40)

Industry Context

The industry of the Friction Disc technology has been mainly positive. Wind energy has been clearly on the rise. During 2014 more than 51 Gigawatt's installed capacity have created an unprecedented increase. In Germany, the share of electricity generated from wind energy made up nearly 10% of the gross electricity consumption. With 28%, overall the renewable energies delivered the highest share of the gross electricity consumption compared to any other energy source in 2014. Politically, these are important steps for the intended energy turnaround (IWES, 2015, p. 5). Consequently, this resulted in a clear trend towards larger power plants and massively increased power ranges. The challenge of minimizing the individual component weights within the nacelle presents a huge opportunity for the SKF Friction Disc (SKF, 2014b; Gläntz, 2011).

However, there were also factors that hamper the acceptance of the Friction Disc in the industry. By 2008 and 2009, the global economic crisis reduced the confidence of the team and hence the speed of implementation (SKF, 2014d).

Competitive Situation

SKF is single supplier of the Friction Disc. Consequently, no other competitor is allowed to deliver a similar product for this specific application (SKF, 2014d; Law, 2012, p. 5). Thus, SKF has just to compete with its technological alternatives which have been introduced and compared previously. However, SKF needs to be aware of emerging and established market rivals that potentially could offer alternatives to their innovation (Schilling, 1998, p. 277).

Market Barriers

A general prerequisite to entering the wind energy market is the certification process. Any technical product has to be certified by an accredited certification organization before being used in a wind turbine and this also applied to the Friction Disc. Together with the TU Chemnitz, SKF applied and tested the friction coating. Ultimately, the team managed to achieve the required certification and thereby the permission to enter the market (SKF, 2014b, 2014d). Further market barriers were the requirements of SKF's customer, but SKF was able to satisfy the customer needs (SKF, 2014b).

Opportunity

Due to the mutual exclusivity contract of SKF and its customer, the success of the Friction Disc was clearly linked to the success of SKF's customer. Their 3.3-MW wind turbine was characterized by competitive energy efficiency, weight distribution advantages, reliability, and size. In profitability assessments of potential investors, the turbine was well ranked. This ultimately led and still leads to good sales figures for SKF's customer (SKF, 2014b, 2014d).

As mentioned previously, the wind energy industry is clearly on the rise. In the last few years, there is a clear trend to more powerful wind turbines. By 2014, the 3 to 4-MW class turbine size had considerably expanded and nearly reached the same installation rate as 2 to 3-MW class turbines. The latter category dominates the market (IWES, 2015, p. 38, 2015, p. 36). By then, the achieved volumes supported the commercialization of the Friction Disc and pushed its success. However, as this trend further evolves the 3.3-MW turbine may be outdated in the near future (SKF, 2014d).

Besides the wind industry, there are additional opportunities for the Friction Disc particularly in applications where the requirement is to transmit high torques by rigid couplings, e.g. in industries like rolling mills, turbo-machines, marine and marine renewables, or power plant constructions (SKF, 2014b, 2014d).

Organization

The Friction Disc has been developed within SKF Germany. The SKF Group is a leading global supplier of products, solutions, seals, mechatronics, services associated with roller bearings, and lubrication systems (SKF, 2015, p. 1). By 2014, the company had more than 48,500 employees and generated net sales of 7.6 billion € (SKF, 2015). In 2006, the project was initiated within the innovation department Flexi Force and was later transferred to the project management department New Business. Following on from this, it was carried out by a cross-functional/divisional team (SKF, 2014d).

Strategy

SKF's vision in the recent years is "[t]*o equip the world with SKF knowledge. To take all the knowledge gained over more than 100 years to develop and deliver products, solutions and services which enable customers to be more successful and profitable in their business*" (SKF, 2015, p. 29). Therefore, the company established the SKF Care strategy model with four dimensions: Business Care, Environmental Care, Employee Care and Community Care. These four categories are the guiding principles of SKF in terms of how they operate and do business (SKF, 2015, p. 11).

For the Friction Disc project, Business Care and Environmental Care were especially relevant. Within the project, a dedicated customer focus when delivering sustainable value was realized (→ Business Care). Furthermore, SKF wanted to provide customers with innovative technologies, products, and services that reduced environmental impact (→ Environmental Care). Both dimensions were perfectly addressed by the Friction Disc. The product offers a great downsizing potential for the overall wind turbine drive train that ultimately leads to huge cost savings and reduces the environmental impact when serving a renewable energy device (SKF, 2015, p. 11).

The objectives of Flexi Force and New Business were complemented within the Friction Disc project. Thus, the Friction Disc project was actually in line with the SKF group goals as well as with the Flexi Force and New Business department goals (SKF, 2014b, 2014d).

Structure and Processes

Since the project started in 2006, there have been two reorganizations of SKF's structure. As of 1st January 2015, SKF merged its two industrial business areas, Strategic Industries and Regional Sales and Service to be more efficient in addressing industrial customer needs. Since then, SKF operates through three business areas: Industrial Market, Automotive Market, and Specialty Business. Although the Friction Disc project was included within the industrial market, finding a suitable product home was a challenge for the team (SKF, 2015, p. 35). The standard portfolio of SKF contains rolling bearings and units, seals, mechatronics, services, and lubrication systems. As the Friction Disc could not be allocated to one of these categories, the former tooling and prototyping machine shop was chosen to become product home (SKF, 2014b, 2014d).

The product innovation process of the Friction Disc was realized based on the SKF internal New Customer Offer (NCO) process. This development process is mainly based on the Stage-Gate process according to Cooper and is meant to develop and launch a product for one specific customer. This process worked well and allowed enough flexibility for the team. On the other hand, the transfer into series production turned out to be more difficult. The Friction Disc was meant to be a niche product. However, the SKF is well positioned to handle high volumes, but the handling of brand-new innovations is a different challenge due to initially low volumes (SKF, 2014b, 2014d).

Company Culture

The overall company culture within SKF was mainly shaped by a low level of failure acceptance and little appreciation for radical innovative initiatives like the Friction Disc. Accordingly, this situation presented real challenges for the Friction Disc project. In the beginning, the team had to defend their project against tough internal criticism. This situation lasted until the first testing of the Friction Disc showed very good results (SKF, 2014b, 2014d).

Funding and Commitment

Initially, it was not easy to persuade project sponsors and stakeholders to support the Friction Disc project and invest in validation testing and analysis. It was important for the success of the project that the first test results turned out to be positive. Following this, senior management supported the project and sanctioned any project expenses without major discussions having to take place. Due to the organizational structure of the SKF, project budgeting was difficult from the beginning. Especially for urgent cash requirements this situation was unfavorable. Thus, it was essential to maintain the high level of upper management commitment so that the team could overcome these hurdles. The support from upper management was not only for the funding aspect important but also when it came to production priorities. This helped considerably when a short-term availability of the manufacturing facilities was required for prototype production (SKF, 2014b, 2014d).

Entrepreneurial Team

During the innovation process, the core entrepreneurial team within SKF consisted of three people: an innovation manager, a project manager, and the key account manager for SKF's customer. The people fulfilling these roles had a high level of experience and professional competence. The innovation manager had very specific knowledge regarding coatings that he gained throughout his career as an engineer in the production line. The project manager was very familiar with the technical aspects and requirements of power transmission applications due to his previous job as an application engineer, whilst the key account manager provided insights into customer needs. Having these attributes meant that, the team saved a lot of time and costs during the innovation process of the Friction Disc (SKF, 2014b, 2014d).

Despite several setbacks during the project caused by internal and external skepticism and contradictions, the core team members showed great perseverance. They were highly motivated to bring the project to a successful conclusion and were convinced of its potential. Furthermore, they trusted each other and worked as a team (SKF, 2014b).

After the development contract with the customer was signed, the core team was joined by further representatives from production, design, and quality management. Having this broad and profound team network in place ensured an efficient innovation process. Due to contrary objectives of daily and innovation business, challenges emerged, e.g. in the case of prototype versus high volume production on the machines of one manufacturing channel (SKF, 2014b, 2014d).

Innovation Process

Opportunity Identification

SKF's key account manager had to constantly have his finger on the pulse when it came to the customer and had to monitor the market closely. Therefore, in 2006, he realized that SKF's customer faced technical challenges during the conception phase of the 3.3-MW wind turbine, the largest onshore wind turbine at that point in time. A major challenge was to design the turbine in such a way that it was still transportable on the streets. Thus, the customer needed a solution that was compact, reliable, and feasible (SKF, 2014b, 2014c, 2014d; Baumann, 2009, p. 1).

Based on discussions with the customer and joint brainstorming sessions, the core project team worked on a possible solution. From this, an idea emerged that a friction increasing intermediate disc for flange couplings could enhance the transmissible torque capacity. Until that point in time, the intended friction increasing coating procedure had just been applied for relatively small surfaces like drills and tools. Thus, the team followed an iterative process to align the application requirements to the product (SKF, 2014b, 2014c). In general, the timing was right as SKF's customer was just developing its new 3.3-MW wind turbine and needed an adequate technical solution (SKF, 2014b).

Product Development

After idea generation, the concept of the Friction Disc had been verified by conduction of several preliminary friction tests. The idea had been checked to determine if it had the potential to be utilized for bigger surfaces as well. Afterward, during the validation phase, several tests had been conducted to optimize the material composition and the particle density of the coating. After prototype testing, the Friction Disc had reached application maturity and could be introduced to the market (SKF, 2014b, 2014d).

Lead User Integration

SKF's customer was similarly lead user of this product. According to Eric von Hippel, lead users face needs that will be general in a marketplace but face them earlier than those in the mainstream market. Furthermore, they benefit significantly by obtaining a solution to those needs (Hippel, 1986, p. 796). This was the case with SKF's customer when the company developed one of the biggest onshore wind turbines at that point in time and needed a solution to transmit the high torques. SKF and its customer initially signed a non-disclosure agreement and subsequently concluded a development contract as a basis for their cooperation. Thus, SKF's customer was closely integrated into the product development and was updated frequently on a regular basis. A further benefit was that SKF had a reference case in the market with the Friction Disc was proving itself in a real life running environment. After two years in use, the first Friction Disc prototypes were dismantled and showed almost no traces of wear (SKF, 2014b, 2014d).

Development Partnerships

SKF involved two further strategic partners in the development process of the Friction Disc. One of these partners was the company that took responsibility for the coating process. SKF deliberately selected this company because of their previous experience in coating parts with comparable dimensions for industrial use. With optimized parameters high process reliability could be realized (SKF, 2014b, 2014d). Furthermore, SKF chose the technical university of Chemnitz as a strategic partner for testing the ultimate friction coefficient of the Friction Disc. Previously, SKF had contacted several scientific institutes and universities that were unable to deal with these high values of the friction coefficient. The technical university of Chemnitz had the essential equipment and could prove their expertise by their participation in several comparable industrial projects (SKF, 2014b, 2014d).

Risk and Quality Management

During the process, SKF undertook a detailed risk assessment and followed a strict quality management process. As mentioned before, the product innovation process of the Friction Disc was based on a Stage-Gate process. Consequently, the progress of the process was constantly reviewed at certain milestones by a project committee. Furthermore, SKF has high quality standards for their own production and suppliers. This quality standard is realized by detailed specifications for production and the final product. The first requirements for the Friction Disc were formulated and subsequently validated by having adequate test procedures in place. However, formulating a reliable test procedure for the Friction Disc was one of the main challenges of the product development process. Together with the technical university of Chemnitz the team ultimately managed it to reliably test the friction coefficient. Based on the validated test results, the internal production and the supplier specifications were elaborated (SKF, 2014b, 2014d).

An essential part of quality management within the product innovation process is risk management. Potential risks from technical as well as from a market perspective were constantly analyzed in short intervals by the team. Every risk and its possible countermeasure was discussed and subsequently documented in detail (SKF, 2014b).

Platform Strategy

The basic result of the Friction Disc product development process that SKF finally achieved was an assured coating process. This process could be utilized not just for the Friction Disc, but for many other shapes of blanks. There is no geometric limit besides the fact that the parts need to be placed in the coating bath. According to the project manager of the Friction Disc project, the interest in the power transmission branch is quite high for such friction increasing coatings (SKF, 2014d).

In general, the Friction Disc is not a standard product that can be used for any application. The disc needs to be customized in close cooperation with the customer and depending on the specific requirements of the application. However, there is further potential for the Friction Disc within the power transmission industry (SKF, 2014c; Gläntz, 2011).

Intellectual Property

SKF's customer is the patent owner and SKF received the license to produce the Friction Disc for their own purposes and in any other but not for applications within the wind industry. SKF subsequently protected the coating process, its associated measurement method, and the technical configuration of the Friction Disc (SKF, 2014b, 2014d).

Commercialization

Because of the mutual exclusivity regulated in the contractual agreement, commercialization of the Friction Disc in the wind industry is limited to this customer. In other industries, SKF is free to commercialize (SKF, 2014b, 2014d).

Value Proposition and Business Model

From a customer perspective, the central value proposition of the Friction Disc is the possibility to downsize the main dimensions of the powertrain, its associated potential for weight reduction, and the simplified assembly process. Since 2009, the Friction Disc is a mature and certified product. Correspondingly, the customer can rely on the agreed performance (SKF, 2014b, 2014d).

Besides the actual Friction Disc, SKF consults extensively its customers regarding application engineering. In cooperation with the customer, each disc needs to be customized with respect to a given application. Based on this, the specific Friction Disc is designed. In general, the SKF value creation contains product development, application engineering, parts of the manufacturing process, and taking the overall responsibility for the final product. For any further value-creating step, SKF involves partners (SKF, 2014b, 2014d).

Commercialization Partnerships

According to the structure of the company, SKF is dependent on suppliers. Within the Friction Disc project, SKF strategically cooperates with a supplier that produces the disc blanks and with another company that takes responsibility for the coating process. SKF and its partners developed an elaborate process for product tracking and documentation that was subsequently realized by them. The Friction Disc is sold directly to SKF's customers. Furthermore, customer service and logistics are SKF's responsibility and the company has full responsibility for distribution (SKF, 2014d).

Timing

The timing of market introduction was exactly right as SKF managed to synchronize the development process of the Friction Disc with that of the wind turbine powertrain of SKF's customer. While SKF's customer developed its wind turbine, SKF simultaneously worked on the Friction Disc. Ultimately, the Friction Disc was available on time as a mature and certified product when SKF's customer started series production of their 3.3-MW wind turbine. Regarding time to market, this represented a perfect fit for SKF (SKF, 2014d).

Marketing

As mentioned before, the former tooling and prototyping machine shop was chosen to be the product home. The product home is responsible for marketing according to SKF's strategy. They are required to produce promotional material and provide this to the sales unit for communication to their customers (SKF, 2014d).

A few trade fair exhibitions and some supporting promotional material attracted some customer attention. However, to increase customer awareness of the Friction Disc and its benefits, a greater focus on marketing should have taken place. In general, this is an essential part of the diffusion process of technical products. This is especially true when it comes to radical technological innovations. In these circumstances, a clear explanation of the technical benefits is required if they are not intuitively obvious. Therefore, adequate promotional material and marketing help to highlight the advantages of the solution (SKF, 2014c, 2014d).

Innovation Success

Sales Performance

Today, every wind turbine of SKF's customer in the 3.3-MW-class is equipped with the Friction Disc. Since its market introduction in 2009, the yearly sales figures have been constantly rising and by 2014, a medium three-digit sales number has been reached. The Friction Disc became a particularly profitable and sustainable business for SKF and overall it has provided a very good return on investment (SKF, 2014b, 2014d).

However, notwithstanding the great potential of the Friction Disc for further applications in other industries, there are just a few alternative applications that have been equipped with the Friction Disc. By now, the wind industry is by far the largest application field. As the Friction Disc is not a standard product and can only be applied to the specific customer application, resources are needed for reliable application engineering and design adaption. According to SKF's strategy, this is the task and responsibility of the organizational product home (SKF, 2014c, 2014d).

Product Performance

The product performance of the Friction Disc is very high and meets the exact requirements of the customer. Several field tests have proven its performance and the friction coefficient which is the main feature of the Friction Disc has been certified by an accredited certification organization. Even after several years of use, the Friction Disc exhibits no loss of quality and by 2014, SKF had not a single return from the customer (SKF, 2014d).

Efficiency

The overall efficiency of the innovation process was considered quite high regarding both dimensions – costs and duration. The period between the first customer contact and series production of the Friction Disc amounted to a very short duration of 2.5 years. This is due to the fact that SKF and its customer synchronized their development processes till the point when series production of the 3.3-MW wind turbine began. Furthermore, the team took particular care to keep the development costs down. The tests of the Friction Disc at the technical university of Chemnitz have been relatively low (SKF, 2014b, 2014d).

5) Case Study Report – Cryogenic Machining by 5ME

Technology

Machining generates heat at the cutting edge due to friction, shearing, and abrasion. The faster the cutting speed the higher the heat. With rising heat tool wear and thus, costs increase rapidly. Correspondingly, the heat needs to be dissipated. Any cooling media helps to reduce the cutting heat. Traditional flood coolants operate at ambient temperature (+70°F/+20°C) and provide therefore insufficient heat removal in cases of particular challenging situations. This could be caused by high speed requirements or in the case of machining difficult materials like stainless steel and other hard alloys like titanium, hardened steels, or carbon fiber composites (5ME, 2014c; MAG IAS, p. 2; MAG IAS, 2012, p. 6).

In such cases, the cryogenic machining technology of 5ME is able to realize extended tool life, faster cutting speeds, and increased material removal compared to conventional coolants. This is possible as the cryogenic system operates at a temperature level of -321°F/-196°C giving the cryogenic machining a -400°F/-220°C advantage in many processes (5ME, 2014b; MAG IAS, p. 2).

This significant difference allows up to five times higher processing speeds and a potential increase of tool life by the factor of ten in some applications (5ME, 2014a, p. 1, 2014b; MAG IAS, p. 2).
In the past, cryogenic machining was difficult and costly. Mostly, the liquid CO_2 or nitrogen was sprayed at high volume at the tool and in one ill-fated test the entire workpiece surface had been submerged in liquid nitrogen. Sprayed systems allowed the nitrogen to contact more than the tool and over cool the workpiece and the machine components. Consequently, it was nearly impossible to implement cryogenic machining for larger products (5ME, 2014b).

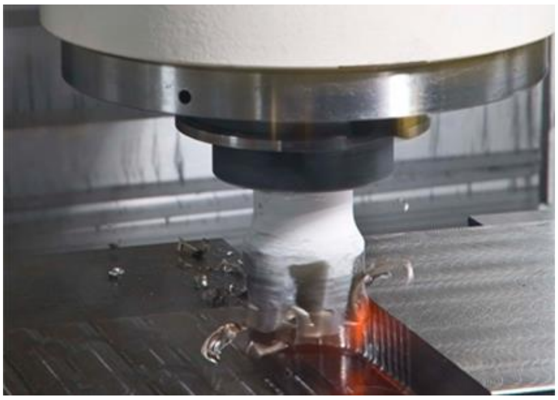

Figure 68: Cryogenic Machining (5ME, 2014i, p. 30)

In contrast, the 5ME technology (cf. Figure 69) utilizes vacuum jacketed feed lines for transmitting small flow rates (~0.04-0.08 l/min/cutting edge) of liquid nitrogen (LN_2) at -321°F (-196°C) through the machine, through the spindle, and through the tool directly to the cutting edge to maximize cooling effectiveness (5ME, 2013, p. 1, 2014b, 2014i, p. 32; MAG IAS, p. 2).

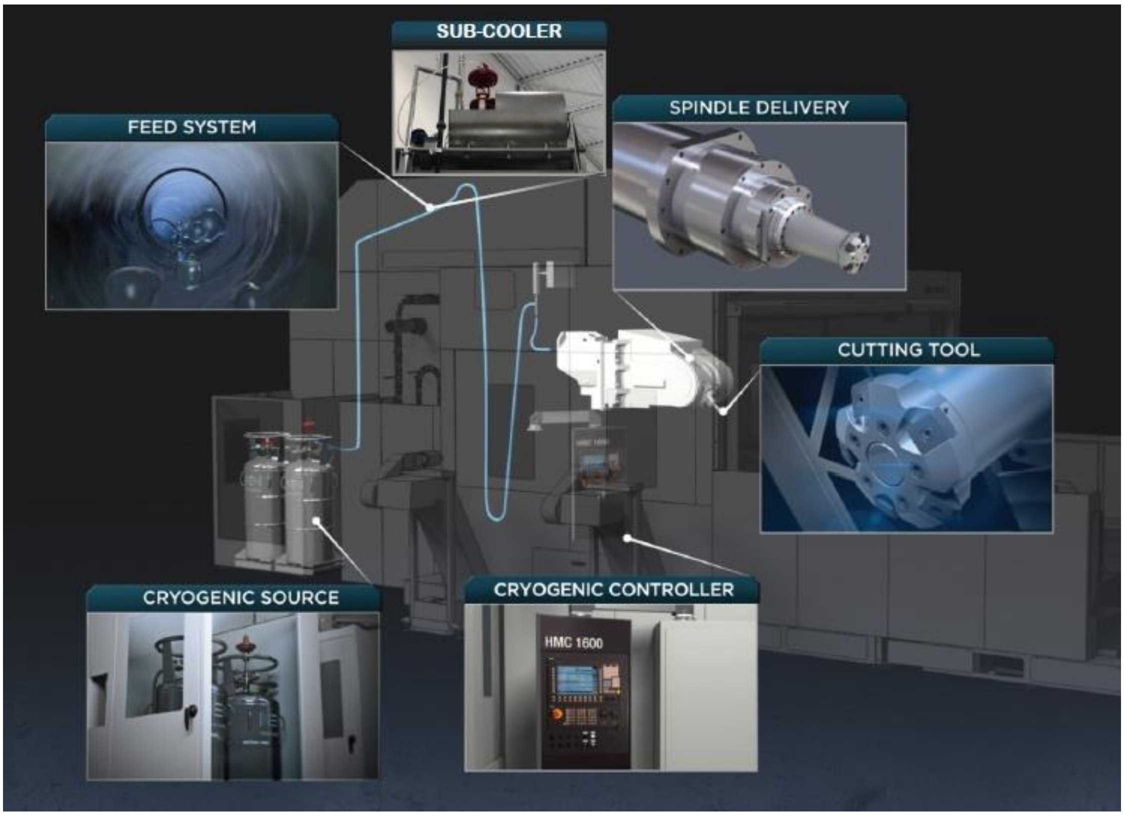

Figure 69: The 5ME Cryogenic-System (5ME, 2014g)

For an easy handling of the cryogenic sourcing, the liquid nitrogen is stored in a central storage location and then fed into the cryogenic machining system. As the system is self-pressurizing, the need for pumps and another additional power consuming assets is eliminated. In principle, there are three options for storing the liquid nitrogen: individual machine storage for standalone machines, cellular storage for small cells of two to six machines, or a centralized external storage for large-scale installations (5ME, 2014g).

The feed system consists of vacuum jacketed feed lines from the liquid nitrogen storage to the spindle, ram or turret system, depending on the machine concept. The feed system is critical to seal out ambient heat and deliver the liquid nitrogen at a constant temperature level of -321°F (-196°C) to its point of use (5ME, 2014g). Within the sub-cooler, the liquid nitrogen is cooled down to its average saturation temperature (~-292°F/-180°C at 2 bar) by following the principles of heat exchangers. The incoming LN_2 is split within a valve. The minor part of LN_2 (-321°F/-196°C at 0 bar) cools down the major part that is piped through a spiral tube within the sub-cooler (previously: ~-292°F/-180°C at 2 bar; and after sub-cooling: -321°F/-196°C at 2 bar). The flow rate of LN_2 within the whole cryogenic system is controlled with an outgoing valve of the sub-cooler which is regulated by the cryogenic control unit (5ME, 2014i, p. 35).

Figure 70: Sub-Cooler (5ME, 2014i, p. 35)

The cryogenic control unit is a programmable numerical control based system. It allows operators to program the automatic control parameters for the flow rate of liquid nitrogen through the feed system. Depending on the appropriate amount of liquid nitrogen for each individual cutting tool type, it is possible to realize the most efficient and cost effective machining process. The control system allows an auto override to emergency shut off or avoids an overflow of the system (5ME, 2014b, 2014g).

For the 5ME cryogenic system, a specifically designed lance needs to be used. This lance is a vacuum insulated tube that is inserted thru the spindle. As the feed lines and the lance are insulated, the liquid nitrogen can be transferred through the spindle without influencing the functional temperatures of these critical machine components (5ME, 2014g). This can be realized for new machines or for existing machines as the 5ME cryogenic system can easily be retrofitted in the form of a kit into almost any existing OEM spindle, turret, or ram (5ME, 2014a, p. 2, 2014g).

The tools for cryogenic machining need to be specifically designed to interface with the cryogenic system for reasons of proper functionality and safety. Correspondingly, 5ME offers a wide range of tools specifically designed and insulated to accept liquid nitrogen in the liquid state and keep it liquid until it reaches the cutting edge. This ensures an efficient use of the liquid nitrogen and optimal cooling at the point of cut (5ME, 2014g).

Table 15: Technical Data of 5ME`s Cryogenic Machining (5ME, 2014i)

Coolant Medium	Liquid Nitrogen – LN_2
System Output	Liquid Nitrogen / Nitrogen gas-mix – LN_2/ N_2
Machining Operations	Drilling, Milling, Turning, Reaming, Boring
Targeted Materials	CGI, Ti, Al, Composites, Hardened/Stainless Steel, Alloys, Inconel
Temperature of LN_2	-321°F / -196°C
Flow Rate	~0.04 to 0.08 l / min / Cutting Edge
System Pressure	~2 bar (self-pressurizing)
Available Tools	Rotary Cutting Tools, Indexable Cutting Tools, Turning Tools, Custom-made Tools
Feed Lines	Vacuum-Jacketed Tube
Coolant Delivery	Through Spindle

Feasibility and Maturity

The LN_2 cryogenic machining has been brought into industrial use. Thus, the technology has left the laboratory and testing status. According to 5ME's Cryogenic Engineering Manager, the engineering team managed to bring the cryogenic delivery system from an art to a science. Cryogenic flow algorithms and math models are used to calculate the appropriate flow delivery for the target cooling effect. Now, the system has reached high quality and reliable cryogenic liquid flow. On the other hand, the market is not familiar with the technology in depth. Correspondingly, it could currently be perceived as not fully mature (5ME, 2014j, 2014n).

Technological Alternatives

There are several alternative cooling methods to dissipate the heat generated by the machining process. 5ME will target hard to machine materials like titanium, compact graphite iron (CGI), stainless steel, and alloys. In the following, technological alternatives will be presented that also address this kind of material. According to 5ME, there are five alternatives to the LN_2 cryogenic machining worth analyzing: conventional flood cooling, high pressure cooling, CO2 cooling technology, dry machining with carbides, and dry machining with ceramics / cubic bore nitride (5ME, 2014k).

Conventional Flood Cooling

Currently, the most common method for dissipating machining heat is the conventional flood cooling technology (cf. Figure 71). Moreover, the flood coolant serves as lubrication medium and facilitates the chip transportation. In general, two types are differentiated: water-based coolants and cutting oils. For the focal comparison, water-based coolants will be focused. These are emulsions composed of petroleum-based lubricant oil (<3%) and water as lubricant carrier (>97%). By external feed lines, the coolant is piped to the cutting edge at ambient temperature and a high flow rate (~30 l/min – 60 l/min). The coolant recirculates but needs to be disposed, after a certain amount of time (Pušavec and Kopač, 2011, pp. 639–641; Reich and Böswetter, 2002, p. 8).

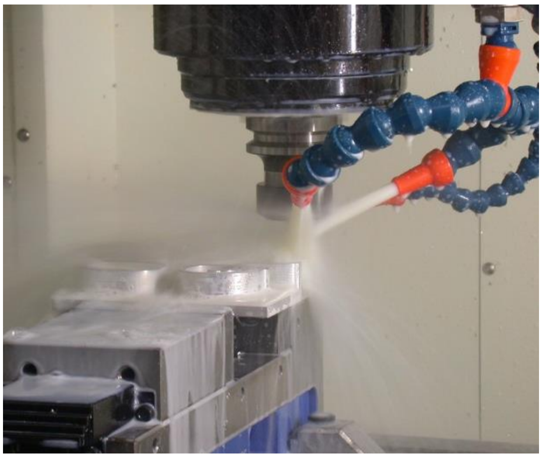

Figure 71: Conventional Flood Cooling (McKechnie)

High Pressure Cooling

High pressure cooling is a technology that delivers the fluid with high pressure to the tool and machined material. Most common is an internal delivery of the coolant through the cutting tools, tool holders, and spindle interface (Diniz and Micaroni, 2007, p. 247; Richt, 2011). Depending on the application, it is possible to employ different pressures (Sandvik recommends 80 bar) and flow rates (5–75 l/min) by using different sized nozzles (∅ 0.8–1.4mm) (Lawal *et al.*, 2013, p. 211; Sandvik, 2010, pp. 5–6). The high fluid pressure allows a better fluid delivery to the cutting zone, thus providing a better cooling effect and decreasing tool wear through lubrication of the contact areas (Diniz and Micaroni, 2007, p. 247). Furthermore, high pressure cooling has a better chip breakability as the jet has, on the one hand, a forming effect, and on the other hand, the cooled chip is brittle and easy to break (Richt, 2011).

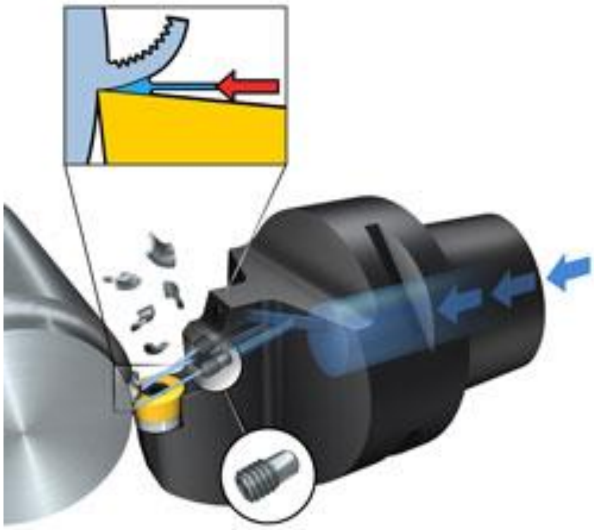

Figure 72: High Pressure Cooling (Richt, 2011)

CO2 Cooling Technology

At the approach of CO_2 cooling technology, compressed gaseous CO_2 is refrigerated into the liquid phase. The chilled liquid is transported through a capillary tube through the machine, spindle, tool holder, and tool to the cutting edge in a liquid state. This is done at a certain pressure and at ambient temperature. The cooling of the CO_2 to a maximum of -99.4°F/-73°C occurs at the nozzle, when the CO_2 expands. This technology gains its biggest advantages at machining high temperature alloys such as titanium, Inconel, stainless steel, and composites. With this technology, users can machine faster or receive an extended tool life compared to conventional flood cooling. Furthermore, the CO_2 cooling technology has advantages with respect to environmental, health, and sustainability issues (CoolClean Technologies, 2014a; Walter, 2013).

Figure 73: CO2 Cooling Technology (Walter, 2013)

Dry Machining with Carbide and with Ceramics / Cubic Bore Nitride

In principle, there are three different tool materials used for dry machining of hard materials: carbide, ceramics, and cubic bore nitride (CBN). Carbide tooling can cut material with hardness up to 55 on the Rockwell hardness scale (HRC). From the hard-to-machine materials, carbides are mainly used to cut titanium. Ceramic and CBN inserts work well when hardness exceeds 50 HRC. For example, ceramic tools are used for machining Inconel 718 and CBN for hard turning processes. Furthermore, ceramics and CBN need to be dry, as they may crack in case of cooling due to high thermal differences. As dry machining with ceramics and CBN mainly exhibits the same characteristics, it makes sense to treat them as one single technology category (5ME, 2014k; CIM, 2011).

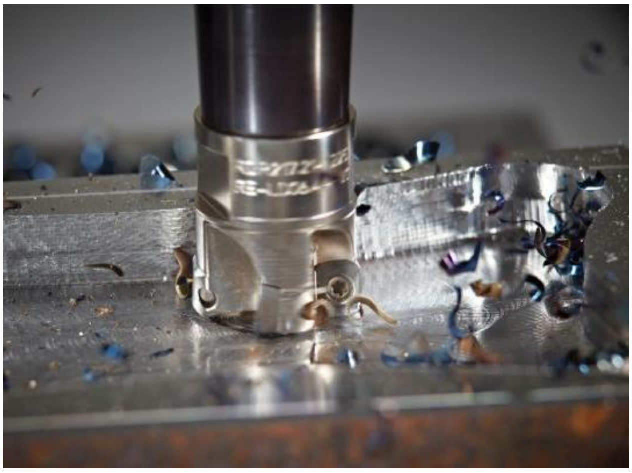

Figure 74: Dry Machining (Machinery Market, 2013)

At the process of dry machining in general, there is no usage of any coolant. Correspondingly, this is ecologically desirable and offers cost reduction opportunities as the conventional coolant infrastructure is made obsolete. As the friction and adhesion between chip and tool tend to be higher at dry machining, the temperatures and wear rates are higher and consequently, the tool lives shorter (Galanis *et al.*, 2008, p. 91). Just getting rid of the cooling system and simultaneously keeping the previous manufacturing parameters, will not be successful (Reich and Böswetter, 2002, p. 9). For efficient manufacturing, the tools need to be specified with respect to materials and geometry (Kissler, 2004, p. 18). To gain reliable control over chip formation, it is necessary to use cutting inserts with, especially adapted chip shaping grooves (Galanis *et al.*, 2008, p. 92).

Relative Advantageousness

To gain the relative advantageousness of the LN_2 cryogenic machining of 5ME with respect to the existent cooling alternatives, ten evaluation criteria have been established in consultation with 5ME's Cryogenic Engineering Manager: ability to machine tough material, tool life, cycle time, product quality, health and safety, environment and sustainability, investment costs, running costs, uptime/downtime, and construction change of machine infrastructure. The analysis is carried out with respect to the conventional flood cooling technology as this is the de facto standard technology in the field (5ME, 2014k).

Ability to Machine Tough Material

Advanced engineering materials, such as titanium, special alloy, and some stainless steel offer a unique combination of properties like high strength, resistance to chemical degradation, and wear resistance. Therefore, these advanced materials are being frequently requested in industry. One of the main obstacles towards the fast commercialization of these materials is the difficulty in machining them to required shapes and the related high machining costs. These difficulties are due to the high heat generation at the energy intensive machining process and the relatively low thermal conductivity of these materials (Wang and Rajurkar, 2000, p. 168). The latter attribute makes it difficult to transport heat away from the machining area and consecutively promoting thermally-related wear. Accordingly, the ability to machine these materials depends on the cooling ability of the considered technology (Richt, 2011; Su *et al.*, 2006, p. 760). As the high cutting temperature acts close to the cutting edge, the LN_2 cryogenic machining of 5ME is advantageous compared to its alternatives. The LN_2 is indirectly applied to the cutting edge at -321°F/-196°C. Traditional flood coolants have temperatures around +70°F/+20°C, giving cryogenic machining a -400°F/-220°C advantage (5ME, 2014b). The cooling with CO_2 happens at -99.4°F/-73°C next to the cutting edge what corresponds to a -220°F/-140°C advantage for 5ME`s technology (Walter, 2013). High pressure coolants have the same temperature level as conventional flood coolants, but due to their high pressure and optimized nozzle design, the coolant is closer delivered to the cutting edge than with conventional flood cooling. In contrast to carbide, ceramics and CBN resist a high amount of heat and are accordingly appropriate for machining tough material (5ME, 2014k).

Tool Life

Metal machining produces extreme temperatures that are the primary cause of tool failure. By using the cryogenic system of 5ME, an increased tool life of up to ten times the tool life of conventional flood coolants could be realized. Longer lasting tools allow decreased direct costs for each part (5ME, 2014f). Within diverse test runs, 5ME could realize a tool life increase of ten times for compacted graphite iron, three times for titanium, and a 40% increase for diverse composites (5ME, 2014e). For the CO_2 cooling technology, several studies showed a potential tool life increase of 20%-200% depending on the machined material (CoolClean Technologies, 2014c). Similarly, the application of coolant at high pressure could increase the tool life up to three times (Lawal *et al.*, 2013). For dry machining, the tool life of ceramics and CBN are comparatively limited, but the tool life of carbide is worst (5ME, 2014k).

Cycle Time

Besides the tool life, the machining cycle time is one of the main factors influencing process profitability. With the 5ME cryogenic machining, it is possible to run two to five times faster for hard-to-machine materials than with conventional cooling. For compacted graphite iron a five times increase in finishing cutting speed, for titanium a two times increase in semi-finish cutting speed, and for steel alloys a 1.6 times increase in semi-finish cutting speed could be realized with the LN_2 cryogenic system compared to conventional flood cooling (5ME, 2014a, pp. 1–2). The CO_2 cooling technology enables 20-75% faster cycle times and with high pressure cooling approximately 40% faster cycle times are possible compared to flood cooling (CoolClean Technologies, 2014b; Sandvik, 2010, p. 11). As the machining heat rises with increasing speed and similarly tool wear, just a low cycle time level is realizable with carbide tooling at dry machining. With ceramics and CBN very high cutting speeds and correspondingly cycle times are possible (5ME, 2014k; CIM, 2011).

Product Quality

As the addressed materials are hard-to-machine, product quality is an important distinguishing characteristic for the alternative technologies. Test results of 5ME have shown that their LN_2 cryogenic machining solution has improved overall surface integrity and part quality. Benefits such as a reduction in white layer, grain boundary distortion, and burr formation have been especially important for the aero structure and aero engine customers (5ME, 2014f). 5ME states that according to their tested parts, the LN_2 cooling technology has produced smoother and more reliable finished items than traditional cooling methods (5ME, 2014c). CoolClean technologies, a provider of a CO_2 cooling system, report of their ChilAire System to leave a good finish after machining. According to their website, the system produces a superior surface finish that frequently will not require a finish cut (CoolClean Technologies, 2014b). Due to low cutting forces generated by the improved cooling and lubrication ability of high pressure cooling, surface finish is at a high level and free from physical damages (Lawal *et al.*, 2013, p. 211). In dry machining operations, cooling and lubrication functions are not available. By comparison, wet machining has correspondingly better part quality and less tool wear than dry machining. For carbide tools, this difference is significantly bigger than for ceramic and CBN inserts (5ME, 2014k; Galanis *et al.*, 2008, pp. 91–92).

Health and Safety

In conventional machining, the coolant emulsions are containing mineral oil and surfactants based on petroleum (Pušavec and Kopač, 2011, p. 639). Prolonged contacts of machine operators with these cutting fluids may cause skin and respiratory diseases (Su *et al.*, 2006, pp. 760–761). Therefore, special care needs to be taken in case of conventional flood coolant for reasons of health and safety. As high pressure cooling utilizes the same coolant, these technologies range on the same level. LN_2 cooling has significant advantages with respect to safety and health related issues. When liquid nitrogen touches the air, it evaporates, leaving only nitrogen, a safe, breathable, non-flammable gas which makes up 78% of the air we breathe. There is no contamination of the work environment in the form of fumes and slippery surfaces (5ME, 2014f). The only health concern is that there is too much nitrogen, but this risk is minor (5ME, 2014m). Similarly, the use of the CO_2 cooling technology eliminates these coolant issues and reduces health risks. As CO_2 is a greenhouse gas and less healthy than LN_2, this technology has been ranked below 5ME`s technology. For both dry machining categories, there are no concerns with respect to hazardous coolants or further safety issues like technology education requirements (Galanis *et al.*, 2008, p. 91).

Environment and Sustainability

Conventional flood coolants have many drawbacks which negatively impact the environment and sustainability during their production, use, and disposal. Flood cooling may lead to workpiece contamination and environmental hazards (5ME, 2014f). An improper disposal of cutting fluids could result in ground, water, or air pollution (Su *et al.*, 2006, pp. 760–761). Aggravating this situation, there is increased energy consumption with high pressure cooling leading to an even worse evaluation compared to conventional flood cooling. Since the LN_2 cryogenic machining and the CO_2 cooling technology cut without coolant, there is no need for mist collection, filtration, or disposal of coolant waste. Energy consumption is lower without coolant fans, pumps, and drives. In addition, chips and workpieces remain dry and uncontaminated for a safer work area and easier recycling (5ME, 2014f; CoolClean Technologies, 2014a). In contrast to the greenhouse gas CO_2 of the corresponding cooling technology, the evaporated nitrogen of the LN_2 cryogenic machining technology is a non-toxic, breathable, atmospheric, non-greenhouse gas (5ME, 2014a, p. 2, 2014b). By not using any cutting fluid, dry machining (carbide and ceramics/CBN) is ecologically desirable and correspondingly obtains the highest evaluation (Galanis *et al.*, 2008, p. 91).

Investment Costs

The cryogenic system of 5ME could be realized for existing machines just like for new machines. Correspondingly, the investment costs for both business cases need to be distinguished. Existing machines will be retrofitted by adding a cryogenic retrofit kit. Thus, the costs for this kit are an additional investment if you start with a conventional flood cooled machine. Nevertheless, if you want to turn to any of the other cooling alternatives (high pressure, dry, CO_2), there are also changing costs that need to be considered. At the focal analysis, the focus will be on the investment costs for a new machine (5ME, 2014m, 2014a, p. 2, 2014g).

As the cooling alternatives should be compared, the costs for the underlying machine will not be considered. For dry machining with carbides, there are no additional elements and accordingly costs. This is the case for dry machining with ceramics/CBN as well, but the cutting tools itself cost more. A conventional flood cooled machine is equipped with a coolant pump, a coolant tank, and a filtration system for the used coolant. According to 5ME's Cryogenic Engineering Manager, the equipment of the cryogenic LN_2 machine (sub-cooler, tank, controller, tools) would currently cost roughly 25% more than a conventional cooling system. While launching this new technology into the market, this issue is one of 5ME`s challenges and the company is continually reducing the costs of its cryogenic system. However, according to 5ME the customers' cost benefit outweighs their investment. The high pressure system would add high pressure pumps to the conventional cooling system and possibly an increased coolant tank. The CO_2 system (tank, pump, controller, tools) costs less but is slightly more expensive than a conventional coolant system (5ME, 2014k, 2014m).

Running Costs

The running costs for the traditional cooling system mainly include the costs for coolants, coolant disposal, energy costs, personnel costs, and costs for tool exchange. The coolant recirculates at a high flow rate (~30 l/min – 60 l/min) but needs to be disposed after a certain time period (Pušavec and Kopač, 2011, pp. 639–641; Reich and Böswetter, 2002, p. 8). Disposal of these coolants is costly and time-consuming. In the case of LN_2, CO_2, and the two dry machining alternatives, these disposal costs do not incur, at high pressure cooling they do. Conventional cooling requires pumps and filters which increase energy consumption. This is worse for high pressure cooling, as this technology demands, even more, energy. The cooling methods LN2, CO2, and the two dry machining technologies consume much less energy. Personnel costs incur at all technologies and will not be further considered. Costs for conventional tools are on the same level for the technologies conventional flood cooling, high pressure cooling, and CO_2 cooling. Currently with low production volumes, the tools used for LN_2 cooling are approximately 20-30% more expensive than conventional tools. With higher volumes this price difference can be reduced by another 50%. Ceramics are expensive, but carbides and CBN are most expensive. Multiplied with its tool life the corresponding tooling costs for each technology could be calculated. With a flow rate of ~0.04-0.08 l/min/cutting edge and costs of 0.06$/l, the LN_2 coolant is comparatively cheap. CO_2 is consumed at high volumes and accordingly high costs. In summary, LN_2 cooling has the lowest running costs, followed by dry machining with ceramics/CBN, CO_2 cooling, dry machining with carbides, conventional flood cooling, and high pressure cooling (5ME, 2014j, 2014k, 2014f, 2014i, p. 51; CIM, 2011).

Uptime / Downtime

One of the critical parameters of process productivity is uptime respectively downtime of a machine. 5ME conducted an analysis of reasons for machine downtime. According to 5ME's Cryogenic Engineering Manager, more or less two thirds of all machine downtimes could be associated with coolant issues: problems with coolant pumps, coolant filtration, or coolant chips. These problems do not occur at LN_2 cooling, CO_2 cooling and dry machining technologies. Nevertheless, 5ME has not run production enough to understand if there are some preventative maintenance issues to consider (5ME, 2014m). Another important influence parameter on downtime is the necessity of tool change. Each time a tool fails, the machine needs to be shut down, the tool removed, a new tool located, installed, and then the program needs to be restarted. This causes productivity loss and can be directly attributed to tool life (5ME, 2014f; CoolClean Technologies, 2014b).

Construction Change of Machine Infrastructure

According to 5ME, their cryogenic system is brand agnostic and can be applied to almost any existing process or by retrofitting even to any existing machine (5ME, 2014c). Nevertheless, LN_2 cooling is a new technology with a new system that causes changes within the existing machine infrastructure of 5ME`s customers. Changing an operating system commonly causes difficulties, but occasionally offers opportunities on the other hand.

Most machine tools are designed for wet machining. Accordingly, this is the standard version and causes no changing effort (Kissler, 2004, p. 19). Dry machining requires the least modification effort of the alternative cooling technologies. Mainly the cutting tools need to be adapted. Hereby, ceramic and CBN tools are slightly more work-intensive than carbide tools. Additionally, the cooling system can be left away at dry machining which is advantageous from the cost perspective. Equally, this could be done for LN_2 cooling and CO_2 cooling. Concerning CO_2 cooling less effort is needed to change the machine tool system compared to LN_2 cooling (5ME, 2014m, 2014f).

There are a few prerequisites for integrating high pressure coolant into a machine. The system`s seals and valves should be able to handle the high pressure. Moreover, special nozzles and high pressure pumps need to be added to achieve the required flow rate. Sometimes an extended filtration system or a bigger tank is needed. Accordingly, an additional infrastructure needs to be added to the existing one for high pressure cooling (5ME, 2014m; Richt, 2011).

Overview of the Relative Advantages of 5ME`s LN_2 Cryogenic Machining

To gain a better overview of the relative advantages of 5ME`s LN_2 cryogenic machining, the alternative cooling technologies have been evaluated with respect to the degree to which they meet the ten evaluation criteria on a ten-stage ordinate scale (cf. Figure 27).

With respect to eight of ten evaluation criteria, the LN_2 cryogenic machining of 5ME is top ranked. Especially, for tough-to-machine materials the technology has great advantages regarding tool life, cycle time, and product quality. Accordingly, the productivity of this process is on a very high level compared to its alternatives. This becomes additionally apparent if the low running costs and low downtime rates are focused which leads to a higher profitability of the focal process. Furthermore, LN_2 cryogenic machining is a very green and safe technology. Concerning this matter, the technology is on the same level as dry machining, as no toxic coolants are used and nitrogen is an atmospheric gas.

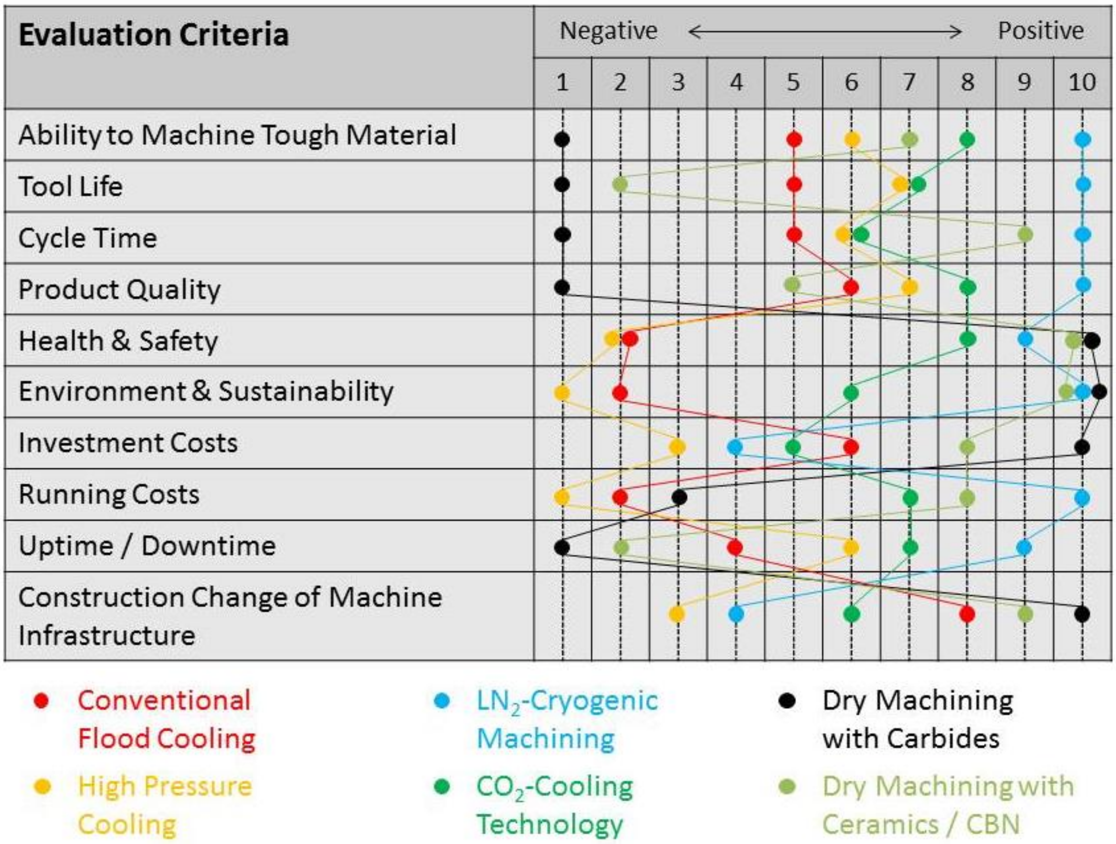

Figure 75: Overview of Relative Advantages of 5ME`s LN_2 Cryogenic Machining

The two dimensions in which the technology is among the lowest ranked technologies are investment costs and construction change of the machine infrastructure. These two characteristics seem to be typical for a disruptive, new technology as there are several obstacles and barriers in the emerging phase that hamper the market entrance of radically new technologies. According to 5ME's Cryogenic Engineering Manager, 5ME is aware of these issues and is reducing the investment costs for the cryogenic system (5ME, 2014m). Equally, 5ME is working on business models to address these factors.

Moreover, in the current emerging phase of this technology, it is essential to address the right market segment to gain references in the market and to proof industrial application maturity.

Therefore, the selected target market for 5ME`s radical LN_2 cryogenic machining technology will be analyzed.

Target Market

5ME's long-term vision is to basically eliminate coolants on every machining operation and shift the market to cryogenic machining. In the short term, the company is focusing on the difficult-to-machine materials as these applications gain an intermediate effect from the new technology (5ME, 2014j). Initially, the biggest benefits for cryogenic machining were found in materials like titanium, hardened and stainless steel, gray and compacted graphite iron, and carbon fiber composites. These materials are most commonly used for applications such as aero-structure, aero-engines, cylinder blocks and heads, pumps, and turbines. Correspondingly, the prime focus of 5ME contains four industries: aerospace, oil & gas, automotive, and construction and agriculture. Due to the costs of the cryogenic system and the tools, the return on investment is better for larger tools and parts. Thus, medium to large size machines with a table size of 500 mm and larger are addressed. Furthermore, a single spindle horizontal machine is preferred, as the gravity would help to transport away the chips. In contrast to endless cutting processes, interrupted cuts as they exist in the case of milling provide the advantage of tool re-cooling at cryogenic machining (5ME, 2014l, 2014o).

Since 5ME is located in Cincinnati and Detroit the geographic focus is the Northern American market for roughly the first three years. Due to limited resources, the company is in the process of attaining a couple of machines as references and commercial successes into running production in close proximity, so they could quickly support them. This geographic focus corresponds to the location where the machine is brought to production, not where the machine tool builder is headquartered (5ME, 2014l, 2014o).

From a customer standpoint, 5ME follows a two group strategy. One group of customers consists of companies that machine parts. They have machines that are already in production and 5ME would sell the cryogenic system to them in the form of retrofit kits. The other group of customers consists of machine tool builders and machine tool distributors. 5ME will work with them to apply cryogenic machining to their machines before they are shipped to the end-user (5ME, 2014n).

According to 5ME's Marketing & Product Manager, the company's target end-users will be those working with expensive or difficult-to-machine materials, employing a large number of assets, with high costs for consumables and energy, and committed to organizational change (5ME, 2014l, 2013, p. 2).

Industry Context

The North American industry has just emerged from one of the deepest depths since the great depression. This has led to a heightened understanding of 5ME's potential customers that efficiency and productivity are important drivers of global competitiveness and having a sustainable business in the end. LN_2 cryogenic machining exactly addresses these needs (5ME, 2014l). In November 2014, the United States and China agreed on targets for carbon emissions reductions for the next years during a summit of the Asia-Pacific Economic Cooperation in Beijing (Landler, 2014). This is one indicator, inter alia, of the ever stricter laws and regulations addressing environmental impacts within the U.S. market. According to 5ME's Cryogenic Business Development Manager, the European market is quite ahead, but environmental impacts get more and more serious in the U.S. industry as well (5ME, 2014o). The regulations are not as strict as they should be, but environmental friendliness becomes increasingly a central factor in the American industry (5ME, 2014l).

Compared to its alternatives, LN_2 cryogenic machining has great advantages with respect to its environmental friendliness. Correspondingly, 5ME has not come across any government related regulations that have been a barrier for the technology. In contrast, ever tougher environmental regulations have a positive impact on the commercialization of this technology (5ME, 2014o).

Competitive Situation

The internal cooling technique of LN_2 cryogenic machining is unique to 5ME. Correspondingly, there is no competitive situation with respect to this specific technology (5ME, 2014l). According to 5ME, it is not competing with other cooling solutions or solution providers to win orders. From a product standpoint, 5ME is not seeing a real competitive issue right now. Of course, there are a lot of questions relative to alternative coolant methods. 5ME's job is more about educating and convincing the end-user to change the way they traditionally machine parts (5ME, 2014o).

Market Barriers

When entering a market with a new technology obligatory approvals are among the basic barriers. These differ fundamentally in the different industries. With respect to the primarily focused industries of 5ME, the highest requirements for technology approval exist in the aerospace industry, followed by the automotive industry. Oil & gas and construction machinery have the lowest requirements (5ME, 2014o).

Due to the critical nature of the parts that go to an airplane, every change that has been done with respect to the materials or the machining process has to be approved by the aircraft manufacturer. This is a very time-consuming procedure and also needs to be done with every aircraft manufacturer. For example, it took 5ME two years to get the approval by Lockheed Martin for rough and finish machining of titanium. Once it is approved, all suppliers are allowed to machine parts according to the certified process (5ME, 2014j, 2014o).

Within the automotive industry, there is no formal certification process, but there are multiple phases of technology implementation. After several test rounds, the automotive OEMs run offline production for several months to check repeatability and robustness of the technology. As mentioned above, the oil & gas industry and the construction machinery have the lowest approval requirements. According to 5ME's Cryogenic Business Development Manager, the single issues were operator health and safety. Therefore, 5ME conducted an audit for their first oil & gas customer to remove his concerns if the evaporating nitrogen affects the health of the machine operator (5ME, 2014o).

Apart from the certification requirements, cryogenic machining is a radical new technology that requires a lot of change. It is not only changing the machine, but it is also changing the supply chain, the tools, and the minds of those who operate and manage the manufacturing operation. Furthermore, the process parameters completely change as the traditional manufacturing rules cannot be applied. Understandably, this leads to a great uncertainty on the customer side. Most of the potential customers want to see references. Once 5ME has established references in each industry, it will be much easier to convince new customers to switch to cryogenic machining, but initially, this is a barrier to overcome (5ME, 2014j, 2014n, 2014o).

Another barrier to overcome is the fact that 5ME is a small start-up company with no established reputation. Correspondingly, it takes a lot of effort to convince suppliers and customers that 5ME is viable and stable. The terms and conditions of contracts to be closed are frequently worse than for big companies (5ME, 2014l, 2014n).

Opportunity

By 2014, the American metalworking machinery manufacturing industry has rebounded from the recession. Dramatic growth in money supply, high and rapidly growing capacity utilization, strong and improving business conditions, and a historically high durable goods production have led to an increased demand for machine tools. According to the 2015 Capital Spending Survey by Gardner Research, U.S. metalworking facilities will spend $ 8.822 billion on new metal cutting equipment in 2015, an increase of almost 37% compared to the latest estimate for 2014 of $ 6.463 billion (Gardner Research, 2014, p. 2; IBISWorld, 2014). Both, the automotive and the aerospace industry, contribute highly to this development. With respect to aerospace, there is a great ramp up of production all across the new generations of aircraft for commercial and military usage over the next few years. Boeing is planning to increase the medium-term production of the “Dreamliner 787” and the medium-haul aircraft “Boeing 737” significantly. Similarly, the production of the “F-35 JSF” by Lockheed Martin and the “A350” by Airbus will be started (5ME, 2014o; Janetzke, 2014).

The following table indicates the estimated spending on new metal cutting equipment for 2014 and 2015 of 5ME’s focus industries in the U.S.:

Table 16: Estimated Spending on New Metal Cutting Equipment in Different U.S. Industries (Gardner Research, 2014, p. 4)

Automotive	Aerospace	Oil/Gas Field/Mining Machinery	Off-Road/Construction Machinery
2014: $ 561.1m	2014: $ 167.4m	2014: $ 235.1m	2014: $ 122.8m
2015: $ 759.3m	2015: $ 307.4m	2015: $ 165.8m	2015: $ 163.3m

According to Kline, roughly 50% of the companies buying a new machine in 2015 are doing this to increase their machine/equipment capacity and roughly 45% want to reduce their costs (Kline, 2014, p. 21). This motivation corresponds to the main advantages of 5ME’s cryogenic machining. Due to the increased demand for production capacity, these national industry trends strongly support the establishment of cryogenic machining. 5ME initially expects the market for retrofit machines to be bigger than for new machines. As they already have machines on their floor, 5ME’s customers can increase their productivity with a reasonable investment. These customers have historical data on parts that were running on those machines like tool life and throughput. Correspondingly, it is easier for them to compare and calculate their return on investment. Furthermore, there are much more machines in the field that could be equipped with cryogenic machining than new machines will be sold over the next few years (5ME, 2014o).

Several machine tool builders are very interested in 5ME’s technology. However, most of them wait until their customers require new machines with an integrated cryogenic system. Thus, 75% of 5ME’s focus is on retrofitting machines over the next two years (5ME, 2014l, 2014o). Assuming that the resources are available, there are roughly 100 machines that could realistically be retrofitted just from the four to five customers 5ME is already working with. From a market opportunity standpoint, 5ME’s Cryogenic Business Development Manager assumes that there are probably thousands of machines that fit the criteria of cryogenic machining. 5ME expects tremendous demand, once each of 5ME’s focus industries has a cryogenic machine running in production (5ME, 2014o).

By now, 5ME has delivered their first cryogenic system to a customer from the oil & gas industry and has sold another kit to a machine tool manufacturer. Several positive test runs have been carried out during 2014 at 5ME’s Tech Center. On this basis, the company expects to get eight to ten incoming orders throughout 2015. If everything goes to plan, 5ME anticipates greater than a 100% order increase every year over the next three years. After that, 5ME estimates to have enough market acceptance to quicker win further orders (5ME, 2014o).

Organization

In July 2013, the non-machinery units of the former MAG IAS machine tool manufacturer were spun-off and emerged as 5ME from then on. The new company consists of the former MAG IAS business units Cryogenics Machining Technology, Manufacturing Software, and Manufacturing Solutions. The company’s facilities are in Cincinnati and Detroit (5ME, 2013, p. 1, 2014i, p. 19).

Strategy

Nowadays, manufacturers are under increasing pressure from agile competitors, capacity constraints, material cost increases, and skilled labor shortages. To deal with these immense pressures requires achieving optimal machine performance. Therefore, 5ME wants to increase their customers' manufacturing efficiency to generate profitable, competitive, and sustainable businesses. This vision is reflected in 5ME's brand name. The company aims to address the five "M's" of man, material, machines, methods, and metrics, to improve a manufacturing enterprise's efficiency (the "E") (5ME, 2013, p. 1, 2014d).

5ME composes a suite of technologies, hardware, software, and services to reach higher productivity, improved quality, and lower working capital for their customers. The company follows a brand and process agnostic strategy, and therefore is able to work with all types of machinery and manufacturing systems. With respect to cryogenic machining, the long-term strategy of 5ME is to eliminate coolants on every machining operation and establish cryogenic machining as the standard machining process. In the short-term, the company primarily targets the difficult-to-machine materials (5ME, 2014j, 2014d, 2014i, p. 19).

Structure and Processes

The incorporated former MAG IAS business units form the basic pillars of 5ME's business: Cryogenic Machining, Manufacturing Solutions, and Manufacturing Software. The organization's structure (cf. Figure 76) constitutes accordingly. According to 5ME, at start-up, it was difficult to change the culture from the former organizational structure of three separate business units to that of "one" company, 5ME. So while 5ME goes to market with three business segments, its operations and organization are consolidated with functional managers having companywide responsibility. Furthermore, project managers are directly allocated to projects from each business sector. The following centralized functions support 5ME's business: Engineering, Business Development, Project Management, Finance, Regional Sales, and Marketing and Product Management (5ME, 2014d, 2015).

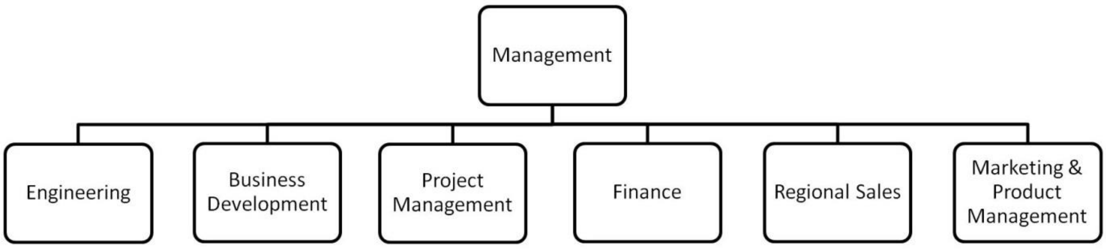

Figure 76: 5ME's Organizational Structure (5ME, 2015)

5ME's President emphasized that the organization is very flat from an organizational standpoint. For the most part, it is two levels and just a few employees are organized in a third level (5ME, 2014n). This becomes apparent when looking at the organizational chart (cf. Figure 76).

Correspondingly, the decision making processes within the company are very lean. Due to the flexibility of a start-up, 5ME is able to adapt its technology goals and strategy roadmap very quickly according to the feedback of its customers. 5ME has defined concrete business processes that its employees follow in their daily work. Furthermore, a business system was established that combines the functionalities of an ERP, CRM, and project management system. Everybody in the company has access to it and every project, purchase, or customer offer needs to be documented within this system (5ME, 2014n).

Company Culture

The innovation climate is very good within 5ME. The management team establishes a kind of thinking among their employees that everyone does his best to push the technology forward and to question the way things have been done traditionally. 5ME's President stated that there are high risk tolerance and failure acceptance in the company. He said the team has innovated and developed a lot by mistake. There is no detailed road map for each test. The technology goals are set and the team can freely innovate to achieve this goal. Afterward the results need to be documented and understood. 5ME's President emphasized that if you tell people exactly what they should do and not accept any other way, you would limit creativity. By giving them the authority to try things and use their best judgment, great innovations are achievable (5ME, 2014n). Furthermore, the whole team is absolutely committed to the technology and the company. Everybody within 5ME believes in the technological advantages of cryogenic machining and provides the passion and the drive to make it a success (5ME, 2014l).

Another issue contributing to a vital innovation climate within a company is internal communication. 5ME's management team evaluates the internal communication within 5ME as good. When the company was started, there were three separate businesses and the management team worked hard to make it one company. Communication in written and verbal form is very important. Within the projects, there is formal communication on a weekly basis. Additionally, for reaching high transparency and visibility among all team members, project reports have to be written and any important information needs to be documented in the business system. This promotes efficient communication as just the decisive questions arise (5ME, 2014n).

Funding and Commitment

During the time at MAG IAS, the development of the cryogenic machining technology was funded as a part of the company's R&D budget. The owner of the previous company MAG IAS and investor of the technology since the spin-off is the owner of 5ME (5ME, 2014n).

5ME estimates that it will take millions of dollars to take cryogenic machining technology to the mainstream market. Break-even sales will not be achieved in the first two full years of the company's business (5ME, 2014n). In the face of this risky endeavor, strong management and owner commitment are essential. 5ME's owner and the management team are absolutely committed to the technology and the company. It is their vision and passion to commercialize this technology and turn it to the mainstream machining technology (5ME, 2014l, 2014n).

Another funding source for 5ME to develop cryogenic machining is customers. 5ME's goal is to get as much customer funding as possible for financing test runs. Correspondingly, 5ME has primarily been focusing on large OEMs and tier one suppliers, as they typically have funds as a part of their business budget to test new technologies. 5ME managed to get customer money for most of their test runs. Furthermore, 5ME has internal R&D budget. So if the customer funds have been exhausted and no satisfying results have been achieved, 5ME puts in internal money to complete the test runs and come up with a satisfying result. For tool development, 5ME primarily uses internal funding to claim ownership to potential intellectual property (5ME, 2014j, 2014o).

Entrepreneurial Team

5ME has about 45 employees. The team consists of managers, engineers, and employees that have originally worked for the former MAG IAS business units which have been incorporated when spinning-off. Most of them have already been engaged in the disciplines 5ME is executing during their time at MAG IAS (5ME, 2014n, 2013, p. 1).

Within the cryogenic machining discipline, the team has been very experienced right from the start with respect to their machine tool background and the standard machining operations. Correspondingly, they already knew how to make a chip effectively. To profoundly understand the cryogenic part, the theory, and physics behind it, 5ME hired a couple of cryogenic experts. Some of them have done their Ph.D. within the field of cryogenic machining. With this combination of knowledge, 5ME managed to bring the technology from an art to a science (5ME, 2014j, 2014n).

The engineering team has to focus on the following four issues: safety, quality, reliability, and costs. As their product designs are the base for the commercialization of the technology, the cryogenic engineers really have a decisive role. On the other hand, there are people in purchasing and sales that negotiate for 5ME to get the costs and profits in the right place (5ME, 2014n).

At selecting the right people to work for 5ME, two areas are essential: professional competence and passion. 5ME's President elucidates that professional competence is an obligatory precondition, but enthusiasm and passion for the focal job are the decisive factors when hiring employees. Potential candidates need to be absolutely committed, passionate, and willing to take risks. By now, 5ME has not grown the employment base, in spite of the fact that the company is planning to grow. 5ME wants to be a 100-million-$-business in five to seven years. However, only after orders are coming in, 5ME starts to add headcounts for not consuming too much money during the ramp up phase. Currently, if people leave the company, 5ME adds employees in those areas the company is investing in (5ME, 2014l, 2014n).

Innovation Process

Opportunity Identification

The through-spindle, through-cutting tool LN_2 cryogenic machining technology was initially developed by Creare, an engineering and development firm located in Hanover, New Hampshire. Between 2003 and 2007, Creare developed and optimized the technology within a U.S. government funded Small Business Innovation Research (SBIR) project together with U.S. Navy, NavAir, and Bell Helicopter to reduce the costs of machining titanium parts (5ME, 2014h; Creare, 2014, p. 1).

In 2007, a visit of the Creare laboratories was made by MAG IAS management. Once they witnessed what Creare was doing with that technology, MAG IAS basically negotiated an agreement with the R&D firm to exclusively license the technology which was primarily based on three patents. With this agreement, MAG IAS received the right to continue to develop the technology, to manufacture, use, and sell it exclusively, globally. From 2007 until 2010, there was a small team formed within MAG IAS to take a look at the technology and to start developing it further. The aim was to figure out, how the technology could be applied to MAG IAS machines and what the benefits would be. This assessment has been done from a technical and a market perspective (5ME, 2014n).

Between 2010 and 2013, there was more effort and budget put into the development of the technology within MAG IAS. A team of four people, three technicians and one marketing representative, was established at MAG America. It was aimed to get closer to application maturity and to specifically address the market. Between 2010 and 2011 MAG Germany also started to get involved in the development of the technology and mainly replicated what MAG America was doing. Within MAG Germany, roughly eight people were involved. The results of technology development have been showcased at the industry trade shows IMTS 2010, imX 2011, EMO 2011, and IMTS 2012. Finally, the non-machinery company units of MAG IAS were spun-off in July 2013 and emerge as 5ME since that time. Spinning-out was due to two main reasons. The first reason was the former limitation to just one single machine tool manufacturer. Inside MAG IAS, cryogenic machining could not be implemented on machines from other machine tool companies. By taking it outside of MAG IAS, 5ME was immediately open to other brands and opportunities (5ME, 2014n, 2013, p. 1, 2014h).

The second reason for spinning out 5ME was the fact that inside MAG IAS, it has not been possible to focus on this new technology. Cryogenic machining is radically new. Correspondingly, potential customers need to be addressed. Now, 5ME advertises itself as a cryogenic company and has a very dedicated marketing focused on the commercialization of cryogenic machining. Within MAG IAS, cryogenic machining was only a minor part of the overall company. Accordingly, just a minor part of the overall communication efforts was put on cryogenic machining. Furthermore, 5ME established a Tech Center in Detroit to show potential customers the technology and to run customer tests. Having a dedicated training and testing center was not possible within MAG IAS (5ME, 2014n).

Especially in the early stages, commercializing a radical technology like cryogenic machining is accompanied by a huge amount of uncertainty (Bullinger, 1994, p. 96). Coping with this uncertainty and being sensitive to the market needs is a precondition for being successful. 5ME is aware of this situation that there are many things that they do not know (5ME, 2014o). As the technology is so new and different to the standard machining approach, it requires much change and a lot of moving pieces (5ME, 2014n). From a market standpoint, 5ME needs to prioritize which industries to address first. This should be done with respect to the greatest possible opportunity. 5ME is focusing on the aerospace, automotive, oil & gas, and construction industries due to their great opportunities for cryogenic machining. A great chance from a customer standpoint offers the F-35 Joint Strike Fighter (JSF) program in the aerospace industry. The prime contractor of the F-35 JSF program, Lockheed Martin, has been involved in the development of cryogenic machining right from the start. Lockheed Martin endorsed the technology for machining F-35 titanium components during the SBIR program with Creare as the technology's advantages have been demonstrated. 5ME has good relationships with high level decision makers of Lockheed Martin who help to promote cryogenic machining throughout their supply chain (5ME, 2014o; Creare, 2012, p. 1).

Furthermore, the timing for commercializing cryogenic machining seems perfect. Besides the opportunities within the aerospace industry, large customers in the automotive and oil & gas industry made significant capital investment approximately 15 to 20 years ago and are up to retooling their facilities in the near term. This could be a great chance for 5ME and cryogenic machining (5ME, 2014o).

Product Development

Lead User Integration

5ME is addressing two entities of customers, end-users and machine tool manufacturers. The end-users play a specific role in commercializing this technology. First of all, persuading a well-known end-user to turn to cryogenic machining will be a very good reference and testimonial in the industry. It will show acceptance by the industry. An installed machine will leverage the technology and can be shown to other potential customers (5ME, 2014l, 2014n, 2014o).

Especially in the ramp-up phase of a radical new technology, it is essential to have a close relationship with the first users of the focal technology. Not everything goes right at the forefront of technology implementation. Thus, it is important to find those customers that have the right culture and mindset to dare the risks. In the early technology phases, constant feedback is decisive (5ME, 2014o).

For 5ME, these early customers play another big role as they fund test runs. Correspondingly, they help to offset 5ME's costs. Furthermore, they shape the applications, the portfolio of products, and the types of machines 5ME is targeting on with their feedback. By listening to these lead-users, 5ME understands where to commercialize first (5ME, 2014n).

Due to the obligatory certification process lead-users are even more important within the aerospace industry. It does not make any sense for 5ME to go to companies that build aircraft parts and try to offer cryogenic machining. They do not have the authority to make this change. Thus, 5ME directly addresses the aircraft manufacturer and tries to get their approval. Once this has been achieved, they would allow their tier suppliers to use the technology. Correspondingly, there is no other chance of commercializing the technology to this industry. On the other hand, this opens up great chances. Typically, supply chains in the aircraft industry a tightly woven of middle-sized companies that are unknown to 5ME. With the aircraft manufacturer leveraging cryogenic machining, 5ME gets access to a huge pool of companies that all supply parts to these aircraft manufacturers (5ME, 2014j, 2014l).

Development Partnerships

5ME established a limited number of strategically chosen development partnerships with several customers. When approaching the customers, there has been great interest in the technology, but the customers wanted to see the technology in action and get some validated results (5ME, 2014o).

Correspondingly, 5ME tries to establish references in each of its target markets. OEMs and machine tool builders are the two best references 5ME can have as this would show acceptance by the industry. With these customers, 5ME is closely working together during the development phase. The company tries to understand their customer's manufacturing processes in detail and communicate very much on a regular basis (5ME, 2014o). These early customers fulfill two essential roles for 5ME. Firstly, they fund the test runs at the Tech Center and help to cover 5ME's development costs. Secondly, they deliver essential feedback for product development and furthermore shape the portfolio of applications and machines 5ME is targeting (5ME, 2014n).

Moreover, 5ME cooperated with certain universities at bringing cryogenic machining to practice. Several research projects were started to scientifically leverage technology development (5ME, 2014n).

Risk and Quality Management

5ME has not a detailed risk and quality management system, but established some instruments to deal with emerging risks and quality issues. Every cryogenic kit that is shipped to customers is checked accurately to avoid that the kit would not work and lead to negative publicity in the market (5ME, 2014n, 2014o).

Similarly, 5ME starts to market their technology in the USA in close proximity and cooperation with a few well-selected customers. 5ME has concrete criteria to select the right customer to work with. In weekly calls, the company supports their customers and wants to figure out if problems occur. If any of the shipped kits would run poorly, it could lead to doubt in the technology and draw back the progress of commercialization (5ME, 2014j, 2014o).

For their technology testing, 5ME does not follow a strict formal structure like the design of experiment. 5ME directly tests what they estimate to be a successful target. Nevertheless, the methodology of running a test is much disciplined. Everything is highly documented and the company put a lot of importance on the feedback from the result analysis after the test (5ME, 2014j).

One of the biggest risks of commercializing cryogenic machining is based on the fact that the technology is radically new. The customers cannot compare it to any existing technology. This leads to long sales cycles as the customer needs to be persuaded to take the change and move to the new technology. On the other hand, it takes time to develop and engineer the technology adaption to different machine platforms. If it is sometimes not possible to quickly show the customer positive results based on the parts that they have asked 5ME to test, this may lead to customer frustration. Furthermore, 5ME is the single supplier to provide it. So some customers may be afraid of being locked to just one supplier (5ME, 2014j, 2014l, 2014o).

Platform Strategy

5ME is working towards a platform strategy to share common parts. However, everything up to this point has been unique on the first sets of machines that 5ME has equipped. Once the company has one or two machines in each of the four primarily addressed industries, 5ME will be in the position to sell more of similar or alike machines to those customers and set up a common part strategy accordingly. By now, the company has realized standardization as far as possible at this point in time. All the elements that do not change based on the size of the machine have been standardized like the LN_2 storage and the sub-cooler. Apart from that, the lines, the lance, and the tools will all vary in size based on the machine types. Any standardization is volume driven. Correspondingly, the more machines of the same type will be sold, the more standardization will be possible (5ME, 2014o).

On the other hand, tools that have been developed by 5ME are easily scalable. As the design will not change for these applications 5ME has already equipped, it is just a matter of scaling. The applications that 5ME has not done are getting few (5ME, 2014j).

Intellectual Property

5ME puts special emphasize on the protection of its intellectual property. The company is building value as intellectual property is developed. This reduces the risk for 5ME's investors and will pay back the investment in the future. The technology of internal cooling was licensed originally to MAG IAS from Creare. The foundation for this agreement was primarily three patents that protect the internal LN_2 delivery through the spindle and through the tool. These patents were transferred to 5ME and form the base of their technology (5ME, 2014j, 2014n).

As 5ME has developed optimizations, this justified further patents. Since those original three patents, 5ME has added another six addressing the technology to prevent people from copying 5ME's system. Any time 5ME comes up with a good idea that has a vital commercial potential, the company tries to protect it and files for a patent. Most of 5ME's patents are on cryogenic machining (5ME, 2014j).

Commercialization

Value Proposition and Business Model

5ME positions itself on three separate business fields: Cryogenic Machining, Manufacturing Solutions, and Manufacturing Software. Within the Cryogenic Machining, 5ME is evolving its environmentally friendly machining technology to increase throughput, quality, tool life, and profitability for its customers while reducing energy consumption and facilitating a safer work environment for plant floor personnel. Manufacturing Solutions offer the corresponding portfolio of manufacturing consumables like tools and coolants and productivity supporting services. Manufacturing Software uncovers inefficiencies and leads to overall process transparency. The three different businesses do not depend on but complement each other (5ME, 2014l, 2014n, 2014d).

From a customer perspective, cryogenic machining offers faster machining times, better surfaces, and little to no cleanup or waste compared to traditional cooling methods. There is no need for mist collection, filtration or collection of waste coolant. Energy costs associated with coolant fans, pumps and drives do not occur. As the equipment and workpieces are not contaminated, secondary processes become obsolete and no slippery work surfaces or toxic fumes emerge (5ME, 2014a, p. 2, 2014c).

Besides its core product, which is the cryogenic system kit, 5ME supports its customers especially during the first few months of production. Application engineers help to bring up the process to high efficiency. Furthermore, 5ME is working on a handbook with basic rules and parameters for cryogenic machining as the conventional manufacturing rules are obsolete with this new technology (5ME, 2014j, 2014l).

5ME does not manufacture any part of their cryogenic system on their own. Their competence lies in the engineering, the designing, and the assembly of the kits. Each component is shipped to 5ME's facility in Detroit and assembled, tested, and shipped to the end-users. A cryogenic kit is typically composed of the source, feed, the lance, and the control unit. Usually, kits and cutting tools are quoted separately. A general rule of thumb says that the price for a kit accounts to 30 – 40% of the price of a new medium-sized or larger machine. Cutting tools are consumables and need to be replaced after a certain amount of time. Therefore, the biggest revenue opportunity for cryogenic machining is cutting tool related. 5ME tries to establish a business model that can be compared to the one of the razors and the razor blades. The razor is sold once and the blades are continuously replaced. With every kit come years of revenue for the cutting tools, assuming the machine stays in production. As the margins are even higher for the tools, the revenue opportunities of cutting tools will be much higher than for the kits (5ME, 2014o).

The business model would be to generate the main revenue out of the peripheral tooling. Selling the cryogenic kits at an entry cost would additionally help to get established as the barriers would be lower for customers to step in. Especially in the early commercialization phase, getting kits in production and generating market references is decisive. For additionally lowering the entrance barriers and developing further testimonials, 5ME has contemplated leasing kits to special well known customers over a certain amount of time (5ME, 2014j).

Another potential revenue stream could be generated by license fees. By now, 5ME has specific partners that manufacture and supply the 5ME-designed cutting tools to them. They subsequently commercialize the tools exclusively. Potentially, 5ME could offer particular cutting tool manufacturers a license to manufacture 5ME-designed cryogenic cutting tools and market them independently to end-users. This requires an appropriately installed base of kits to be interesting for cutting tool manufacturers. Thus, this opportunity could evolve in the next year or two (5ME, 2014n).

Commercialization Partnerships

5ME has several strategically chosen partnerships with selected customers. The company focuses on these customers to fully support them and closely cooperate at bringing cryogenic machining to practice. If any of those projects fails, it could put back 5ME several steps in the process of technology commercialization. Correspondingly, 5ME maintains close relations with its customers and similarly, expects them to be totally committed to commercializing cryogenic machining. Appropriate customers should enjoy being at the forefront of technology implementation, have the right culture, be less risk averse, and allocate adequate resources for the project (5ME, 2014o).

In principle, there are two entities of customers for 5ME: machine tool builders and end-users. The machine tool builders help to leverage cryogenic machining by equipping their machines with this technology and offer potential end-users cryogenic equipped machines as an alternative to the conventional machines (5ME, 2014n). Among the most cooperative machine tool builders are Okuma and MAG Automotive. Both companies have a showroom at their facility and showcase cryogenic machining to potential customers on their machines (5ME, 2014l). Between MAG Automotive and 5ME is no legal relation anymore and consequently, there is no difference from a business perspective compared to other customers. Nevertheless, 5ME is familiar with MAG Automotive's product portfolio and MAG Automotive with cryogenic machining. This facilitates the discussion and thus the technology commercialization (5ME, 2014n).

By addressing the end-users of cryogenic machining, the technology could be spread across the entire end user's supply chain. Especially in the case of a very tightly woven supply chain net of mainly middle-sized companies potentially unknown to 5ME, this opens up great opportunities for 5ME (5ME, 2014l).

5ME's business model is to design and engineer all parts of the cryogenic system, but not to produce them. Thus, all components are manufactured by suppliers according to 5ME's specification and shipped to Detroit. In the Tech Center, 5ME assembles, flow-tests, and ships the kits to its customers. Therefore, 5ME needs to have competent suppliers. From a component standpoint, the suppliers of the lance and the cutting tools need to be very strategic partners as these parts are particularly demanding. Correspondingly, 5ME's development team maintains a close relationship with weekly meetings (5ME, 2014j, 2014o).

Furthermore, 5ME facilitates strategic partnerships to certain universities and industry trade publications authors. This supports the publication and subsequently acceptance of the technological advantages of cryogenic machining across the industry by scientific and industry-specific reporting (5ME, 2014o).

Timing

By the end of 2014, the industry in North America, which will be 5ME's focus over the next few years, has just come out of one of the greatest depths since the great depression. The value of efficiency and the concept of global competitiveness have become very present and this is beneficial for cryogenic machining (5ME, 2014l).

Furthermore, some markets are especially interesting for 5ME's new technology. Above all, the aerospace industry is just in front of a huge production ramp up across the new aircraft generations for commercial and military use. According to customer data, the available production capacity will exceed what directly affects the commercialization of cryogenic machining. For this industry 5ME's Cryogenic Business Development Manager rated 5ME's timing to be perfect (5ME, 2014o).

The timing to enter 5ME's further target industries automotive and oil & gas are good as well. As several larger automotive and oil & gas customers made significant capital investments 15 to 20 years ago, a lot of them are planning to retool their facilities within the next years. This additionally fosters the commercialization of cryogenic machining (5ME, 2014o).

Marketing

5ME is currently positioning cryogenic machining as a premium solution for niche applications of tough material (5ME, 2014l). Due to the early technology stadium, 5ME started to focus on the large customers with R&D-funding budgets for testing cryogenic machining to offset their development costs. Subsequently, the selling process is slow as the approval procedures within those organizations are time-consuming. By now, the mode has been to approach interested target customers. Then, these customers usually like to see their material being run in the Tech Center to get validated test results. Afterward, they take these test data and make up a business case by calculating their individual return on investment for selling it to their upper management. Not until the investment is internally approved, a cryogenic system order is placed (5ME, 2014n, 2014o).

Since spinning out, 5ME does considerably more marketing. The company addresses the market with a new brand-name and positions itself as completely dedicated to manufacturing efficiency and cryogenic machining. Within MAG IAS, this was not possible as the parent company was a machine tool company and cryogenic machining was just a part of it (5ME, 2014n). By 2014, 5ME had a focused marketing approach. The company established a dedicated website with detailed information and case studies on cryogenic machining. Furthermore, 5ME leverages social media via YouTube and LinkedIn, installed some blogs, and attends several trade shows to exhibit the benefits of cryogenic machining (5ME, 2014l).

Innovation Success

Sales Performance

Since foundation, 5ME continues to grow its revenue for cryogenic machining. Thus far, virtually all of that revenue was generated by customer testing. The first customer and user machine is already shipped and installed and will be going into production in the first quarter of 2015. The second one will be shipped by beginning of 2015. Due to positive test runs in 2014, 5ME expects to win another eight to ten retrofit orders during 2015 (5ME, 2014o).

This would start to cover 5ME's investments. Because of the lead times of these systems, 5ME estimates to reach the break-even point for cryogenic machining within 2017. From then on, the cryogenic machining business unit will be profitable (5ME, 2014n).

For 2015, 5ME expects cryogenic machining to be 25% of the company's total new business. An equal revenue share of one third for each of the three business segments is anticipated over the next two to three years. By the end of 2018, 5ME estimates cryogenic machining and manufacturing software to account for 75% and manufacturing solutions for 25% of the company's overall revenue (5ME, 2014o).

Product Performance

Within the Tech Center, the performance results of cryogenic machining have been successful. 5ME had ten to twelve positive test runs for customers during 2014. Different materials were tested to run with cryogenic machining on turning centers, horizontal, and vertical machining centers. The results were robust, repeatable, and thus reliable. Furthermore, the involved customers were very excited with respect to the achieved test results. Accordingly, 5ME brought cryogenic machining into industrial use at its first customer. This machine will be in production in the first quarter of 2015. Thus, no industry performance data are available by the end of 2014(5ME, 2014n, 2014o).

However, 5ME received several awards for establishing cryogenic machining: the MM Award for Innovation (2011), the New Equipment Digest King Award (2012), and the Frost & Sullivan Best Practice Award (2013) (5ME, 2014h).

Efficiency

While there is a high investment in the development of cryogenic machining technology, 5ME sustains a certain level of income to stay liquid. Therefore, the company has a run rate business of tools and coolant it offers through its manufacturing solution business segment and sells machine monitoring software through its manufacturing software business segment. Exposures are limited within an agreed budget for each year by 5ME's investor. The achievement of these objectives is measured on a monthly, quarterly, and yearly basis and correspondingly adapted (5ME, 2014j).

To keep the costs down, 5ME tries to get test funding by customers. Most of the test runs have been funded by potential customers. For tests that are outside the scope of the customer or tests that do not deliver a satisfying result after the customer money was consumed, 5ME has internal R&D funding. To keep the intellectual property, tool development is exclusively funded with internal R&D-money (5ME, 2014j, 2014n).

Furthermore, the engineering team saves time and resources by following a smart testing approach. Instead of testing a huge spectrum of parameters, 5ME directly targets the highest level of requirements. By following this approach, 5ME was able to set several land speed records on different materials, i.e. machining these materials faster than anybody ever before (5ME, 2014j).

However, commercializing this radical technology takes time, as it has a great level of novelty and differentness. It took 5ME a whole year to get the first customer on board and the cryogenic system into industrial use. Probably, the following ones are faster, but as cryogenic machining requires a high level of change on behalf of the customer, 5ME estimates that each sales cycle will take at least a period of six months (5ME, 2014n, 2014o).

5ME is satisfied with its technological development in the short term of cryogenic machining thus far. The customer feedback has been good and several customers asked 5ME to quote cryogenic systems. However, with respect to the concrete commercialization, the low amount of incoming orders is frustrating as 5ME wants to see things happen much faster. One reason therefor is the reluctant behavior of the technology adopters that have a lot of questions and fear. On a scale from one to ten, 5ME ascribes the technological development a seven and the commercialization a five (5ME, 2014n).

Appendix IV – Variables and Hypotheses

The operationalization of categories has been published by Dahl in his master thesis (Dahl, 2015, pp. 35–43).

Innovation Success

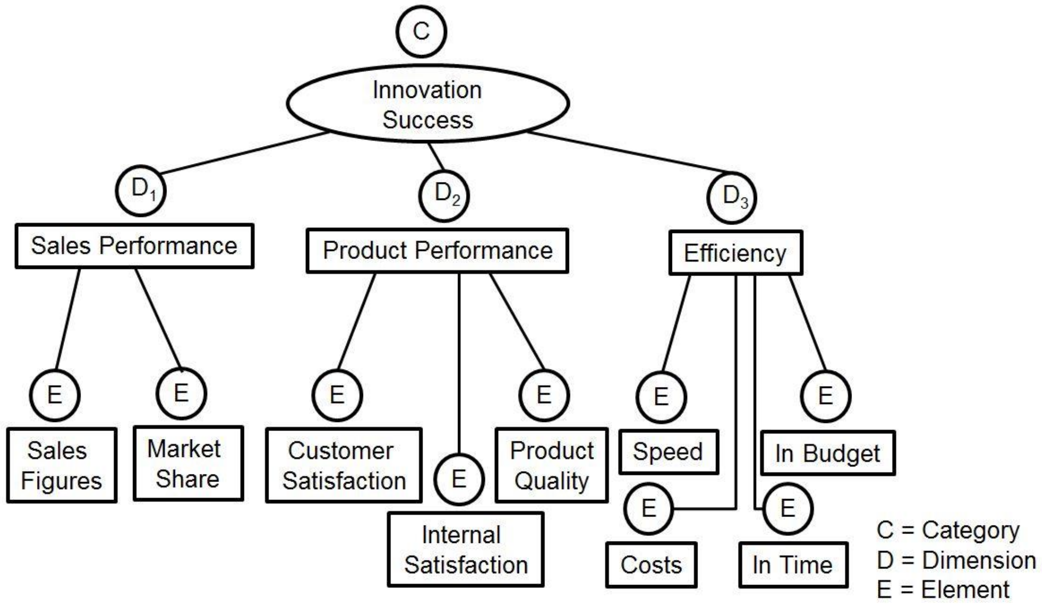

Figure 77: Operationalization of the Category "Innovation Success"

Innovation Context

Technology

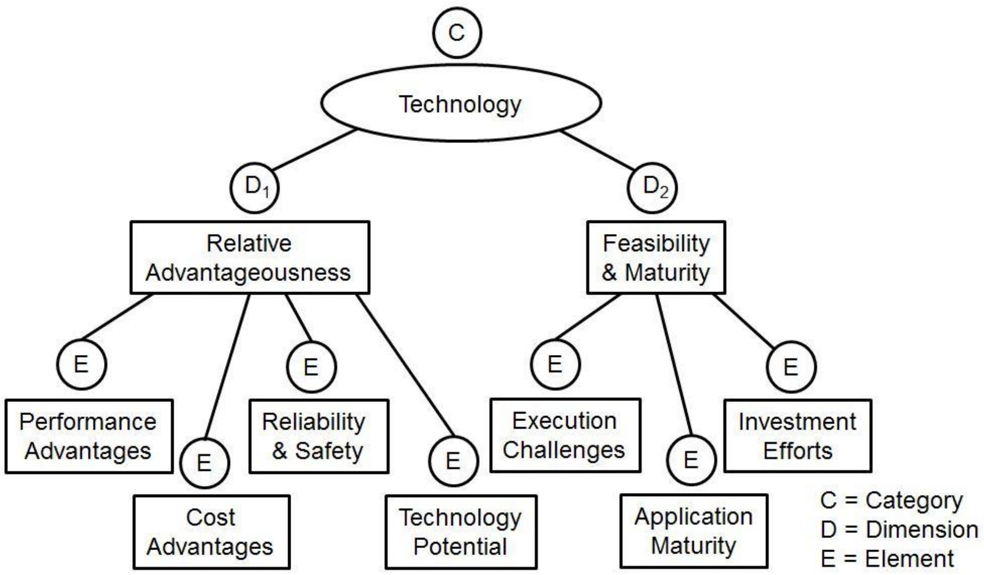

Figure 78: Operationalization of the Category "Technology"

Target Market

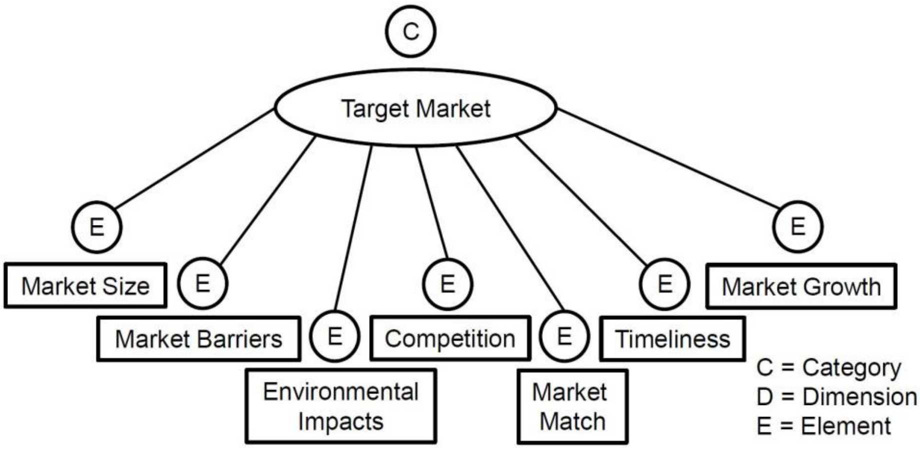

Figure 79: Operationalization of the Category "Target Market"

Organization

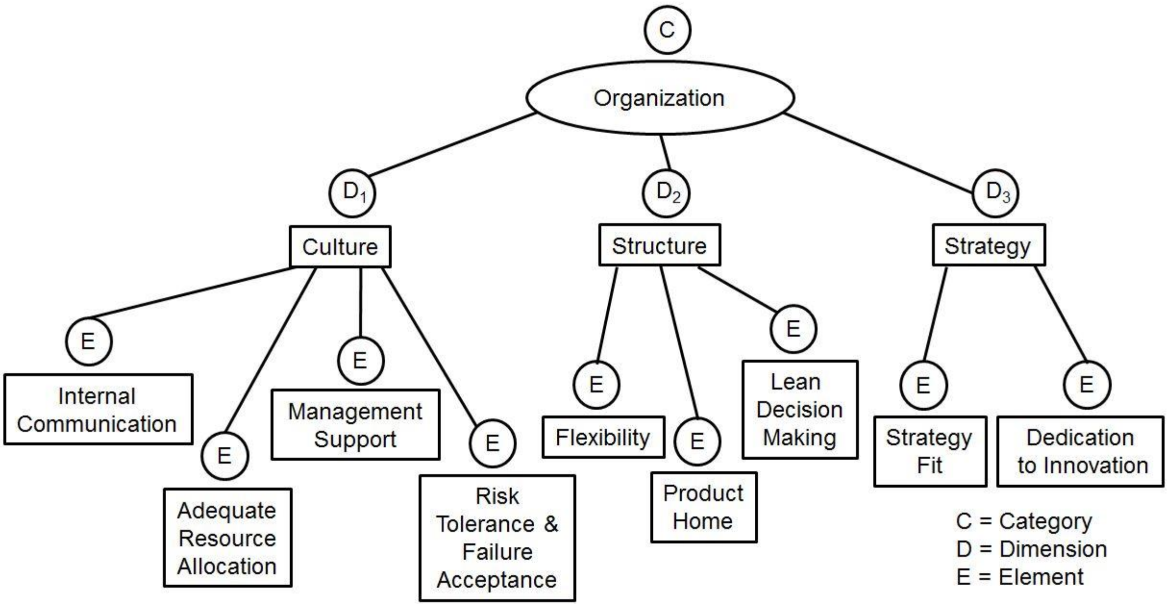

Figure 80: Operationalization of the Category "Organization"

Entrepreneurial Team

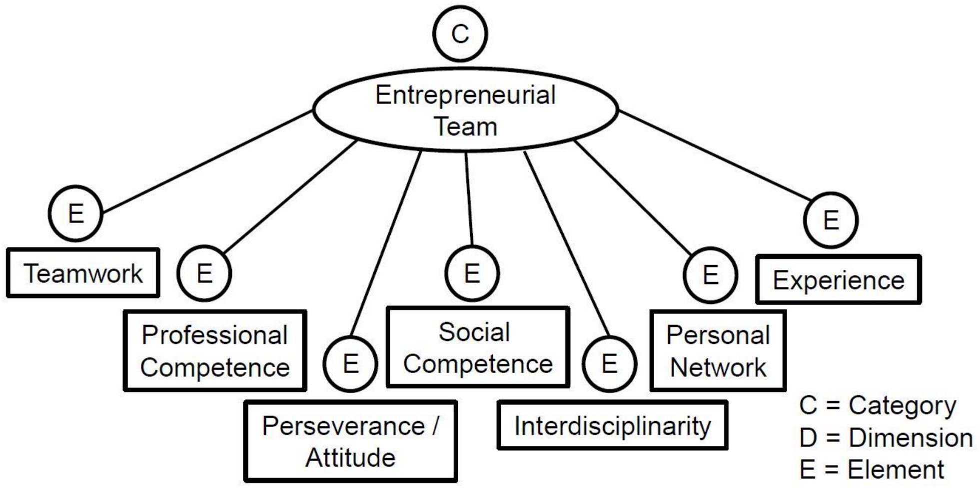

Figure 81: Operationalization of the Category "Entrepreneurial Team"

Innovation Process

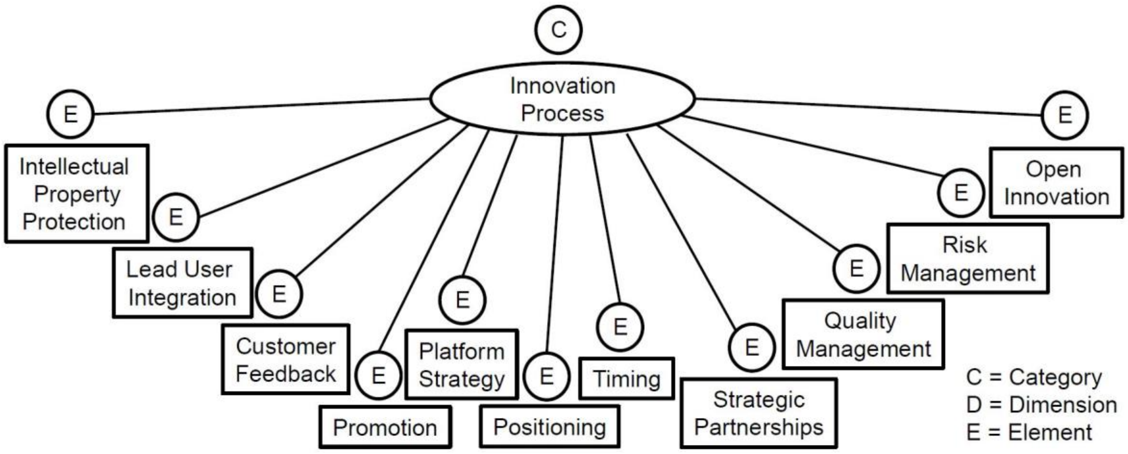

Figure 82: Operationalization of the Category "Innovation Process"

Appendix V – Quantitative Survey

1) Survey Wording and Previous Studies

Table 17: Survey Wording (Dahl, 2015, pp. 93–97)

Variable	Survey Wording	Previous Studies	Wording within these Studies
Innovation Success			
Sales Figures	Der erzielte Umsatz entsprach in vollem Umfang den zu Projektbeginn formulierten Erwartungen.	-	
Market Share	Der mit der Innovation erreichte Marktanteil entsprach den zu Projektbeginn formulierten Erwar-tungen.	-	
Customer Satisfaction	Der Kunde war mit der erreichten Produktperformance der Innovation unzufrieden.	Mu, Peng, MacLachlan – Effect of risk manage-ment strategy on NPD performance	Overall performance of the product is satisfacto-ry.
Internal Satisfaction	Die Produktperformance der Innova-tion entsprach den zu Beginn des Projektes formulierten Vorgaben.	Mu, Peng, MacLachlan – Effect of risk manage-ment strategy on NPD performance	The product meets intended functions.
Product Quality	Die erreichte Qualität des neu entwickelten Produktes war auf einem hohen Niveau.	-	
Speed	Die Geschwindigkeit des Entwick-lungsprojektes war hoch.	Mu, Peng, MacLachlan – Effect of risk manage-ment strategy on NPD performance	Overall performance of the NPD process is good.
Costs	Die vorhandenen Ressourcen wurden im Innovationsprojekt effizient eingesetzt.	Mu, Peng, MacLachlan – Effect of risk manage-ment strategy on NPD performance	The cost management of NPD is satisfactory.
In Time	Der zu Beginn formulierte Zeitplan für das Innovationsprojekt konnte nicht eingehalten werden.	Mu, Peng, MacLachlan – Effect of risk manage-ment strategy on NPD performance	The product reaches the market timely.
In Budget	Das zu Projektbeginn kalkulierte Budget wurde nicht überschritten.	-	
Technology			
Performance Advantages	Aus Kundensicht war die Technologie leistungsfähiger als mögliche Alterna-tivtechnologien.	Cooper, Kleinschmidt – New Products: What Separates Winners from Losers?	Product offered unique benefits to the customer - benefits not found in competitive products
Cost Advantages	Über die gesamte Produktlebensdauer betrachtet hatte die Technologie aus Kundensicht große Kostenvorteile gegenüber Alternativtechnologien.	-	
Reliability & Safety	Aus Kundensicht war die Technologie verlässlich und sicher.	-	
Technology Potential	Die Technologie kann grundsätzlich in weiteren Produkten eingesetzt werden (z.B. in anderen Firmen/Branchen).	Wind, Mahajan - Issues and Opportunities in New Product Develop-ment: An Introduction to the Special Issue	Our NPD focus is increasingly on the development of product platforms, including the development of multi-generation products

		Gruber, MacPhearson - Look Before You Leap: Market Opportunity Identification in Emerg-ing Technology Firms	Generality of Technology
Execution Challenges	Die technologische Entwicklung der Produktinnovation bis zur Anwendungsreife war mit Schwierigkeiten verbunden.	Cooper – Identifying Industrial New Product Success: Project New-Prod	Mechanical-technical complexity of the product
Application Maturity	Die Technologie wurde schon in anderen Produkten (z.B. in anderen Firmen/Branchen) eingesetzt.	Fortune, White – Fram-ing of project critical success factors by a systems model	Proven / familiar technology
Investment Efforts	Für die technologische Entwicklung der Produktinnovation bis zur Anwendungsreife waren hohe Investitionen nötig.	-	
Target Market			
Market Size	Der ausgewählte Zielmarkt war aufgrund seiner Größe interessant.	Cooper - Identifying Industrial New Product Success: Project New-Prod	Market Size
Market Barriers	Es gab kaum Barrieren auf dem Markt, welche die Markteinführung der Produktinnovation behinderten.		
Environmental Impacts	Die externen Einflüsse, z.B. politischer oder makro-ökonomischer Art, behinderten die Markteinfüh-rung der Produktinnovation.	Fortune, White - Framing of project critical success factors by a systems model	Environmental influ-ences were taken into account successfully
Competition	Es gab bei der Markteinführung der Produktinnovation großen Wettbewerb auf dem Markt.	Cooper - Identifying Industrial New Product Success: Project New-Prod	Degree of competition in the market
		Cooper, Kleinschmidt - New Products: What Separates Winners from Losers?	Intensity of competition in the marketplace
Market Match	Aus heutiger Sicht wäre es besser gewesen die Produktinnovation auf einem anderen Markt einzuführen.	-	
Timeliness	Aus heutiger Sicht betrachtet war der Zeitpunkt der Markteinführung richtig.	-	
Market Growth	Der ausgewählte Zielmarkt wies zum Zeitpunkt des Markt-eintritts gute Aussichten auf ein großes Markt-wachstum auf.	-	
Organization			
Internal Communication	Die interne Kommunikation war offen und ehrlich.	Hoegel, Gemuenden - Teamwork Quality and the Success of Innovative Projects	Is there sufficiently frequent, informal, direct, and open com-munication?
		C. Brooke Dobni, (2008),"Measuring innovation culture in organizations", European Journal of Innovation	Communications are open and honest.
Adequate Ressource Allocation	Im Rahmen des Innovationsprojekts konnten wir auf alle für die Umsetzung notwendigen Ressourcen zurückgreifen.	Fortune, White - Framing of project critical success factors by a systems model	All types of resources were sufficient and well allocated.

		Mu, Peng, MacLachlan - Effect of risk management strategy on NPD performance	There are stable monetary and other resources for the project.
Management Support	Unser Management half uns dabei Hindernisse bei der Innovationsumsetzung zu überwinden.	Cooper, Kleinschmidt - New Products: What Separates Winners from Losers?	Top management commitment; Top management guidance / direction for the project
		Brooke Dobni, (2008),"Measuring innovation culture in organizations", European Journal of Innovation	Our management helps break down barriers that stand in the way of implementation.
Risk Tolerance & Failure Acceptance	Bei der Innovationsumsetzung zeichnete sich unsere Organi-sation durch ein Klima aus, in welchem Risiken toleriert und Misserfolge akzeptiert wurden.	-	
Flexibility	Die Organisationsstruktur des Unternehmens ermöglichte eine flexible Umsetzung des Innovationsprojekts.	Wind, Mahajan - Issues and Opportunities in New Product Development: An Introduction to the Special Issue	Our development efforts allow for flexibility and the utilization of alternative NPD approaches and associated marketing research and modeling, depending on the specific situation.
		Mu, Peng, MacLachlan - Effect of risk management strategy on NPD performance	The firm can respond quickly to its NPD plan in case of dramatic changes.
Product Home	Nach Projektabschluss war es schwierig einen Zuständigkeitsbereich für die Produktinnovation in der Organisation zu finden.	Griffin - PDMA research on new product development practices- Updating trends and benchmarking best practices	Which of the following best describes the way the new product effort is structured in your organization: 1. New product department with permanent staff members. 2. Distinct division or venture group. 3. A new product committee oversees all development efforts. 4. Each business unit's general manager directs their own NPD efforts. 5. A single function is responsible for NPD: (Which function?) (R&D, engineering, planning, marketing) 6. A product development process owner helps deploy our process across the firm.
Lean Decision Making	Die Prozesse zur Entscheidungsfindung im Rahmen des Innovationspro-jekts waren schlank.	-	
Strategy Fit	Die strategische Ausrichtung des Unternehmens war für die Umsetzung der Produktinnovation hinderlich.	Griffin – PDMA research on new product development practices- Updating trends and benchmarking best practices	Does your organization have a specific strategy for its new product activities which directs and integrates the entire new product program?
		Lilien, Von Hippel – Performance Assessment for Lead-User Idea Generation Process	Fit with current strategic plan of our business unit

Dedication to Innovation	Unser Unternehmen ist geprägt von einer starken Innovationskultur und einer Fokussierung auf die Entwicklung neuer Produkte.	-	
Entrepreneurial Team			
Teamwork	Die beteiligten Personen arbeiteten gut im Team zusammen.	Hoegel, Gemuenden - Teamwork Quality and the Success of Innovative Projects	Are team members motivated to maintain the team? Is there team spirit?
		Brooke Dobni - Measuring innovation culture in organizations", European Journal of Innovation	The employees in my area act as a team.
Professional Competence	Im Hinblick auf die benötigten fachlichen Kompetenzen waren genau die richtigen Personen am Innovations-projekt beteiligt.	Nieto, Quevedo - Absorp-tive capacity, technologi-cal opportunity, knowledge spillovers, and innovative effort	Most of our staff are highly skilled and qualified
Perseverance / Attitude	Die beteiligten Personen wollten trotz aller Schwierig-keiten das Innovationsprojekt unbedingt zum Erfolg bringen.	Hoegel, Gemuenden - Teamwork Quality and the Success of Innovative Projects	Do team members exert all efforts to the team's tasks?
		Hofstede – Measuring Organisational Cultures: Qulitative and quantita-tive study	People put in maximal effort
Social Competence	Die beteiligten Personen hatten eine niedrig ausgeprägte Sozialkompetenz.	-	
Interdisciplinarity	Bei der Innovationsumsetzung waren Personen mit verschiedenen Kompetenzen betei-ligt, z.B. aus verschiedenen Organisations-bereichen wie Marketing, Vertrieb und Entwicklung.	-	
Personal Network	Die beteiligten Personen verfügten über ein großes persönliches Netzwerk, was bei der Innovationsumsetzung hilfreich war.	Lilien, Von Hippel – Performance Assessment for Lead-User Idea Generation Process for NPD	Establish a network of valuable internal contacts
		Lilien, Von Hippel – Performance Assessment for Lead-User Idea Generation Process for NPD	Develop contacts with external experts
Experience	Die beteiligten Personen hatten wenig Erfahrung bei der Durchführung von derartigen Innovationsprojekten.	Fortune, White - Framing of project critical success factors by a systems model	All members had worked on earlier projects using the same 'in-house' Project Management Method and most had worked with the project manag-er before
		Mu, Peng, MacLachlan - Effect of risk manage-ment strategy on NPD performance	The new product management team is experienced in new project development.

Innovation Process			
	Bitte geben Sie an, wie viel Wert im konkreten Innovationsprojekt auf die folgenden Maßnahmen gelegt wurde:		
Intellectual Property	Schutz von geistigem Eigentum	-	
Lead User Integration	Integration von Lead-Usern bei der Innovationsumsetzung	Wind, Mahajan - Issues and Opportunities in New Product Development: An Introduction to the Special Issue	Our NPD process incorporates the voice of the customer at all levels.
		Coviello, Joseph - Creating innovations with customers	Customer engages in hands-on development and trials through development and testing.
Customer Feedback	Einbeziehen von Kundenfeedback in die Innovationsumsetzung	Coviello, Joseph – Creating innovations with customers	Firm asks customer for feedback on the concept, product. or market (can occur throughout NPD)
		Coviello, Joseph – Creating innovations with customers	Customer offers extensive opinions, feedback, or data on the concept, product, or market (can occur throughout NPD)
Promotion	Gezielte Kommunikationsmaßnahmen (z.B. Messeauftritte, Presseberichte, Broschüren)	-	
Platform Strategy	Verfolgung einer Plattformstrategie für eine gezielte Produktportfolioplanung	Wind, Mahajan - Issues and Opportunities in New Product Development: An Introduction to the Special Issue	Our NPD focus is increasingly on the development of product platforms, including the development of multi-generation products
Positioning	Bewusste Positionierung des Produkts am Markt (z.B. als Premiumprodukt)	-	
Timing	Bewusste Wahl des Zeitpunkts für den Markteintritt	Cooper - Identifying Industrial New Product Success: Project NewProd	First to the market
Strategic Partnerships	Bildung strategischer Partnerschaften	Zahra, Bogner - Technology Strategy and Software New Ventures Performance_ Exploring the Moderating Effect of the Competitive Environment	Is heavily engaged in strategic alliances.
		Nieto, Quevedo - Absorptive capacity, technological opportunity, knowledge spillovers, and innovative effort	We have developed new products and/or processes in collaboration with other firms
Quality Management	Qualitätsmanagement	-	
Risk Management	Risikomanagement	Mu, Peng, MacLachlan - Effect of risk management strategy on NPD performance	We take action to minimize the uncertainty of total project investment.
Open Innovation	Open Innovation	-	

2) Survey Design

Table 18: Survey Design

Survey Parts	No. of Questions	Scales
1. Lead-In Questions	**2**	Dichotomous/Ordinal
2. Warm-Up Questions	**6**	Dichotomous/Nominal/Ordinal
3. Questions addressing the Independent Variables (Innovation Context)		
• **Target Market**	**7**	Interval (5-point Likert Scale)
• **Organization**	**9**	Interval (5-point Likert Scale)
• **Technology**	**7**	Interval (5-point Likert Scale)
• **Entrepreneurial Team**	**7**	Interval (5-point Likert Scale)
4. Questions addressing the Dependent Variables (Innovation Success)		
• **Innovation Success**	**9**	Interval (5-point Likert Scale)
5. Questions addressing the Independent Variables (Innovation Process)		
• **Innovation Process (descriptive – Part 1)**	**5**	Nominal/Interval/Ordinal
• **Innovation Process**	**11**	Interval (5-point Likert Scale)
• **Innovation Process (descriptive – Part 2)**	**10**	Nominal/Interval/Ordinal
6. Demographic Questions	**3**	Nominal/Interval/Ordinal

3) Survey Instrument

Karlsruher Institut für Technologie

Umfrage des Karlsruher Instituts für Technologie zum Thema:

„Radikale technische Innovationen in der Antriebstechnik“

Liebe Teilnehmer/-innen,

die Bearbeitung des Fragebogens wird in etwa **15 Minuten** Ihrer Zeit in Anspruch nehmen. Wir bitten Sie, möglichst alle Fragen vollständig zu beantworten, da nur so aussagekräftige Ergebnisse gewonnen werden können.

Als kleines Dankeschön verlosen wir unter allen Teilnehmern, die den Fragebogen vollständig ausgefüllt haben, **drei Amazon-Gutscheine** im Wert von jeweils **30 €**. Gerne senden wir Ihnen bei Interesse nach Auswertung der Studie die **Ergebnisse** zu.

Ihre Angaben werden selbstverständlich **absolut vertraulich** behandelt.

Anmerkung:

Bei der vorliegenden Studie stehen **radikale technische Produktinnovationen** im Fokus der Betrachtung. ***Radikale Innovationen*** weisen einen **hohen Neuheitsgrad** auf und bewirken oft **umfassende Veränderungen** im Unternehmen und dem Markt. Dadurch eröffnen sich große Marktchancen, wobei das unternehmerische Risiko allerdings auch dementsprechend hoch ist.

Umfrage:

Radikale technische Innovationen sind längerfristig für das Fortbestehen von technologiegetriebenen Unternehmen entscheidend.

○ Ja ○ Nein

Ordnen Sie die folgenden Faktoren nach ihrem Grad der Wichtigkeit für den Erfolg von radikalen technischen Innovationen in der Antriebstechnik.

Bitte nummerieren Sie die aufgelisteten Faktoren in der Reihenfolge ihrer Wichtigkeit, beginnen Sie mit 1 (am wichtigsten) bis 5 (am wenigsten wichtig).

Eigenschaften der Organisation	☐
Beteiligte Personen	☐
Marktpotenzial	☐
Vorteilhaftigkeit der Technologie	☐
Innovationsprozess	☐

Wie viele Jahre Berufserfahrung haben Sie?

< 1	1 - 3	3 - 7	7 - 15	> 15	Keine Angabe
○	○	○	○	○	○

An wie vielen Innovationsprojekten waren Sie in den vergangenen 5 Jahren beteiligt?

0	1	2 - 5	6 - 10	> 10	Keine Angabe
○	○	○	○	○	○

KIT – Universität des Landes Baden-Württemberg und nationales Forschungszentrum in der Helmholtz-Gemeinschaft

www.kit.edu

Waren Sie in der Vergangenheit in irgendeiner Form an einem Projekt beteiligt, bei welchem eine radikale technische Produktinnovation für die Antriebstechnik entwickelt und in den Markt eingeführt wurde?

○ Ja ○ Nein

In welcher Branche ist Ihr Unternehmen tätig?
*Bitte wählen Sie **nur eine** der folgenden Antworten aus:*

○ Herstellung von Datenverarbeitungsgeräten, elektronischen und optischen Erzeugnissen (z.B. Leiterplatten, Messgeräte…)
○ Herstellung von elektrischen Ausrüstungen (z.B. Generatoren, Elektromotoren…)
○ Maschinenbau
○ Herstellung von Kraftwagen und Kraftwagenteilen
○ Sonstiger Fahrzeugbau (z.B. Schiffbau, Schienenfahrzeuge, Luft- & Raumfahrt...)
○ Andere Branche, bitte angeben: ____________

ACHTUNG:

Bei der Beantwortung der folgenden Fragen soll bewusst **ein konkretes Projekt im Fokus** stehen, auf welches Sie **rückblickend alle Antworten beziehen** sollen. Bitte denken Sie also an ein konkretes Projekt, bei welchem **eine radikale technische Produktinnovation** für die Antriebstechnik zunächst entwickelt und dann in den Markt eingeführt wurde.

Wählen Sie am besten diese Produktinnovation aus, welche den größten Neuheitsgrad aufwies. Vielen Dank!

Welche Bezeichnung trifft am besten auf Ihre Rolle im konkreten Innovationsprojekt zu?
*Bitte wählen Sie **nur eine** der folgenden Antworten aus:*

○ Projektmanager
○ Entwickler
○ Fertigungsverantwortlicher
○ Mitarbeiter im Marketing
○ Vertriebsmitarbeiter
○ Beteiligter im Entscheidungsprozess
○ Externer Berater
○ Andere Rolle, bitte angeben: ____________

Bitte bewerten Sie Ihre Zufriedenheit im Hinblick auf das konkrete Innovationsprojekt.
*Bitte wählen Sie **nur eine** der folgenden Antworten aus:*

	Überhaupt nicht zufrieden (1)	Nicht zufrieden (2)	Weder noch (3)	Zufrieden (4)	Sehr zufrieden (5)	Keine Angabe
Waren Sie mit dem Resultat dieses Innovationsprojekts zufrieden?	○	○	○	○	○	○

Bitte geben Sie auf den folgenden Seiten an, inwiefern Sie der jeweiligen Aussage im Hinblick auf das konkrete Innovationsprojekt zustimmen oder nicht. **Unterscheiden Sie** hierbei **den Grad Ihrer Zustimmung** auf einer Skala von **1 (Stimme überhaupt nicht zu)** bis **5 (Stimme voll und ganz zu)**.

Die Aussagen sind zum Teil bewusst ähnlich formuliert. Bitte geben Sie dennoch für alle Aussagen jeweils Ihre Zustimmung an.

Bitte bewerten Sie die folgenden Aussagen gemäß Ihrer Zustimmung:

	Stimme überhaupt nicht zu (1)	Stimme nicht zu (2)	Weder noch (3)	Stimme zu (4)	Stimme voll und ganz zu (5)	Keine Angabe
Der ausgewählte Zielmarkt war aufgrund seiner **Größe interessant**.	○	○	○	○	○	○
Es gab **kaum Barrieren** auf dem Markt, welche die Markteinführung der Produktinnovation behinderten.	○	○	○	○	○	○
Die **externen Einflüsse**, z.B. politischer oder makro-ökonomischer Art, **behinderten** die Markteinführung der Produktinnovation.	○	○	○	○	○	○
Es gab bei der Markteinführung der Produktinnovation **großen Wettbewerb** auf dem Markt.	○	○	○	○	○	○
Aus heutiger Sicht wäre es **besser** gewesen die Produktinnovation auf einem **anderen Markt** einzuführen.	○	○	○	○	○	○
Aus heutiger Sicht betrachtet war der **Zeitpunkt** der **Markteinführung richtig**.	○	○	○	○	○	○
Der ausgewählte Zielmarkt wies zum Zeitpunkt des Markteintritts **gute Aussichten** auf ein **großes Marktwachstum** auf.	○	○	○	○	○	○

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Bitte bewerten Sie die folgenden Aussagen gemäß Ihrer Zustimmung:

	Stimme überhaupt nicht zu (1)	Stimme nicht zu (2)	Weder noch (3)	Stimme zu (4)	Stimme voll und ganz zu (5)	Keine Angabe
Die **interne Kommunikation** war **offen und ehrlich**.	○	○	○	○	○	○
Im Rahmen des Innovationsprojekts konnten wir auf **alle** für die Umsetzung **notwendigen Ressourcen** zurückgreifen.	○	○	○	○	○	○
Unser **Management half uns** dabei Hindernisse bei der Innovationsumsetzung zu überwinden.	○	○	○	○	○	○
Bei der Innovationsumsetzung zeichnete sich unsere Organisation durch ein **Klima** aus, in welchem **Risiken toleriert** und **Misserfolge akzeptiert** wurden.	○	○	○	○	○	○
Die **Organisationsstruktur** des Unternehmens ermöglichte eine **flexible Umsetzung** des Innovationsprojekts.	○	○	○	○	○	○
Nach Projektabschluss war es **schwierig** einen **Zuständigkeitsbereich** für die Produktinnovation in der Organisation zu finden.	○	○	○	○	○	○
Die **Prozesse** zur **Entscheidungsfindung** im Rahmen des Innovationsprojekts waren **schlank**.	○	○	○	○	○	○
Die **strategische Ausrichtung** des Unternehmens war für die Umsetzung der Produktinnovation **hinderlich**.	○	○	○	○	○	○
Unser Unternehmen ist geprägt von einer **starken Innovationskultur** und einer Fokussierung auf die Entwicklung neuer Produkte.	○	○	○	○	○	○

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Bei den folgenden Fragen steht die **Technologie, welche der Innovation zugrunde liegt, im Fokus** der Fragestellung. Bitte beantworten Sie deshalb die folgenden Fragen im Hinblick auf die der Innovation zugrunde liegenden Technologie.

Bitte bewerten Sie die folgenden Aussagen gemäß Ihrer Zustimmung:

	Stimme überhaupt nicht zu (1)	Stimme nicht zu (2)	Weder noch (3)	Stimme zu (4)	Stimme voll und ganz zu (5)	Keine Angabe
Aus Kundensicht war die **Technologie leistungsfähiger** als mögliche Alternativ-technologien.	○	○	○	○	○	○
Über die gesamte Produktlebensdauer betrachtet hatte die **Technologie** aus Kundensicht große **Kostenvorteile** gegenüber Alternativtechnologien.	○	○	○	○	○	○
Aus Kundensicht war die **Technologie verlässlich** und **sicher**.	○	○	○	○	○	○
Die **Technologie** kann grundsätzlich in **weiteren Produkten eingesetzt** werden (z.B. in anderen Firmen/ Branchen).	○	○	○	○	○	○
Die **technologische Entwicklung** der Produktinnovation bis zur Anwendungsreife war **mit Schwierigkeiten verbunden**.	○	○	○	○	○	○
Die **Technologie** wurde **schon in anderen Produkten** (z.B. in anderen Firmen/Branchen) eingesetzt.	○	○	○	○	○	○
Für die **technologische Entwicklung** der Produktinnovation bis zur Anwendungsreife waren **hohe Investitionen** nötig.	○	○	○	○	○	○

Bitte bewerten Sie die folgenden Aussagen gemäß Ihrer Zustimmung:

	Stimme überhaupt nicht zu (1)	Stimme nicht zu (2)	Weder noch (3)	Stimme zu (4)	Stimme voll und ganz zu (5)	Keine Angabe
Die beteiligten Personen arbeiteten gut im **Team** zusammen.	○	○	○	○	○	○
Im Hinblick auf die benötigten **fachlichen Kompetenzen** waren genau die **richtigen Personen** am Innovations-projekt **beteiligt**.	○	○	○	○	○	○
Die **beteiligten Personen wollten** trotz aller Schwierig-keiten das **Innovationsprojekt unbedingt zum Erfolg bringen**.	○	○	○	○	○	○
Die beteiligten Personen hatten eine **niedrig** ausgeprägte **Sozialkompetenz**.	○	○	○	○	○	○
Bei der Innovationsumsetzung waren **Personen mit verschiedenen Kompetenzen beteiligt**, z.B. aus verschiedenen Organisations-bereichen wie Marketing, Vertrieb und Entwicklung.	○	○	○	○	○	○
Die beteiligten Personen verfügten über ein **großes persönliches Netzwerk**, was bei der Innovationsumsetzung hilfreich war.	○	○	○	○	○	○
Die **beteiligten Personen** hatten **wenig Erfahrung** bei der Durchführung von derartigen Innovationsprojekten.	○	○	○	○	○	○

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Bitte bewerten Sie die folgenden Aussagen gemäß Ihrer Zustimmung:

	Stimme überhaupt nicht zu (1)	Stimme nicht zu (2)	Weder noch (3)	Stimme zu (4)	Stimme voll und ganz zu (5)	Keine Angabe
Die **Geschwindigkeit** des Innovationsprojektes war **hoch**.	○	○	○	○	○	○
Die **vorhandenen Ressourcen** wurden im Innovationsprojekt **effizient eingesetzt**.	○	○	○	○	○	○
Der zu Beginn formulierte **Zeitplan** für das Innovationsprojekt konnte **nicht eingehalten** werden.	○	○	○	○	○	○
Das zu Projektbeginn **kalkulierte Budget** wurde **nicht überschritten**.	○	○	○	○	○	○
Der **Kunde** war **mit** der erreichten **Produktperformance** der Innovation **unzufrieden**.	○	○	○	○	○	○
Die **Produktperformance** der Innovation **entsprach** den zu Beginn des Projektes formulierten **Vorgaben**.	○	○	○	○	○	○
Die **erreichte Qualität** des neu entwickelten Produktes war auf einem **hohen Niveau**.	○	○	○	○	○	○
Der erzielte **Umsatz entsprach** den zu Projektbeginn formulierten **Erwartungen**.	○	○	○	○	○	○
Der mit der Innovation erreichte **Marktanteil entsprach** den zu Projektbeginn formulierten **Erwartungen**.	○	○	○	○	○	○

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Bitte geben Sie bei den folgenden Fragestellungen an, wie Sie im Hinblick auf das **konkrete Innovationsprojekt vorgegangen** sind.

*Bitte wählen Sie **nur eine** der angegebenen Antwortmöglichkeiten pro Fragestellung aus:*

	Nie	Eher sporadisch	Zu gewissen Meilensteinen / am Ende von Projektphasen	Häufig	Kontinuierlich	Keine Angabe
In welcher **Regelmäßigkeit** wurde im Innovationsprojekt **Feedback von Kunden** eingeholt?	◯	◯	◯	◯	◯	◯
In welcher **Regelmäßigkeit** wurde dieses **Feedback in den Entwicklungsprozess** des Innovationsprojekts **zurückgeführt**?	◯	◯	◯	◯	◯	◯

In welcher Form wurde im Innovationsprojekt Feedback von Kunden eingeholt?

*Bitte wählen Sie **alle** zutreffenden Antworten aus:*

- ◯ Nie
- ◯ Befragung zu Projektstart
- ◯ Vorstellung des Produktkonzepts
- ◯ Vorstellung des Prototyps
- ◯ Praxistest des Prototyps beim Kunden
- ◯ Praxistest des Endprodukts beim Kunden
- ◯ Befragung vor Markteinführung
- ◯ Befragung nach Markteinführung
- ◯ Weitere, bitte angeben: ____________________

In welchen Phasen sind Lead-User am Innovationsprojekt beteiligt worden?

*Bitte wählen Sie **alle** zutreffenden Antworten aus:*

- ◯ Nie
- ◯ Ideengenerierung
- ◯ Formulierung von Anforderungen
- ◯ Produktentwicklung
- ◯ Produkttest
- ◯ Markteinführung
- ◯ Weitere, bitte angeben: ____________________

Lead-User sind technisch versierte Nachfrager, deren Bedürfnisse als repräsentativ für die zukünftigen Anforderungen in einen Markt angesehen werden können. Zudem weisen sie eine hohe Kaufbereitschaft für Produktinnovationen auf und können somit als Referenzkunden im ausgewählten Zielmarkt dienen.

In welcher Form wurde die vorliegende Innovation mithilfe von gewerblichen Schutzrechten (wie z.B. Patenten oder Gebrauchsmustern) geschützt?

*Bitte wählen Sie **alle** zutreffenden Antworten aus:*

- ◯ Gar nicht
- ◯ Anmeldung von Schutzrechten für die zugrunde liegende Technologie
- ◯ Anmeldung von Schutzrechten für das Kernprodukt
- ◯ Anmeldung von Schutzrechten für ergänzende Komponenten
- ◯ Andere, bitte angeben: ______________________

Bitte geben Sie in der folgenden Tabelle auf einer Skala von 1 (sehr wenig Wert) bis 5 (sehr viel Wert) an, wie viel **Wert** im konkreten Innovationsprojekt auf die **folgenden Maßnahmen** gelegt wurde.

	Sehr wenig Wert (1)	(2)	(3)	(4)	Sehr viel Wert (5)	Keine Angabe
Schutz von **geistigem Eigentum**	◯	◯	◯	◯	◯	◯
Integration von **Lead-Usern** bei der Innovationsumsetzung	◯	◯	◯	◯	◯	◯
Einbeziehen von **Kundenfeed-back** in die Innovationsumsetzung	◯	◯	◯	◯	◯	◯
Gezielte **Kommunikationsmaß-nahmen** (z.B. Messeauftritte, Presseberichte, Broschüren)	◯	◯	◯	◯	◯	◯
Verfolgung einer **Plattformstra-tegie** für eine gezielte Pro-duktportfolioplanung	◯	◯	◯	◯	◯	◯
Bewusste Positionierung des Produkts am Markt (z.B. als Premiumprodukt)	◯	◯	◯	◯	◯	◯
Bewusste Wahl des **Zeitpunkts** für den **Markteintritt**	◯	◯	◯	◯	◯	◯
Bildung **strategischer Partnerschaften**	◯	◯	◯	◯	◯	◯
Qualitätsmanagement	◯	◯	◯	◯	◯	◯
Risikomanagement	◯	◯	◯	◯	◯	◯
Open Innovation	◯	◯	◯	◯	◯	◯

Unter dem Begriff ***Open Innovation*** wird die Öffnung des Innovationsprozesses von Organisationen gegenüber der Außenwelt verstanden. Es beschreibt die zweckmäßige Nutzung von unternehmensinternem und -externem Wissen.

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Zum Abschluss der Befragung benötigen wir nun noch **einige allgemeine Angaben** zum Innovationsprojekt und Ihrer Organisation.

Bitte geben Sie an, ob das Innovationsprojekt aus Ihrer Sicht eher markt- oder eher technologiegetrieben war. Bitte beantworten Sie die Frage auf einer Skala von 1 (marktgetrieben) bis 5 (technologiegetrieben).

*Bitte wählen Sie **nur eine** der folgenden Antwortmöglichkeiten aus:*

Markt-getrieben				Technologie-getrieben	
(1)	(2)	(3)	(4)	(5)	Keine Angabe
○	○	○	○	○	○

Bitte bewerten Sie den Neuheitsgrad der Produktinnovation. Die Innovation war meiner Einschätzung nach…

*Bitte wählen Sie **nur eine** der folgenden Antworten aus:*

- ○ neu für unser Unternehmen
- ○ neu für unsere Branche
- ○ neu für die Welt
- ○ Anderer Neuheitsgrad, bitte angeben: ………………………

Welche Bezeichnung trifft am besten auf die Strategie zur Einführung der Produktinnovation auf dem Markt zu?

*Bitte wählen Sie **nur eine** der folgenden Antworten aus:*

- ○ Pionier (First Mover) - Einführung des Produkts als Erster auf dem Markt.
- ○ Verfolger (Fast Follower) - frühzeitige Markteinführung des Produkts, allerdings erst nach Pionierunternehmen.
- ○ Nachzügler (Laggard) - späte Markteinführung der Produkts, als bereits eine größere Anzahl an Anbietern existierte.
- ○ Andere, bitte angeben: ………………………

Welche Bezeichnung trifft am besten auf die Strategie zur Positionierung der Produktinnovation am Markt zu?

*Bitte wählen Sie **nur eine** der folgenden Antworten aus:*

- ○ Differenzierung – Abgrenzung vom Wettbewerb primär durch Kundenmehrwert und Qualität.
- ○ Nischenstrategie – Besetzung einer Marktnische.
- ○ Kostenführerschaft – Abgrenzung vom Wettbewerb primär über den Preis.
- ○ Andere, bitte angeben: ………………………

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Welche strategischen Partner wurden während des Innovationsprojekts eingebunden?

*Bitte wählen Sie **alle** zutreffenden Antworten aus:*

- ○ Keine
- ○ Kunden
- ○ Zulieferer
- ○ Wettbewerber
- ○ Endnutzer
- ○ Vertriebspartner
- ○ Andere Zulieferer des Kunden
- ○ Forschungsinstitute
- ○ Weitere, bitte angeben: ____________________

Welche Bezeichnung trifft am besten auf die Projektorganisation zu, in der das Innovationsprojekt durchgeführt wurde?

*Bitte wählen Sie **nur eine** der folgenden Antworten aus:*

- ○ Matrixorganisation – Mitarbeiter sind neben dem Projekt weiterhin in ihre operativen Tätigkeiten eingebunden.
- ○ Autonome Projektorganisation – Bildung einer Task Force, Mitarbeiter werden aus Ihrer operativen Tätigkeit herausgelöst.
- ○ Eigenes Unternehmen - Produktinnovation wird in einem rechtlich eigenständigen Unternehmen umgesetzt.
- ○ Andere Organisationsform, bitte angeben: ____________________

Welche Bezeichnung trifft am besten auf den Grad der Prozessstandardisierung im Innovationsprojekt zu?

*Bitte wählen Sie **nur eine** der folgenden Antworten aus:*

- ○ Das Innovationsprojekt folgte keinem standardisierten Prozessablauf.
- ○ Das Innovationsprojekt folgte einem im Unternehmen gängigen Ablauf, war aber formal nicht standardisiert.
- ○ Das Innovationsprojekt folgte einem formal standardisierten Prozessablauf.
- ○ Anderer Standardisierungsgrad, bitte angeben: ____________________

Falls das Innovationsprojekt einem formal standardisierten Prozessablauf folgte, war dies ein Stage-Gate-Prozess?

Bitte diese Frage nur beantworten, wenn das Innovationsprojekt formal standardisiert war:

○ Ja ○ Nein

Das ***Stage-Gate Modell*** teilt den Innovationsprozess in mehrere, einzelne Phasen, an deren Ende vereinbarte Ergebnisse präsentiert und abteilungsübergreifend anhand von Go/Kill-Kriterien überprüft werden.

Falls das Innovationsprojekt einem formal standardisierten Stage-Gate-Prozessablauf folgte, wurde das Team bei der Projektdurchführung durch einen Prozessexperten unterstützt?

Bitte diese Frage nur beantworten, wenn das Innovationsprojekt einem formal standardisierten Stage-Gate-Prozess folgte:

○ Ja ○ Nein

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Welchen Marktanteil erzielte die Innovation zum Zeitpunkt der größten Marktdurchdringung?

*Bitte wählen Sie **nur eine** der folgenden Antworten aus:*

< 5%	6 - 10%	11 - 30%	31 - 50%	> 51%	Keine Angabe
○	○	○	○	○	○

Welchen Umsatz-Anteil machen nach Ihrer Einschätzung Produkte in Ihrem Unternehmen aus, die nicht älter als 5 Jahre sind?

*Bitte wählen Sie **nur eine** der folgenden Antworten aus:*

< 5%	6 - 10%	11 - 30%	31 - 50%	> 51%	Keine Angabe
○	○	○	○	○	○

Wie viele Mitarbeiter sind in Ihrem Unternehmen beschäftigt?

*Bitte wählen Sie **nur eine** der folgenden Antworten aus:*

< 25	25 - 100	100 - 1.000	1.000 - 10.000	> 10.000	Keine Angabe
○	○	○	○	○	○

Welche Rechtsform hat Ihr Unternehmen?

*Bitte wählen Sie **nur eine** der folgenden Antworten aus:*

- ○ Einzelunternehmen
- ○ Personengesellschaft (z.B. OHG, KG, GbR, ...)
- ○ Kapitalgesellschaft (z.B. GmbH, GmbH & Co. KG, ...)
- ○ Aktiengesellschaft
- ○ Gesellschaft des öffentlichen Rechts
- ○ Andere Rechtsform, bitte angeben: ____________________

Kommentar zum Fragebogen: Gibt es etwas, dass Sie uns noch gerne mitteilen möchten?

Vielen Dank für die Bearbeitung des Fragebogens. Wie anfangs beschrieben, haben Sie die Möglichkeit hier Ihre **E-Mailadresse** zu hinterlassen, um an der **Verlosung von drei Amazon-Gutscheinen** im Wert von **30 €** teilzunehmen oder um die **Ergebnisse der Studie** zu erhalten. Selbstverständlich werden Ihre **Daten absolut vertraulich** behandelt.

Ich möchte...

- ○ die Ergebnisse der Studie per E-Mail erhalten.
- ○ an der Verlosung der Amazon-Gutscheine teilnehmen.

Meine E-Mailadresse:

____

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4) Pretest Form

Karlsruher Institut für Technologie

Feedbackbogen zur Fragebogengestaltung

Sehr geehrte/r Teilnehmer/in,

vielen Dank für die Teilnahme am Pretest der wissenschaftlichen Studie des Karlsruher Instituts für Technologie zum Thema „Radikale technische Innovationen in der Antriebstechnik“. Um die Qualität des Fragebogens zu erhöhen, bitten wir Sie um ein kurzes Feedback bzgl. einiger Punkte des Fragebogens. Herzlichen Dank für Ihre Mitarbeit.

Mit freundlichen Grüßen,
Florian Wohlfeil & Philipp Dahl

1. **Fragestellung:**
   Gab es Fragen, die für Sie unverständlich formuliert waren (z.B. bzgl. Terminologie, Formulierungen etc.)? Falls ja, welche Formulierungen waren dies?
   Klicken Sie hier, um Text einzugeben.

2. **Skalen / Antwortoptionen:**
   Waren diverse Skalen oder Antwortoptionen für Sie unverständlich? Falls ja, welche Fragen betraf dies?
   Klicken Sie hier, um Text einzugeben.

3. **Gelenkte Fragestellung:**
   Waren diverse Fragen so formuliert, dass Sie bei der Beantwortung beeinflusst wurden? Falls ja, bei welchen Fragen war dies der Fall?
   Klicken Sie hier, um Text einzugeben.

4. **Reihenfolge:**
   War die Reihenfolge der Fragen für Sie sinnvoll? Wenn nein, welche Fragen sollten in einer anderen Reihenfolge abgefragt werden?
   Klicken Sie hier, um Text einzugeben.

5. **Benötigte Zeit:**
   Wie lange haben Sie für die Beantwortung der Umfrage benötigt?
   Klicken Sie hier, um Text einzugeben.

6. **Zeitrahmen:**
   War für Sie der benötigte Zeitrahmen zur Beantwortung der Umfrage in Ordnung? Wenn nein, wie viel Zeit sollte die Beantwortung maximal in Anspruch nehmen?
   Klicken Sie hier, um Text einzugeben.

7. **Layout & Schriftgröße:**
   Fanden Sie das Layout der Umfrage übersichtlich und die Schriftgröße der Fragen ausreichend groß? Wenn nein, welche Teile der Umfrage würden Sie diesbezüglich verändern?
   Klicken Sie hier, um Text einzugeben.

8. **Verbesserungsvorschläge:**
   Haben Sie ergänzende Verbesserungsvorschläge (z.B. methodischer oder fachspezifischer Art), die Sie uns gerne mitgeben würden?
   Klicken Sie hier, um Text einzugeben.

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5) Test of Normal Distribution

Table 19: Overview of Skewness & Kurtosis

	TM_1	TM_2	TM_3	TM_4	TM_5	TM_6	TM_7				
Skewness	-1,258	,016	-,598	-,090	-1,071	-,600	-1,034				
Kurtosis	1,576	-1,275	-,645	-1,090	1,027	-,359	1,512				
	TEC_1	TEC_2	TEC_3	TEC_4	TEC_5	TEC_6	TEC_7				
Skewness	-1,229	-,501	-,690	-,900	,922	,035	,557				
Kurtosis	2,007	-,112	,637	,530	1,534	-1,199	-,537				
	ORG_1	ORG_2	ORG_3	ORG_4	ORG_5	ORG_6	ORG_7	ORG_8	ORG_9		
Skewness	-1,148	-,070	-,328	-,243	-,477	-,276	-,155	-,412	-,249		
Kurtosis	1,447	-1,024	-,604	-,795	-,668	-,989	-,976	-,799	-,897		
	ET_1	ET_2	ET_3	ET_4	ET_5	ET_6	ET_7				
Skewness	-1,200	-,728	-1,123	-,726	-1,034	-,537	-,224				
Kurtosis	1,618	-,098	1,130	,385	,456	,071	-,809				
	PI_1	PI_2	PI_3	PI_4	PI_5	PI_6	PI_7	PI_8	PI_9	PI_10	PI_11
Skewness	-1,030	-,087	-,496	-,299	-,455	-,760	,222	-,069	-,549	-,283	,497
Kurtosis	,500	-1,120	-,662	-,951	-,802	-,222	-,739	-,882	-,548	-,705	-,477
	IS_1	IS_2	IS_3	IS_4	IS_5	IS_6	IS_7	IS_8	IS_9		
Skewness	-,197	-,450	,528	,370	-,288	-,974	-1,097	-,171	-,132		
Kurtosis	-,901	-,462	-,671	-,679	-,969	1,011	1,908	-,722	-,900		

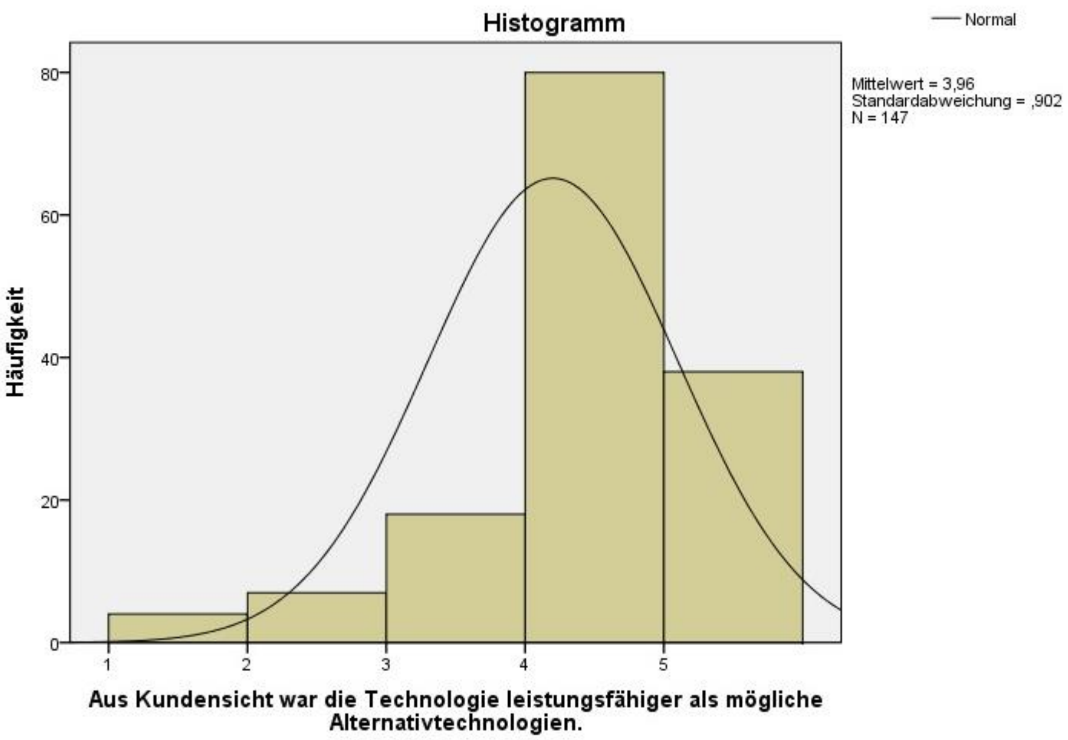

Figure 83: Frequency Histogram of TEC_1

6) Explorative Factor Analysis

Table 20: KMO and Barlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		,654
Bartlett's Test of Sphericity	Approx. Chi-Square	357,406
	df	15
	Sig.	,000

Table 21: Evaluation-Table for KMO & MSA-Values (Brosius, 2013, p. 798)

Value	Evaluation
0.9 – 1.0	marvelous
0.8 – 0.9	meritorious
0.7 – 0.8	middling
0.6 – 0.7	mediocre
0.5 – 0.6	miserable
< 0.5	unacceptable

Table 22: Anti-Image Matrices

		IS_1	IS_2	IS_6	IS_7	IS_8	IS_9
Anti-image Covariance	IS_1	,629	-,326	-,005	,118	-,002	-,059
	IS_2	-,326	,614	-,103	-,099	-,029	,021
	IS_6	-,005	-,103	,691	-,269	-,031	-,002
	IS_7	,118	-,099	-,269	,647	,026	-,093
	IS_8	-,002	-,029	-,031	,026	,257	-,203
	IS_9	-,059	,021	-,002	-,093	-,203	,240
Anti-image Correlation	IS_1	,629[a]	-,524	-,008	,184	-,005	-,152
	IS_2	-,524	,667[a]	-,159	-,157	-,072	,056
	IS_6	-,008	-,159	,760[a]	-,403	-,074	-,005
	IS_7	,184	-,157	-,403	,690[a]	,065	-,236
	IS_8	-,005	-,072	-,074	,065	,629[a]	-,817
	IS_9	-,152	,056	-,005	-,236	-,817	,621[a]

a. Measures of Sampling Adequacy(MSA)

Table 23: Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings[a]
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total
1	2,856	47,595	47,595	2,856	47,595	47,595	2,291
2	1,159	19,317	66,911	1,159	19,317	66,911	1,850
3	,974	16,239	83,150	,974	16,239	83,150	1,899
4	,488	8,131	91,281				
5	,388	6,472	97,752				
6	,135	2,248	100,000				

Extraction Method: Principal Component Analysis.
a. When components are correlated, sums of squared loadings cannot be added to obtain a total variance.

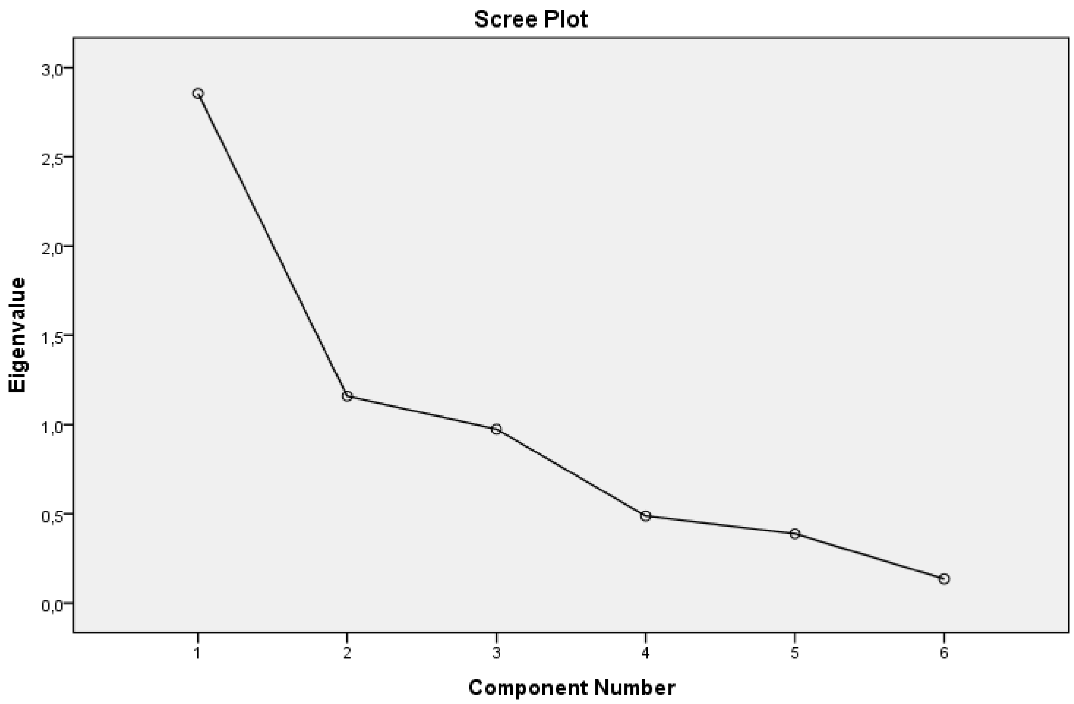

Figure 84: Scree Plot

Table 24: Communalities

	Initial	Extraction
IS_1	1,000	,825
IS_2	1,000	,801
IS_6	1,000	,750
IS_7	1,000	,761
IS_8	1,000	,921
IS_9	1,000	,930

Extraction Method: Principal Component Analysis.

Table 25: Pattern Matrix

	Component		
	1	2	3
IS_8 Der erzielte Umsatz entsprach den zu Projektbeginn formulierten Erwartungen.	,950	,022	,007
IS_9 Der mit der Innovation erreichte Marktanteil entsprach den zu Projektbeginn formulierten Erwartungen.	,937	,015	,060
IS_1 Die Geschwindigkeit des Entwicklungsprojektes war hoch.	,140	,883	-,176
IS_2 Die vorhandenen Ressourcen wurden im Innovationsprojekt effizient eingesetzt.	-,078	,846	,227
IS_6 Die Produktperformance der Innovation entsprach den zu Beginn des Projektes formulierten Vorgaben.	-,032	,118	,845
IS_7 Die erreichte Qualität des neu entwickelten Produktes war auf einem hohen Niveau.	,136	-,099	,835

Extraction Method: Principal Component Analysis.
Rotation Method: Oblimin with Kaiser Normalization.[a]
a. Rotation converged in 6 iterations.

7) Reliability Analysis

Sales Performance

Table 26: Reliability Statistics "Sales Performance"

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
,924	,924	2

Table 27: Inter-Item Correlation Matrix "Sales Performance"

	IS_8 Der erzielte Umsatz entsprach den zu Projekt-beginn formulierten Erwar-tungen.	IS_9 Der mit der Innovation erreichte Marktanteil entsprach den zu Projekt-beginn formulierten Erwartungen.
IS_8 Der erzielte Umsatz entsprach den zu Projekt-beginn formulierten Erwartungen.	1,000	,859
IS_9 Der mit der Innovati-on erreichte Marktanteil entsprach den zu Projekt-beginn formulierten Erwartungen.	,859	1,000

Table 28: Item-Total Statistics "Sales Performance"

	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Squared Multiple Correlation	Cronbach's Alpha if Item Deleted
IS_8 Der erzielte Umsatz entsprach den zu Projektbeginn formulierten Erwartungen.	3,13	1,412	,859	,739	
IS_9 Der mit der Innovati-on erreichte Marktanteil entsprach den zu Projektbeginn formulierten Erwartungen.	3,14	1,261	,859	,739	

Efficiency

Table 29: Reliability Statistics "Efficiency"

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
,714	,718	2

Table 30: Inter-Item Correlation Matrix "Efficiency"

	IS_1 Die Geschwindigkeit des Entwicklungsprojektes war hoch.	IS_2 Die vorhandenen Ressourcen wurden im Innovationsprojekt effizient eingesetzt.
IS_1 Die Geschwindigkeit des Entwicklungsprojektes war hoch.	1,000	,560
IS_2 Die vorhandenen Ressourcen wurden im Innovationsprojekt effizient eingesetzt.	,560	1,000

Table 31: Item-Total Statistics "Efficiency"

	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Squared Multiple Correlation	Cronbach's Alpha if Item Deleted
IS_1 Die Geschwindigkeit des Entwicklungsprojektes war hoch.	3,42	,907	,560	,313	
IS_2 Die vorhandenen Ressourcen wurden im Innovationsprojekt effizient eingesetzt.	3,21	1,169	,560	,313	

Product Performance

Table 32: Reliability Statistics "Product Performance"

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
,673	,673	2

Table 33: Inter-Item Correlation Matrix "Product Performance"

	IS_6 Die Produktperformance der Innovation entsprach den zu Beginn des Projektes formulierten Vorgaben.	IS_7 Die erreichte Qulität des neu entwickleten Produktes war auf einem hohen Niveau.
IS_6 Die Produktperformance der Innovation entsprach den zu Beginn des Projektes formulierten Vorgaben.	1,000	,507
IS_7 Die erreichte Qulität des neu entwickleten Produktes war auf einem hohen Niveau.	,507	1,000

Table 34: Item-Total Statistics "Product Performance"

	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Squared Multiple Correlation	Cronbach's Alpha if Item Deleted
IS_6 Die Produkt-performance der Innovation ent-sprach den zu Beginn des Projek-tes formulierten Vorgaben.	4,03	,744	,507	,257	
IS_7 Die erreichte Qulität des neu entwickleten Pro-duktes war auf einem hohen Niveau.	3,96	,734	,507	,257	

8) Correlation Analysis

Table 35: Orientation-Table for "Pearson r" (Brosius, 2013, p. 523)

Value of Pearson r	Potential Interpretation
0	No correlation
0 – 0.2	Very weak correlation
0.2 – 0.4	Weak correlation
0.4 – 0.6	Middling correlation
0.6 – 0.8	Strong correlation
0.8 – 1	Very strong correlation
1	Perfect correlation

9) Larger Version of the Adjusted ICPS Framework

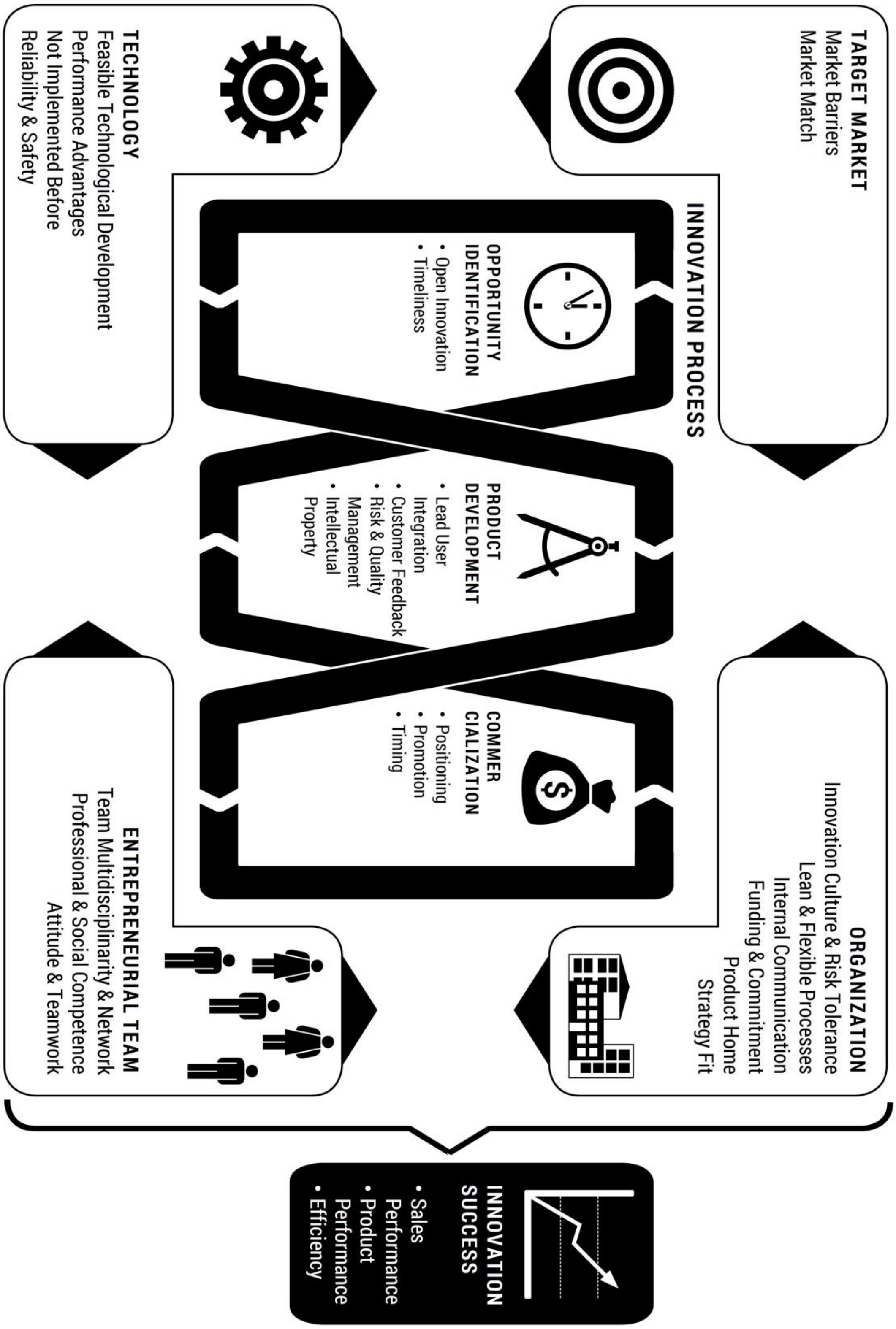

Figure 85: Larger Version of the Adjusted ICPS Framework

10) Cluster Analysis

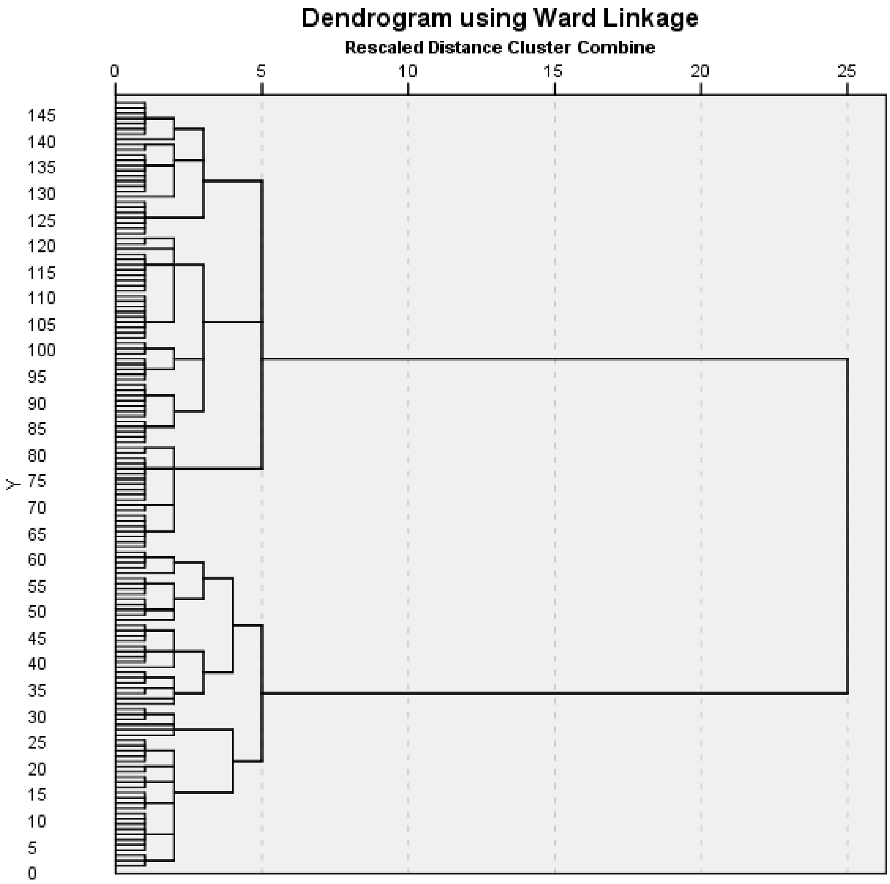

Figure 86: Dendogram

11) Analysis of Variance

Table 36: Levene-Test of Homogeneity of Variances

	Levene Statistic	df1	df2	Sig.
PI_1 Schutz von geistigem Eigentum	4,224	4	142	,003
PI_2 Integration von Lead-Usern bei der Innovationsumsetzung	1,205	4	142	,311
PI_3 Einbeziehen von Kundenfeedback in die Innovationsumsetzung	6,874	4	142	,000
PI_4 Gezielte Kommunikationsmaßnahmen (z.B. Messeauftritte, Presseberichte, Broschüren)	1,903	4	142	,113
PI_5 Verfolgung einer Plattformstrategie für eine gezielte Produktportfolioplanung	4,230	4	142	,003
PI_6 Bewusste Positionierung des Produkts am Markt (z.B. als Premiumprodukt)	5,155	4	142	,001
PI_7 Bewusste Wahl des Zeipunkts für den Markteintritt	1,461	4	142	,217
PI_8 Bildung strategischer Partnerschaften	1,814	4	142	,129
PI_9 Qualitätsmanagement	4,648	4	142	,001
PI_10 Risikomanagement	1,508	4	142	,203
PI_11 Open Innovation	3,440	4	142	,010

Table 37: Results of ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
PI_1 Schutz von geistigem Eigentum	Between Groups	19,395	4	4,849	4,520	,002
	Within Groups	152,325	142	1,073		
	Total	171,720	146			
PI_2 Integration von Lead-Usern bei der Innovationsumsetzung	Between Groups	56,365	4	14,091	10,498	,000
	Within Groups	190,611	142	1,342		
	Total	246,976	146			
PI_3 Einbeziehen von Kundenfeedback in die Innovationsumsetzung	Between Groups	79,718	4	19,929	19,704	,000
	Within Groups	143,627	142	1,011		
	Total	223,345	146			
PI_4 Gezielte Kommunikationsmaßnahmen (z.B. Messeauftritte, Presseberichte, Broschüren)	Between Groups	38,395	4	9,599	6,915	,000
	Within Groups	197,119	142	1,388		
	Total	235,514	146			
PI_5 Verfolgung einer Plattformstrategie für eine gezielte Produktportfolioplanung	Between Groups	61,433	4	15,358	12,420	,000
	Within Groups	175,596	142	1,237		
	Total	237,030	146			
PI_6 Bewusste Positionierung des Produkts am Markt (z.B. als Premiumprodukt)	Between Groups	53,896	4	13,474	14,543	,000
	Within Groups	131,566	142	,927		
	Total	185,462	146			
PI_7 Bewusste Wahl des Zeipunkts für den Markteintritt	Between Groups	76,979	4	19,245	20,735	,000
	Within Groups	131,795	142	,928		
	Total	208,774	146			
PI_8 Bildung strategischer Partnerschaften	Between Groups	18,386	4	4,596	3,261	,014
	Within Groups	200,158	142	1,410		
	Total	218,544	146			
PI_9 Qualitätsmanagement	Between Groups	63,582	4	15,895	23,893	,000
	Within Groups	94,468	142	,665		
	Total	158,050	146			
PI_10 Risikomanagement	Between Groups	54,122	4	13,531	17,942	,000
	Within Groups	107,087	142	,754		
	Total	161,209	146			
PI_11 Open Innovation	Between Groups	31,315	4	7,829	7,070	,000
	Within Groups	157,244	142	1,107		
	Total	188,559	146			

Table 38: Welch-Test

		Statistic[a]	df1	df2	Sig.
PI_1 Schutz von geistigem Eigentum	Welch	6,855	4	58,579	,000
PI_2 Integration von Lead-Usern bei der Innovationsumsetzung	Welch	11,647	4	65,786	,000
PI_3 Einbeziehen von Kundenfeedback in die Innovationsumsetzung	Welch	18,579	4	63,739	,000
PI_4 Gezielte Kommunikationsmaß-nahmen (z.B. Messeauftritte, Pressebe-richte, Broschüren)	Welch	8,032	4	65,774	,000
PI_5 Verfolgung einer Plattformstrategie für eine gezielte Produktportfolioplanung	Welch	16,877	4	67,192	,000
PI_6 Bewusste Positionierung des Produkts am Markt (z.B. als Premium-produkt)	Welch	16,654	4	63,935	,000
PI_7 Bewusste Wahl des Zeipunkts für den Markteintritt	Welch	22,069	4	66,530	,000
PI_8 Bildung strategischer Partnerschaf-ten	Welch	3,226	4	65,528	,018
PI_9 Qualitätsmanagement	Welch	25,702	4	61,650	,000
PI_10 Risikomanagement	Welch	16,202	4	66,006	,000
PI_11 Open Innovation	Welch	6,851	4	64,597	,000

a. Asymptotically F distributed.

Appendix VI – Operational Framework

1) Discriminant Analysis

Table 39: Test of Equality of Group Means

	Wilks' Lambda	F	df1	df2	Sig.
TM_2	,928	2,763	4	142	,030
TM_5_REC	,904	3,767	4	142	,006
TM_6	,871	5,272	4	142	,001
ORG_1	,753	11,646	4	142	,000
ORG_2	,593	24,318	4	142	,000
ORG_3	,586	25,097	4	142	,000
ORG_4	,693	15,739	4	142	,000
ORG_5	,616	22,100	4	142	,000
ORG_6_REC	,761	11,178	4	142	,000
ORG_7	,822	7,663	4	142	,000
ORG_8_REC	,613	22,440	4	142	,000
ORG_9	,706	14,811	4	142	,000
TEC_1	,955	1,657	4	142	,163
TEC_3	,878	4,930	4	142	,001
TEC_5_REC	,963	1,378	4	142	,245
TEC_6	,791	9,352	4	142	,000
ET_1	,822	7,699	4	142	,000
ET_2	,790	9,418	4	142	,000
ET_3	,835	7,009	4	142	,000
ET_4_REC	,906	3,664	4	142	,007
ET_5	,835	6,999	4	142	,000
ET_6	,906	3,688	4	142	,007
ET_7_REC	,880	4,858	4	142	,001

Table 40: Eigenvalues of the Discriminant Function

Function	Eigenvalue	% of Variance	Cumulative %	Canonical Correlation
1	2,794[b]	72,5	72,5	,858
2	,513[b]	13,3	85,8	,582
3	,358[b]	9,3	95,1	,513
4	,188	4,9	100,0	,398

a. Maximum number of functions is 3.

b. First 3 canonical discriminant functions were used in the analysis.

Table 41: Wilks' Lambda of Discriminant Function

Test of Function(s)	Wilks' Lambda	Chi-square	df	Sig.
1 through 4	,108	296,007	84	,000
2 through 4	,410	118,664	60	,000
3 through 4	,620	63,627	38	,006
4	,842	22,934	18	,193

Table 42: Functions at Group Centroids

	Function		
CLU5_1	1	2	3
1	2,160	,147	,830
2	-1,260	,958	-,448
3	1,150	-,646	-,678
4	,413	,728	,238
5	-2,379	-,741	,489

Unstandardized canonical discriminant functions evaluated at group means

Table 43: Structure Matrix of the Discriminant Function Coefficients

	Function		
	1	2	3
ORG_3	,501*	-,002	,052
ORG_2	,487*	-,183	,075
ORG_5	,464*	-,159	,044
ORG_8_REC	,461*	,021	,290
ORG_4	,391*	-,117	,080
ORG_9	,383*	-,076	,108
ORG_6_REC	,322*	,154	-,189
ET_2	,303*	,033	-,084
ET_1	,266*	-,149	-,151
TM_6	,220*	,142	-,075
ET_7_REC	,177*	-,099	,142
ET_4_REC	,162*	-,056	-,048
TEC_6	-,158	,588*	,212
TM_2	,012	-,328*	-,051
ORG_1	,312	-,322*	-,102
ORG_7	,240	,281*	,044
ET_6	,101	,101	-,430*
ET_5	,187	,248	-,419*
TEC_3	,185	-,104	-,289*
ET_3	,231	,005	-,270*
TM_5_REC	,135	-,239	,266*

Pooled within-groups correlations between discriminating variables and standardized canonical discriminant functions
Variables ordered by absolute size of correlation within function.

*. Largest absolute correlation between each variable and any discriminant function

Table 44: Standardized Canonical Discriminant Function Coefficients

	Function		
	1	2	3
TM_2	-,172	-,436	-,076
TM_5_REC	-,172	-,292	,468
TM_6	,040	,179	-,125
ORG_1	,182	-,294	,081
ORG_2	,405	-,151	,191
ORG_3	,037	-,006	-,040
ORG_4	,146	-,079	,004
ORG_5	,168	-,066	-,023
ORG_6_REC	,277	,160	-,293
ORG_7	,133	,533	,278
ORG_8_REC	,479	,061	,284
ORG_9	,320	-,120	,045
TEC_3	,307	,035	-,338
TEC_6	,023	,669	,457
ET_1	-,086	-,103	-,179
ET_2	,335	,315	,123
ET_3	,062	,175	-,096
ET_4_REC	,174	,077	-,097
ET_5	,022	,206	-,505
ET_6	-,079	-,131	-,439
ET_7_REC	-,144	,151	,430

Table 45: Classification Results

CLU5_1			Predicted Group Membership					Total
			1	2	3	4	5	
Original Group Membership	Count	1	21	0	4	1	0	26
		2	0	24	2	3	2	31
		3	6	2	30	2	0	40
		4	1	1	4	13	1	20
		5	0	3	1	1	25	30
	%	1	80,8	0,0	15,4	3,8	0,0	100,0
		2	0,0	77,4	6,5	9,7	6,5	100,0
		3	15,0	5,0	75,0	5,0	0,0	100,0
		4	5,0	5,0	20,0	65,0	5,0	100,0
		5	0,0	10,0	3,3	3,3	83,3	100,0

a. 76,9% of original grouped cases correctly classified.

Table 46: Box-M-Test of Equality of Covariance Matrices

Log Determinants

CLU5_1	Rank	Log Determinant
1	21	-23,011
2	21	-11,442
3	21	-18,859
4	.[a]	.[b]
5	21	-13,632
Pooled within-groups	21	-7,269

The ranks and natural logarithms of determinants printed are those of the group covariance matrices.

a. Rank < 20

b. Too few cases to be non-singular

Test Results

Box's M		1526,344
F	Approx.	1,488
	df1	693
	df2	27226,595
	Sig.	,000

Tests null hypothesis of equal population covariance matrices.

a. Some covariance matrices are singular and the usual procedure will not work. The non-singular groups will be tested against their own pooled within-groups covariance matrix. The log of its determinant is -4,252.

```
DISCRIMINANT
  /GROUPS=CLU5_1(1 5)
  /VARIABLES=TM_2 TM_5_REC TM_6
   ORG_1 ORG_2 ORG_3 ORG_4 ORG_5
   ORG_6_REC ORG_7 ORG_8_REC ORG_9
   TEC_3 TEC_6 ET_1 ET_2
   ET_3 ET_4_REC ET_5 ET_6 ET_7_REC
  /ANALYSIS ALL
  /FUNCTIONS 3
  /SAVE=CLASS SCORES PROBS
  /PRIORS SIZE
  /STATISTICS=UNIVF BOXM TABLE
  /PLOT=CASES
  /CLASSIFY=NONMISSING SEPARATE.
```

Figure 87: Syntax for Discriminant Analysis

2) Questionnaire for Operational Framework

Questionnaire Part 1

Please indicate your consent according to the following statements:

	Strongly disagree (1)	Disagree (2)	Undecided (3)	Agree (4)	Strongly agree (5)
TM_2: There are rarely market barriers, which hamper the market launch of the respective innovation.	○	○	○	○	○
TM_5: The addressed market does not seem to have a good match with the innovation.	○	○	○	○	○
TM_6: The intended date for market introduction of the innovation seems to fit well.	○	○	○	○	○
ORG_1: The internal communication is open and honest.	○	○	○	○	○
ORG_2: For realizing the innovation project, the team has access to any needed resources.	○	○	○	○	○
ORG_3: The management totally supports the project team at realizing the innovation.	○	○	○	○	○
ORG_4: The organization is shaped by a climate in which risks are tolerated and failures are accepted.	○	○	○	○	○
ORG_5: The organizational structure of the company enables a flexible realization of the innovation project.	○	○	○	○	○
ORG_6: From today's point of view, it seems to be quite difficult to find an organizational home for the respective innovation.	○	○	○	○	○
ORG_7: The processes for decision making within the innovation project are lean.	○	○	○	○	○
ORG_8: The strategic direction of the company is hampering innovation realization.	○	○	○	○	○
ORG_9: The company is shaped by a strong innovation culture and a focus on the development of new products.	○	○	○	○	○

Questionnaire Part 2

Please indicate your consent according to the following statements:

	Strongly disagree (1)	Disagree (2)	Undecided (3)	Agree (4)	Strongly agree (5)
TEC_3: From customer perspective, the technology that underlies the innovation is reliable and safe.	○	○	○	○	○
TEC_6: The technology that underlies the innovation has been implemented within previous products (e.g. in different companies or industries).	○	○	○	○	○
ET_1: The people being involved in the innovation project work together as a team.	○	○	○	○	○
ET_2: With respect to the essential professional competences, the right people are involved at innovation realization.	○	○	○	○	○
ET_3: Despite any obstacles, the involved people want to bring the respective innovation to success.	○	○	○	○	○
ET_4: The involved people have a low level of social competence.	○	○	○	○	○
ET_5: At realizing the innovation, people with different competences are involved, e.g. people from different organizational units like marketing, sales, and development.	○	○	○	○	○
ET_6: The involved people have a great personal network, which supports innovation realization.	○	○	○	○	○
ET_7: The involved people are not very experienced with the implementation of such innovation projects.	○	○	○	○	○

3) Cluster Assignment for the Cases of Pinion, SKF, and 5ME

Table 47: Answers to the Questionnaire for the Cases of Pinion, SKF, and 5ME

	Pinion	SKF	5ME
TM_2: There are rarely market barriers which hamper the market launch of the respective innovation.	4	4	3
TM_5: The addressed market does not seem to have a good match with the innovation	1	1	1
TM_6: The intended date for the market introduction of the innovation seems to fit well.	5	5	5
ORG_1: The internal communication is open and honest.	5	4	5
ORG_2: For realizing the innovation project, the team has access to any needed resources.	4	4	5
ORG_3: The management totally supports the project team at realizing the innovation.	5	4	5
ORG_4: The organization is shaped by a climate in which risks are tolerated and failures are accepted.	5	2	4
ORG_5: The organizational structure of the company enables a flexible realization of the innovation project.	5	3	5
ORG_6: From today's point of view, it seems to be quite difficult to find an organizational home for the respective innovation.	1	3	1
ORG_7: The processes for decision making within the innovation project are lean.	5	3	4
ORG_8: The strategic direction of the company is hampering innovation realization.	1	1	1
ORG_9: The company is shaped by a strong innovation culture and a focus on the development of new products.	5	2	5
TEC_3: From the customer perspective, the technology that underlies the innovation is reliable and safe.	5	5	4
TEC_6: The technology that underlies the innovation has been implemented within previous products (e.g. in different companies or industries).	3	2	2
ET_1: The people being involved in the innovation project work together as a team.	5	5	5
ET_2: With respect to the essential professional competences, the right people are involved at innovation realization.	4	4	5
ET_3: Despite any obstacles, the involved people want to bring the respective innovation to success.	5	5	5
ET_4: The involved people have a low level of social competence.	2	2	2
ET_5: At realizing the innovation, people with different competences are involved, e.g. people from different organizational units like marketing, sales, and development.	4	4	4
ET_6: The involved people have a great personal network which supports innovation realization.	3	5	4
ET_7: The involved people are not very experienced with the implementation of such innovation projects.	4	4	3

Table 48: Classification Results of Discriminant Analysis

		Highest Group					Second Highest Group		
			P(D>d | G=g)						
Case Number	Actual Group	Pre-dicted Group	p	df	P(G=g | D=d)	Squared Mahalanobis Distance to Centroid	Group	P(G=g | D=d)	Squared Mahalanobis Distance to Centroid
148*	ungrouped	1	,235	3	,725	4,258	3	,274	6,982
149**	ungrouped	3	,925	3	,791	,471	4	,128	3,871
150***	ungrouped	1	,167	3	,727	5,066	3	,273	7,803

* = Pinion; ** = SKF; *** = 5ME

References

3M (2015a), "3M Friction Shims".

3M (2015b), "3M Reibwerterhöhende Scheiben und Beschichtungen für Windenergie-Anwendungen".

3M (2015c), "Technical Data Sheet - 3M Friction Shims".

5ME (2013), "5ME Press Release", available at: http://5me.netcrafters.com/files/5ME_Press_Release.pdf (accessed 10 September 2013).

5ME (2014a), "5ME Cryogenic Machining Systems Product Overview Sheet", available at: http://www.5me.com/files/5ME_Cryogenic_Machining_Systems_Product_Overview_Sheet.pdf (accessed 7 October 2014).

5ME (2014b), "Cryogenic Machining: Superior Metal Cutting Technology", available at: http://www.5me.com/home/cryogenic_machining/what_is_cryo.html (accessed 7 October 2014).

5ME (2014c), "Is Cryogenic Machining the Right Call?", available at: http://www.5me.com/home/cryogenic_machining/cryo_metal_cutting.html (accessed 7 October 2014).

5ME (2014d), "Maximize Profitability With 5 ME", available at: http://www.5me.com/home/about_5me.html (accessed 7 October 2014).

5ME (2014e), "Product Overview Sheet", available at: http://www.5me.com/files/5ME_Cryogenic_Machining_Systems_Product_Overview_Sheet.pdf (accessed 12 November 2014).

5ME (2014f), "Save Time, Tools, and Money with Cryogenic Machining", available at: http://www.5me.com/home/cryogenic_machining/cryogenic_machine_benefits.html (accessed 7 October 2014).

5ME (2014g), "The Cryogenic Machining System", available at: http://www.5me.com/home/cryogenic_machining/cryogenic_machine_system.html (accessed 7 October 2014).

5ME (2014h), "The Evolution of 5ME Cryogenic Machining Technology", available at: http://www.5me.com/home/cryogenic_machining/sustainable_manufacturing.html (accessed 7 October 2014).

5ME (2014i), *Presentation to MAG IAS GmbH & MAG Auto, LP*, Warren.

5ME (2014j), *Expert interview with 5ME's Cryogenic Engineering Manager regarding the technological development of Cryogenic Machining (conducted by Florian Wohlfeil)*, Detroit.

5ME (2014k), *Discussion with 5ME's Cryogenic Engineering Manager regarding technological alternatives to Cryogenic Machining - Part 1 (conducted by Florian Wohlfeil)*, Detroit.

5ME (2014l), *Expert interview with 5ME's Marketing & Product Manager regarding the commercialization of Cryogenic Machining (conducted by Florian Wohlfeil)*, Detroit.

5ME (2014m), *Discussion with 5ME's Cryogenic Engineering Manager regarding technological alternatives to Cryogenic Machining - Part 2 (conducted by Florian Wohlfeil)*, Detroit.

5ME (2014n), *Expert interview with 5ME's President regarding the commercialization of Cryogenic Machining (conducted by Florian Wohlfeil)*, Cincinnati.

5ME (2014o), *Expert interview with 5ME's Cryogenic Business Development Manager regarding the commercialization of Cryogenic Machining (conducted by Florian Wohlfeil)*, Cincinnati.

5ME (2015), *Organizational Structure 5ME*, Cincinnati.

Abetti, P.A. (2000), "Critical Success Factors for Radical Technological Innovation: A Five Case Study", *Creativity and Innovation Management*, Vol. 9 No. 4, pp. 208–221.

Arbuckle, J. (2013), *IBM® SPSS ® Amos™ 22 User's Guide*.

Atteslander, P. (2008), *Methoden der empirischen Sozialforschung, ESV basics,* 12., durchges. Aufl, Erich Schmidt, Berlin.

Backhaus, K., Erichson, B., Plinke, W. and Weiber, R. (2000), *Multivariate Analysemethoden: Eine anwendungsorientierte Einführung ; mit 230 Tabellen, Springer-Lehrbuch,* 9., überarb. und erw. Aufl, Springer, Berlin [u.a.].

Backhaus, K., Erichson, B., Plinke, W. and Weiber, R. (2016), *Multivariate Analysemethoden: Eine anwendungsorientierte Einführung, Lehrbuch,* 14., überarbeitete und aktualisierte Auflage, Springer Gabler, Berlin, Heidelberg.

Baker, J. (2012), "The Technology–Organization–Environment Framework", in Dwivedi, Y.K., Wade, M.R. and Schneberger, S.L. (Eds.), *Information Systems Theory*, *Integrated Series in Information Systems*, Vol. 28, Springer New York, pp. 231-245.

Balachandra, R. and Friar, J.H. (1997), "Factors for success in R&D projects and new product innovation: a contextual framework", *IEEE Transactions on Engineering Management*, Vol. 44 No. 3, pp. 276–287.

Baumann, M. (2009), *Diploma Thesis - Quantifizierung der Einflussgrößen und Ableitung der Grenzbereiche einer reibungserhöhenden Beschichtung*.

Bergleben (2014), "Shimano XT Schaltung", available at: http://www.bergleben.de/mountainbike/2269-e_418667,parentE_418669.html#thePic (accessed 12 February 2014).

Berth, R. (1993), *The Return of Innovation*, Düsseldorf.

Berth, R. (1995), *Erfolg: Überlegenheitsmanagement: 12 Mind-Profit-Strategien mit ausführlichem Testprogramm, Mind-Profit-Strategien,* 2. Aufl., ECON, Düsseldorf.

Birkenmeier, B. and Brodbeck, H. (2010), *Wunderwaffe Innovation: Was Unternehmen unschlagbar macht - ein Ratgeber für Praktiker*, Orell Füssli, Zürich.

Birkhofer, M. (2013), *Pinion 2014 - Eurobike*.

Blunch, N. (2013), *Introduction to structural equation modelling using IBM SPSS statistics and AMOS,* 2nd ed., Sage Publications, Los Angeles.

Bogner, A., Littig, B. and Menz, W. (2014), *Interviews mit Experten: Eine praxisorientierte Einführung, Qualitative Sozialforschung*, Springer VS, Wiesbaden.

Boretos, G.P. (2012), "S-curves and their Applications in Marketing, Business, and the Economy", *MRA's Alert! Magazine - February 2012*, pp. 34–39.

Boutellier, R., Gassmann, O. and Zedtwitz, M. von (2008), *Managing global innovation: uncovering the secrets of future competitiveness*, Springer Science & Business Media.

Boynton, A.C. and Zmud, R.W. (1984), "An Assessment of Critical Success Factors", *Sloan Management Review (pre-1986)*, Vol. 25 No. 4, pp. 17–27.

Brockhoff, K. (1991), "Competitor technology intelligence in German companies", *Industrial Marketing Management*, Vol. 20 No. 2, pp. 91–98.

Brosius, F. (2013), *SPSS 21,* 1. Aufl, mitp/bhv, Heidelberg [u.a.].

BSC Designer (2015), "The Difference Between Key Performance Indicators (KPIs) and Critical Success Factors (CSFs) That a Manager Should Know", available at: http://www.bscdesigner.com/kpis-vs-csfs.htm (accessed 11 December 2015).

Bullinger, H.-J. (1994), *Einführung in das Technologiemanagement: Modelle, Methoden, Praxisbeispiele*, Teubner, Stuttgart.

Burgelman, R.A., Meza, P.E. and Berret, E. (2009), "Intel Centrino in 2007: A New "Platform" Strategy For Growth", in Burgelman, R.A., Christensen, C.M. and Wheelwright, S.C. (Eds.), *Strategic management of technology and innovation*, 5th ed., McGraw-Hill Irwin, Boston, pp. 1140–1160.

Butler, T. and Fitzgerald, B. (1999), "Unpacking the systems development process: an empirical application of the CSF concept in a research context", *The Journal of Strategic Information Systems*, Vol. 8 No. 4, pp. 351–371.

BWMi, "The EXIST program", available at: http://www.exist.de/englische_version/index.php (accessed 5 March 2014).

Byers, T.H., Dorf, R.C. and Nelson, A.J. (2010), *Technology ventures: From idea to enterprise,* 3rd Revised ed, McGraw-Hill.

Caragay, A.B. (1983), "Pacing technologies in the fats and oils industry", *Journal of the American Oil Chemists Society*, Vol. 60 No. 9, pp. 1641-1644.

Cassar, G. (2004), "The financing of business start-ups", *Journal of Business Venturing*, Vol. 19 No. 2, pp. 261–283.

Chandy, R.K. and Tellis, G.J. (1998), "Organizing for Radical Product Innovation: The Overlooked Role of Willingness to Cannibalize", *Journal of Marketing Research*, Vol. 35 No. 4, pp. 474–487.

Chiesa, V. and Frattini, F. (2011), “Commercializing Technological Innovation: Learning from Failures in High-Tech Markets”, *Journal of Product Innovation Management*, Vol. 28 No. 4, pp. 437–454.

Christensen, C.M. (1992), “Exploring the Limits of the Technology S-Curve. Part II: Architectural Technologies”, *Production and Operations Management*, Vol. 1 No. 4, pp. 358–366.

Christensen, C.M. (1997), *The innovator's dilemma: When new technologies cause great firms to fail*, Harvard Business School Press, Boston, Mass.

Christensen, C.M. and Anthony, S.D. (2009), “Making SMal Big: SMal Camera Technologies”, in Burgelman, R.A., Christensen, C.M. and Wheelwright, S.C. (Eds.), *Strategic management of technology and innovation*, 5th ed., McGraw-Hill Irwin, Boston, pp. 350–363.

Christensen, C.M. and Rogers, G.C. (1997), “Hewlett-Packard: The Flight of the Kittyhawk”.

Christensen, C.M. and Yu, H. (2009), “Pitney Bowes Inc.”, in Burgelman, R.A., Christensen, C.M. and Wheelwright, S.C. (Eds.), *Strategic management of technology and innovation*, 5th ed., McGraw-Hill Irwin, Boston, pp. 878–889.

Christiansen, E., Hamermesh, R. and Bower, J. (1988), “PC&D, Inc.”, in Burgelman, R.A. and Maidique, M.A. (Eds.), *Strategic management of technology and innovation*, *The Irwin series in management and the behavioral sciences*, Irwin, Homewood, Ill, pp. 519–537.

CIM (2011), “Hard Turning - Examining the machining of prehardened materials”, available at: http://www.cimindustry.com/article/tooling/-hard-turning- (accessed 14 November 2014).

Cohen, H., Keller, S. and Streeter, D. (1988), “The Transfer of Technology from Research to Development”, in Burgelman, R.A. and Maidique, M.A. (Eds.), *Strategic management of technology and innovation*, *The Irwin series in management and the behavioral sciences*, Irwin, Homewood, Ill, pp. 459–469.

Colibi (2013), “European Bicycle Market & Industry Profile - Edition 2013”, available at: http://www.colibi.com/docs/issuu/European%20Bicycle%20Market%20&%20Industry%20Profile%20-%20Edition%202013.pdf (accessed 27 February 2014).

Conceição, P., Hamill, D. and Pinheiro, P. (2002), “Innovative science and technology commercialization strategies at 3M: a case study”, *Journal of Engineering and Technology Management*, Vol. 19 No. 1, pp. 25–38.

CoolClean Technologies (2014a), “Chill Aire - Why CO2”, available at: http://www.mwdwebs.com/testsite/chill/whyco2.html (accessed 12 November 2014).

CoolClean Technologies (2014b), “Productivity”, available at: http://www.mwdwebs.com/testsite/chill/pm.html (accessed 13 November 2014).

CoolClean Technologies (2014c), “Tool Life”, available at: http://www.mwdwebs.com/testsite/chill/tl.html (accessed 12 November 2014).

Cooper, R.G. (1979), “Identifying industrial new product success: Project NewProd”, *Industrial Marketing Management*, Vol. 8 No. 2, pp. 124–135.

Cooper, R.G. and Kleinschmidt, E.J. (1987), “New Products: What Separates Winners from Losers?”, *Journal of Product Innovation Management*, Vol. 4 No. 3, pp. 169–184.

Creare (2012), “Creare People & Technology Newsletter Fall 2012”, available at: http://www.creare.com/newsletters/2012cryomachining.html (accessed 7 October 2014).

Creare (2014), “About Creare Engineering Research & Development”, available at: http://www.creare.com/about/about.html (accessed 7 October 2014).

Creditreform Deutsche Firmenprofile (2014), “Pinion GmbH” (accessed 22 January 2015).

Cross, N. (2008), *Engineering design methods: Strategies for product design,* 4th ed., J. Wiley, Chichester, England, Hoboken, NJ.

Crowe, J.M. and Maidique, M.A. (1988), “Biodel, Inc. (A)”, in Burgelman, R.A. and Maidique, M.A. (Eds.), *Strategic management of technology and innovation*, *The Irwin series in management and the behavioral sciences*, Irwin, Homewood, Ill, pp. 172–189.

Curlee, T. and Goel, R. (1989), *The Transfer and Diffusion of New Technologies: A Review of the Economics Literature*.

Dahl, P. (2015), *Radical Technological Innovations within the Power Transmission Industry – Design and Conduction of a Quantitative Survey: Master Thesis under the supervision of F. Wohlfeil and O. Terzidis*, Karlsruhe.

Dahmus, J.B., Gonzalez-Zugasti, J.P. and Otto, K.N. (2001), “Modular product architecture”, *Design Studies*, Vol. 22 No. 5, pp. 409–424.

Daniel, D.R. (1961), “Management information crisis”, *Harvard business review HBR*, Vol. 39 No. 5, pp. 111–121.

Denend, L., Burgelman, R.A. and Siegel, R.E. (2009), “Matrix Semiconductor Inc: Tackling Challenges of Strategic Dimensions”, in Burgelman, R.A., Christensen, C.M. and Wheelwright, S.C. (Eds.), *Strategic management of technology and innovation*, 5th ed., McGraw-Hill Irwin, Boston, pp. 105–121.

Diniz, A.E. and Micaroni, R. (2007), “Influence of the direction and flow rate of the cutting fluid on tool life in turning process of AISI 1045 steel”, *International Journal of Machine Tools and Manufacture*, Vol. 47 No. 2, pp. 247–254.

Donner, J. (2012), “Die Pinions kommen”, *Trekkingbike No.* 4, pp. 22–29.

Eisenhardt, K.M. (1989), “Building Theories from Case Study Research”, *The Academy of Management Review*, Vol. 14 No. 4, pp. 532–550.

Enders, C.K. (2010), *Applied missing data analysis, Methodology in the social sciences*, Guilford Press, New York.

European Commission, “Mechanical Engineering”, available at: http://ec.europa.eu/growth/sectors/mechanical-engineering/index_en.htm (accessed 16 March 2016).

Fallbrook (2012), "Nuvinci_N360_Datasheet", available at: http://www.fallbrooktech.com/sites/default/files/videos/N360_Datasheet_English_Web.pdf (accessed 12 February 2014).

Fallbrook (2014), "FAQ - Fallbrook Technologies Inc.", available at: http://www.fallbrooktech.com/cycling/faq (accessed 12 February 2014).

Figueroa, E. and Conceição, P. (2000), "Rethinking the innovation process in large organizations: a case study of 3M", *Journal of Engineering and Technology Management*, Vol. 17 No. 1, pp. 93–109.

Fischer, G. and Risch, S. (1993), "Kinder an die Macht", *manager magazin No.* 4, p. 212.

Flick, U. (2007), *Qualitative Sozialforschung: Eine Einführung, Rororo Rowohlts Enzyklopädie*, Vol. 55694, Orig.-Ausg., vollst. überarb. und erw. Neuausg, Rowohlt-Taschenbuch-Verl., Reinbek bei Hamburg.

Foster, R.N. (2006), *Innovation: Die technologische Offensive, McKinsey classics*, Bd. 6, Sonderausg, Redline Wirtschaft, Heidelberg.

Freepik (2015), "Icons designed by Freepik", available at: www.flaticon.com (accessed 8 December 2015).

Frevola, A.L. and Maidique, M.A. (1988), "Data Net", in Burgelman, R.A. and Maidique, M.A. (Eds.), *Strategic management of technology and innovation*, *The Irwin series in management and the behavioral sciences*, Irwin, Homewood, Ill, pp. 388–414.

FVA, "Forschungsvereinigung Antriebstechnik = Innovationsnetzwerk", available at: http://fva-net.de/fva-portraet/ (accessed 27 January 2016).

Gable, J., Tylka S. and Maidique, M.A. (1988), "Apple Computer", in Burgelman, R.A. and Maidique, M.A. (Eds.), *Strategic management of technology and innovation*, *The Irwin series in management and the behavioral sciences*, Irwin, Homewood, Ill, pp. 257–279.

Galanis, N., Manolakos, D.E. and Vaxevanidis, N. (2008), "Comparison between dry and wet machining of stainless steel".

Gardner Research (2014), "Capital Spending Survey 2015 - Executive Summary", available at: http://www.gardnerweb.com/cdn/cms/GBM15_CapSpending.pdf (accessed 24 November 2014).

Gibson, D.V. and Smilor, R.W. (1991), "Key variables in technology transfer: A field-study based empirical analysis", *Journal of Engineering and Technology Management*, Vol. 8 3–4, pp. 287–312.

Gläntz, W. (2011), "Reibung verbindet. Reibwertsteigernde Beschichtung für Flanschverbindungen und Schrumpfscheibenkupplungen", available at: http://www.kem.de/windenergie/-/article/30599594/34389029/Reibung-verbindet/art_co_INSTANCE_0000/maximized/ (accessed 27 May 2014).

Gläser, J. and Laudel, G. (2010), *Experteninterviews und qualitative Inhaltsanalyse,* 4th ed., VS Verlag, Wiesbaden.

GloboMeter, "Die Welt in Zahlen", available at: http://de.globometer.com/sport-fahrrad.php (accessed 27 February 2014).

Hair, J.F. (2010), *Multivariate data analysis: A global perspective,* 7th ed., Pearson Education, Upper Saddle River, N.J, London.

Hellmann, L. (2014), *Critical Success Factors for the Management of Radical Technological Innovation: Master Thesis under the supervision of F. Wohlfeil and O. Terzidis*, Karlsruhe.

Henderson, R. (1993), "Underinvestment and Incompetence as Responses to Radical Innovation: Evidence from the Photolithographic Alignment Equipment Industry", *The RAND Journal of Economics*, Vol. 24 No. 2, pp. 248–270.

Henderson, R.M. and Clark, K.B. (1990), "Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms", *Administrative Science Quarterly*, Vol. 35 No. 1, pp. 9–30.

Henkel, J. and Jung, S. (2009), "The Technology-Push Lead User Concept: A New Tool for Application Identification", available at: http://www.econbiz.de/archiv1/2010/106892_technology_lead_user.pdf (accessed 15 March 2013).

Herstatt, C. and Hippel, E. von (1992), "FROM EXPERIENCE: Developing New Product Concepts Via the Lead User Method: A Case Study in a "Low-Tech" Field", *Journal of Product Innovation Management*, Vol. 9 No. 3, pp. 213–221.

Heumann, C. and Toutenburg, H. (2006), *Deskriptive Statistik: Eine Einführung in Methoden und Anwendungen mit SPSS ; mit 48 Tabellen, Springer-Lehrbuch,* 5., aktualisierte und erw. Aufl, Springer, Berlin [u.a.].

Hevner, A.R., March, S.T., Park, J. and Ram, S. (2004), "Design Science in Information Systems Research", *MIS Quarterly*, Vol. 28 No. 1, pp. 75–105.

Hilgers, Y. (2015), *An Empirical Analysis of Radical Technological Innovation within the Power Transmission Industry: Master Thesis under the supervision of F. Wohlfeil and O. Terzidis*, Karlsruhe.

Hippel, E. von (1986), "Lead Users: A Source of Novel Product Concepts", *Management Science*, Vol. 32 No. 7, pp. 791–805.

Hippel, E. von, Thomke, S. and Sonnack, M. (1999), "Creating Breakthroughs at 3M", pp. 47–57.

Holzschuher, W. von and Pechlaner, H. (2007), "Wie sollen Ausgründungen ablaufen? - Realisisierung von Ausgründungen im Rahmen eines prozessbezogenen Transformationskonzeptes", in Pechlaner, H., Hinterhuber, H., Holzschuher, W. von and Hammann, E.-M. (Eds.), *Unternehmertum und Ausgründung: Wissenschaftliche Konzepte und praktische Erfahrungen*, 1st ed., Deutscher Universitäts-Verlag, Wiesbaden, pp. 41–54.

Hoppenstedt Firmenprofile (2014), “Pinion GmbH” (accessed 22 January 2015).

Horling, P., Kaiser, T., Liesegang, H.-J. and Wagner, R. (2009), *Beschichtungsanordnung*, B32B 5/16 DE 10 2007 057 907 A1.

IBISWorld (2014), “Metalworking Machinery Manufacturing in the US: Market Research Report”, available at: http://www.ibisworld.com/industry/default.aspx?indid=704&partnerid=ValuationResources (accessed 24 November 2014).

Industriemagazin (2016), “Chinas schwieriger Wandel vom Schwellenland zum Industrieland”, available at: http://industriemagazin.at/a/chinas-schwieriger-wandel-vom-schwellenland-zum-industrieland (accessed 15 March 2016).

IWES (2015), “Windenergie Report Deutschland 2014”, available at: http://windmonitor.iwes.fraunhofer.de/opencms/export/sites/windmonitor/img/Windenergie_Report_2014.pdf (accessed 24 November 2015).

Jakimo, A.I. and Bupp, I.C. (1988), “Texas Instruments' "Speak and Spell" Product”, in Burgelman, R.A. and Maidique, M.A. (Eds.), *Strategic management of technology and innovation*, *The Irwin series in management and the behavioral sciences*, Irwin, Homewood, Ill, pp. 113–135.

Janetzke, C. (2014), “US-Markt für Werkzeugmaschinen soll kräftig expandieren”, available at: http://www.gtai.de/GTAI/Navigation/DE/Trade/maerkte,did=1085840.html (accessed 24 November 2014).

Jolly, V.K. (1997), *Commercializing new technologies: Getting from mind to market*, Harvard Business School Press, Boston, Mass.

Kautzsch, T. and Sitte, T. (2016), “Mechanical Engineering 2015. Strategies for a changed world”, available at: http://www.oliverwyman.com/content/dam/oliver-wyman/global/en/files/archive/2011/mechanical2015.pdf.

Keinz, P. and Prügl, R. (2010), “A User Community-Based Approach to Leveraging Technological Competences: An Exploratory Case Study of a Technology Start-Up from MIT”, *Creativity and Innovation Management*, Vol. 19 No. 3, pp. 269–289.

Kelly, P. and Kranzberg, M. (1978), “Technological innovation: A critical review of current knowledge”.

Kerth, K., Asum, H. and Nührich, K. (2007), *Die besten Strategietools in der Praxis: Welche Werkzeuge brauche ich wann? - Wie wende ich sie an? - Wo liegen die Grenzen?,* 2., erw. Aufl, Hanser, Carl, München.

Kissler, H. (2004), “Trockenbearbeitung in der Praxis”, available at: http://abag-itm.de/fileadmin/Dateien/ABAG/Dokumente/WM_Trockenbearbeitung_in_der_Praxis_2004.pdf (accessed 11 November 2014).

Kline, S. (2014), *Gardner Research: 2015 Capital Spending Results Presentation*.

Kotler, P., Bliemel, F. and Keller, K.L. (2007), *Marketing-Management: Strategien für wertschaffendes Handeln,* 12th ed., Pearson Studium, München [u.a.].

Kuckartz, U. (2012), *Qualitative Inhaltsanalyse. Methoden, Praxis, Computerunterstützung,* 1. Aufl., Juventa, Weinheim, Bergstr.

Kurzawa, T. (1993), *Gestaltung und Berechnung von nichtschaltbaren reibschlüssigen Flanschkupplungen: Dissertation*.

Lamnek, S. (2005), *Qualitative Sozialforschung: Lehrbuch, Lehrbuch,* 4., vollst. überarb. Auflage, Beltz, PVU, Weinheim, Basel.

Landler, M. (2014), "U.S. and China Reach Climate Accord After Months of Talks", available at: http://www.nytimes.com/2014/11/12/world/asia/china-us-xi-obama-apec.html?_r=0 (accessed 17 December 2014).

Law, R. (2012), "How we create and capture value through strategic partnerships. SKF - Capital Markets Day 2010", available at: http://www.skf.com/irassets/afw/files/cmd2010/SKF-Robert-Law.pdf (accessed 27 May 2014).

Lawal, S.A., Choudhury, I.A. and Nukman, Y. (2013), "A critical assessment of lubrication techniques in machining processes: a case for minimum quantity lubrication using vegetable oil-based lubricant", *Journal of Cleaner Production*, Vol. 41 No. 0, pp. 210–221.

Leedy, P.D. and Ormrod, J.E. (2009), *Practical research: Planning and design,* 9th ed., Pearson Education, Upper Saddle River, N.J, Harlow.

Leidecker, J.K. and Bruno, A.V. (1984), "Identifying and using critical success factors", *Long Range Planning*, Vol. 17 No. 1, pp. 23–32.

Lermen, C. (2010), *Eurobike 2010 - Pinion Getriebenabe*.

Lermen, C. (2011), *Fahrbericht Pinion / Nicolai Helius AM*.

Machinery Market (2013), "Keeping machining 'dry' - Machinery Market News", available at: http://www.machinery-market.co.uk/news/3263/Keeping-machining-dry (accessed 11 November 2014).

MAG IAS, "Cryogenic Machining", available at: http://www.mag-ias.com/fileadmin/user_upload/Mag_One/technologies/cryogenics/ID1431/120820_Cryogenics_Brochure_US_Low.pdf (accessed 15 March 2013).

MAG IAS (2012), *Cryogenic Machining - Presentation*.

Mankins, J.C. (1995), "Technology readiness levels", *White Paper, April*, Vol. 6.

Mankins, J.C. (2009), "Technology readiness assessments: A retrospective", *Acta Astronautica*, Vol. 65 9–10, pp. 1216–1223.

March, A. (2009), "R. R. Donnelley & Sons: The Digital Division", in Burgelman, R.A., Christensen, C.M. and Wheelwright, S.C. (Eds.), *Strategic management of technology and innovation*, 5th ed., McGraw-Hill Irwin, Boston, pp. 901–914.

Mayring, P. (1997), *Qualitative Inhaltsanalyse: Grundlagen und Techniken,* 6. Aufl., Beltz, Weinheim.

Mayring, P. (2000), “Qualitative Content Analysis”, *Forum Qualitative Sozialforschung / Forum: Qualitative Social Research; Vol 1, No 2 (2000): Qualitative Methods in Various Disciplines I: Psychology*.

Mayring, P. (2002), *Einführung in die qualitative Sozialforschung: Eine Anleitung zu qualitativem Denken, Beltz-Studium,* 5., überarb. und neu ausgestattete Aufl., Beltz, Weinheim [u.a.].

Mayring, P. (2010), *Qualitative Inhaltsanalyse: Grundlagen und Techniken,* 11.th ed., Beltz, Weinheim.

McDermott, C.M. and O'Connor, G.C. (2002), “Managing radical innovation: an overview of emergent strategy issues”, *Journal of Product Innovation Management*, Vol. 19 No. 6, pp. 424–438.

McKechnie, G., “Makino-S33-MachiningCenter-example”, available at: http://de.wikipedia.org/wiki/K%C3%BChlschmiermittel (accessed 11 November 2014).

McVie, C., Burgelman, R.A. and Siegel, R.E. (2009), “Pixim (A): August 2001”, in Burgelman, R.A., Christensen, C.M. and Wheelwright, S.C. (Eds.), *Strategic management of technology and innovation*, 5th ed., McGraw-Hill Irwin, Boston, pp. 78–97.

Meier, J. (2007), “Wie man Ausgründungen zum Erfolg führt – Die Sicht des Finanziers”, in Pechlaner, H., Hinterhuber, H., Holzschuher, W. von and Hammann, E.-M. (Eds.), *Unternehmertum und Ausgründung: Wissenschaftliche Konzepte und praktische Erfahrungen*, 1st ed., Deutscher Universitäts-Verlag, Wiesbaden, pp. 263–284.

Michel, S. (2011), “Schrumpfscheibe für den Triebstrang in 5 MW-Windkraftanlagen”, available at: http://www.konstruktionspraxis.vogel.de/schrumpfscheibe-fuer-den-triebstrang-in-5-mw-windkraftanlagen-a-315797/ (accessed 20 November 2015).

Moore, G.A. (2005), *Crossing the chasm: Marketing and selling technology products to mainstream customers,* Rev. ed., [Nachdr.], HarperCollins Publ., New York.

Nevens, T.M. (1990), “Commercializing technology: What the best companies do”, *Strategy & Leadership*, Vol. 18 No. 6, pp. 20–24.

Norman, G. (2010), “Likert scales, levels of measurement and the “laws” of statistics”, *Advances in Health Sciences Education*, Vol. 15 No. 5, pp. 625–632.

O`Connor, G.C. and DeMartino, R. (2006), “Organizing for Radical Innovation: An Exploratory Study of the Structural Aspects of RI Management Systems in LargeEstablished Firms”, *The Journal of Product Innovation Management No.* 23, pp. 475–497.

O’Keeffe, E. (2002), “ARM Holdings Plc INSEAD-EAC, Teaching case”, pp. 1–21.

OECD (1971), *The conditions for success in technological innovation*, Paris.

OECD (2005), *Oslo manual: Guidelines for collecting and interpreting innovation data,* 3rd ed., Organisation for Economic Co-operation and Development; Statistical Office of the European Communities, Paris.

Osterwalder, A., Pigneur, Y. and Clark, T. (2010), *Business model generation: A handbook for visionaries, game changers, and challengers*, Wiley, Hoboken, NJ.

Oxford dictionary (2015), "definition of expert", available at: http://www.oxforddictionaries.com/definition/english/expert (accessed 22 March 2015).

Pavia, T. and Dodson, K. (2008), "The Rover Project: A Corporate Start-Up Within TechCo", in Tesar, G., Anderson, S., Ghosh, S. and Bramorski, T. (Eds.), *Strategic technology management: Building bridges between sciences, engineering, and business management*, 2nd ed., Imperial College Press, London, pp. 127–154.

Pinion, "Testberichte | PINION / P1.18 / DRIVE TECHNOLOGY", available at: http://pinion.eu/discover-pinion/test-reports/ (accessed 12 March 2014).

Pinion (2013a), "Pinion Imagebrochure 2014", available at: http://www.pinion.eu/PDF/pinion-broschure-2014-web.pdf (accessed 22 January 2014).

Pinion (2013b), *Expert interview with one of Pinion's founders regarding the realization of the P1.18 (conducted by Florian Wohlfeil)*, Telefoninterview.

Pinion (2014a), "HÄNDLER-Netzt Pinion", available at: http://pinion.eu/discover-pinion/haendler/ (accessed 22 January 2014).

Pinion (2014b), *Expert interview with one of Pinion's founders regarding the realization of the P1.18 (conducted by Florian Wohlfeil)*, Telefoninterview.

Poel, M. van den and Burgelman, R.A. (1988), "Control Data Corporation", in Burgelman, R.A. and Maidique, M.A. (Eds.), *Strategic management of technology and innovation*, *The Irwin series in management and the behavioral sciences*, Irwin, Homewood, Ill, pp. 581–594.

Pro Activ GmbH (2014), "Handbike - Tetra-Ausstattung - Kettenschaltungen - Komponenten", available at: http://www.proactiv-gmbh.de/tetra-ausstattung_handbikes_kettenschaltungen_komponenten.php (accessed 12 February 2014).

Pušavec, F. and Kopač, J. (2011), "Sustainability assessment: cryogenic machining of Inconel 718", *Strojniški vestnik-Journal of Mechanical Engineering*, Vol. 57 No. 9, pp. 637–647.

Raab-Steiner, E. and Benesch, M. (2008), *Der Fragebogen: Von der Forschungsidee zur SPSS-Auswertung, UTB L (Large-Format)*, Vol. 8406, UTB, Wien.

Reich, S. and Böswetter, G. (2002), "Trockenbearbeitung - Möglichkeiten und Grenzen einer Technologie", pp. 7–11.

Reidl, A. (2012), "Getriebe-Gründer Pinion: Tandem mit dem Trauminvestor", available at: http://www.spiegel.de/karriere/berufsstart/pinion-am-fahrrad-wie-die-getriebe-gruender-ihren-investor-fanden-a-869417.html (accessed 23 January 2014).

Richt, C. (2011), "Using High-pressure Coolant", available at: http://www.cimindustry.com/article/tooling/using-high-pressure-coolant (accessed 11 November 2014).

Ries, E. (2011), *The lean startup: How today's entrepreneurs use continuous innovation to create radically successful businesses,* 1st ed., Crown Business, New York.

Ringfeder (2015), "Schrumpfscheibe", available at: http://www.ringfeder.com/de/international/produkte/ringfeder/RINGFEDER/?p=6672 (accessed 22 November 2015).

Rockart, J.F. (1979), "Chief executives define their own data needs", *Harvard Business Review*, Vol. 57 No. 2, pp. 81–93.

Rogers, E.M. (2003), *Diffusion of innovations,* 5th ed, Free Press, New York.

Rohloff (2011), "SPEEDHUB", available at: http://www.rohloff.de (accessed 12 February 2014).

Rothwell, R., Freeman, C., Horlsey, A., Jervis, V., Robertson, A.B. and Townsend, J. (1974), "SAPPHO updated - project SAPPHO phase II", *Research Policy*, Vol. 3 No. 3, pp. 258–291.

Rüger, B. (2002), *Test- und Schätztheorie, Lehr- und Handbücher der Statistik*, Oldenbourg, München, Wien.

Saleh, S.D. and Wang, C.K. (1993), "The management of innovation: strategy, structure, and organizational climate", *Engineering Management, IEEE Transactions on*, Vol. 40 No. 1, pp. 14–21.

Samsonowa, T. (2012), *Industrial Research Performance Management: Key Performance Indicators in the ICT Industry, Contributions to Management Science*, Springer-Verlag Berlin Heidelberg, Heidelberg.

Sanderson, S. and Uzumeri, M. (1995), "Managing product families: The case of the Sony Walkman", *Research Policy*, Vol. 24 No. 5, pp. 761–782.

Sandvik (2010), "Zerspanung mit Hochdruck-Kühlung", available at: http://www.sandvik.coromant.com/sitecollectiondocuments/downloads/global/brochures/de-de/c-1040-091.pdf (accessed 11 November 2014).

Sankara, H. and Winkmann, H. (2009), "Elio Engineering, Inc.", in Burgelman, R.A., Christensen, C.M. and Wheelwright, S.C. (Eds.), *Strategic management of technology and innovation*, 5th ed., McGraw-Hill Irwin, Boston, pp. 13–32.

Saunders, M., Lewis, P. and Thornhill, A. (2012), *Research methods for business students,* 6th ed., Pearson, Harlow, England, New York.

Schäfer, M. (2013), "Ein Fahrradgetriebe für den Alltag - Stuttgarter Zeitung", available at: http://www.stuttgarter-zeitung.de/inhalt.technik-ein-fahrradgetriebe-fuer-den-alltag.2b53d10d-33fb-4293-a2fd-764bcb01fd45.html (accessed 23 January 2014).

Schendera, C. (2008), *Clusteranalyse mit SPSS,* 1. Aufl, Oldenbourg, München.

Schilling, M.A. (1998), "Technological Lockout: An Integrative Model Of The Economic And Strategic Factors Driving Technology Success And Failure", *Academy of Management Review*, Vol. 23 No. 2, pp. 267–284.

Schilling, M.A. (2008), *Strategic management of technological innovation,* 2nd ed., McGraw-Hill/Irwin, Boston.

Schilling, M.A. (2010), *Strategic management of technological innovation,* 3rd ed., McGraw-Hill/Irwin, New York.

Schumpeter, J. (1952), *Theorie der wirtschaftlichen Entwicklung: eine Untersuchung über Unternehmergewinn, Kapital, Kredit, Zins und den Konjunkturzyklus*, Duncker & Humblot.

Schumpeter, J.A. (2006 reprint of 1939), *Business cycles: A theoretical, historical, and statistical analysis of the capitalist process*, Reprint of the first edition of 1939, Martino Pub., Mansfield Centre, CT.

Schumpeter, J.A. and Röpke, J. (2006 reprint of 1912), *Theorie der wirtschaftlichen Entwicklung,* Nachdr. der 1. Aufl. von 1912., Duncker und Humblot, Berlin.

Seitz, C. (2015), *Diffusion innovativer Antriebstechnologien zur CO2-Reduktion von Nutzfahrzeugen - Empirische Untersuchung des organisationalen Adoptionsverhaltens und systemdynamische Prognose für den deutschen Automobilmarkt*, (Dissertationsschrift).

Sekaran, U. and Bougie, R. (2010), *Research Methods for Business: A Skill Building Approach,* 5th ed, Wiley, Chichester.

Senvion (2014), "Pressrelease - REpower is now Senvion", available at: http://www.senvion.com/fileadmin/user_upload/06_Press/PressReleases/2014_01_20_REpower_is_now_Senvion_FINAL.pdf (accessed 16 July 2014).

Senvion (2015a), "Senvion Annual Report 2015", available at: https://www.senvion.com/fileadmin/senvion_annual_report_FY15.pdf (accessed 25 November 2015).

Senvion (2015b), "Senvion Wind Energy Solutions", available at: https://www.senvion.com/global/de/unternehmen/ (accessed 24 November 2015).

Shapiro, R. (2009), "Vitreon Corporation: The Hyalite Project", in Burgelman, R.A., Christensen, C.M. and Wheelwright, S.C. (Eds.), *Strategic management of technology and innovation*, 5th ed., McGraw-Hill Irwin, Boston, pp. 1013–1025.

Shelton, R. and Percival, D. (2013), *Breakthrough innovation and growth*.

Shimano (2011), "Shimano Alfine", available at: http://www.shimano.com/publish/content/global_cycle/en/us/index/products/0/alfine/product.-code-SG-S700-S.-type-.html (accessed 12 February 2014).

Simpel-ch (2014), "Shimano Alfine 11 Gang Nabe - simpel.ch Velos", available at: http://www.simpel-ch.de/fahrrad/nabenschaltung/shimano_alfine_11gang.html (accessed 12 February 2014).

SKF (2014a), "Annual Report 2013", available at: http://www.skf.com/group/investors/reports/skf-annual-report-2013-financial-environmental-and-social-performance (accessed 22 April 2014).

SKF (2014b), *Expert interview with the innovation manager of the Friction Disc project (conducted by Florian Wohlfeil)*, Schweinfurt.

SKF (2014c), *Expert interview with the manager of the Friction Disc project - Part 1 (conducted by Florian Wohlfeil)*, Schweinfurt.

SKF (2014d), *Expert interview with the manager of the Friction Disc project - Part 2 (conducted by Florian Wohlfeil)*, Schweinfurt.

SKF (2015), *Annual Report 2014*.

Song, M., Podoynitsyna, K., Van Der Bij, Hans and Halman, Johannes I. M. (2008), "Success Factors in New Ventures: A Meta-analysis", *Journal of Product Innovation Management*, Vol. 25 No. 1, pp. 7–27.

Souder, W.E. (1989), "Improving productivity through technology push", *Research-Technology Management*, Vol. 32 No. 2, pp. 19–24.

Stahl, S. (2013), "Pinion 2014 mit optimiertem Zubehör von Gates und Carbocage", available at: http://www.mtb-news.de/news/2013/08/28/eurobike-2013-pinion-mit-optimiertem-zubehoer-von-gates-und-carbocage/ (accessed 23 January 2014).

Stahl, T. (2011), "Nicolai Helius AM Pinion - Fahrbericht vom ersten Mountainbike mit Pinion Getriebe", available at: http://www.mtb-news.de/news/2011/08/23/nicolai-helius-am-pinion-fahrbericht-vom-ersten-mountainbike-mit-pinion-getriebe/ (accessed 23 January 2014).

Statista, "Umsatz der deutschen Antriebstechnikbranche bis 2014", available at: http://de.statista.com/statistik/daten/studie/235436/umfrage/umsatz-im-bereich-antriebstechnik-in-deutschland/ (accessed 23 October 2015).

Statista (2015), "Wichtigste Länder weltweit nach Umsatz im Maschinenbau", available at: http://de.statista.com/statistik/daten/studie/154143/umfrage/umsatz-im-maschinenbau-2009-nach-laendern/ (accessed 14 March 2016).

Statistisches Bundesamt (2015), "Produzierendes Gewerbe 2014. Beschäftigung und Umsatz der Betriebe des Verarbeitenden Gewerbes sowie des Bergbaus und der Gewinnung von Steinen und Erden", available at: https://www.destatis.de/DE/Publikationen/Thematisch/IndustrieVerarbeitendesGewerbe/Konjunkturdaten/MonatsberichtJ2040411147004.pdf?__blob=publicationFile (accessed 23 October 2015).

Staudt, J. (2011), available at: http://www.mtb-news.de/news/2011/08/23/nicolai-helius-am-pinion-fahrbericht-vom-ersten-mountainbike-mit-pinion-getriebe/ (accessed 7 February 2014).

Steinke, A. (2013), "Dauertest-Review #02: Die Pinion P1.18 im Alutech Fanes", available at: http://enduro-mtb.com/dauertest-review-02-die-pinion-p1-18-im-alutech-fanes/ (accessed 23 January 2014).

Stiener, S. (2012), "Pinion-Getriebe in der Fahrpraxis", available at: http://velotraum.de/news/pinion-getriebe-in-der-fahrpraxis (accessed 23 January 2014).

Su, Y., He, N., Li, L. and Li, X.L. (2006), “An experimental investigation of effects of cooling/lubrication conditions on tool wear in high-speed end milling of Ti-6Al-4V”, *Wear*, Vol. 261 7–8, pp. 760–766.

Tabachnick, B.G. and Fidell, L.S. (2007), *Using multivariate statistics,* 5th ed, Pearson/Allyn & Bacon, Boston.

Tellis, W. (1997), “Introduction to Case Study”, The Qualitative Report, available at: http://www.nova.edu/ssss/QR/QR3-2/tellis1.html (accessed 18 January 2013).

Terziovski, M. (2007), *Building innovation capability in organizations: An international cross-case perspective, Series on technology management*, v. 13, Imperial College Press; Distributed by World Scientific, London, Singapore, Hackensack, NJ.

Tidd, J., Bessant, J.R. and Pavitt, K. (2005), *Managing innovation: Integrating technological, market and organizational change,* 3rd ed., Wiley, Hoboken.

Tornatzky, L.G. and Fleischer, M. (1990), *The processes of technological innovation, Issues in organization and management series*, Lexington Books, Lexington, Mass.

Tornatzky, L.G., Fleischer, M. and Chakrabarti, A.K. (1990), “Processes of technological innovation”.

Trott, P. (2012), *Innovation management and new product development,* 5th ed., Financial Times/Prentice Hall, Harlow, England, New York.

TTI (2014), “Gründen an der Uni Stuttgart TTI GmbH Stuttgart”, available at: http://www.tti-stuttgart.de/ (accessed 29 January 2014).

Ullman, D.G. (2003), *The mechanical design process,* 3rd ed., McGraw-Hill, Boston, Mass.

Ulrich, K. (1995), “The role of product architecture in the manufacturing firm”, *Research Policy*, Vol. 24 No. 3, pp. 419–440.

Utterback, J.M. (1971), “The Process of Technological Innovation Within the Firm”, *Academy of Management Journal*, Vol. 14 No. 1, pp. 75–88.

Utterback, J.M. (1974), “Innovation in Industry and the Diffusion of Technology”, *Science*, Vol. 183 No. 4125, pp. 620–626.

Vahs, D. and Brem, A. (2012), *Innovationsmanagement: Von der Idee zur erfolgreichen Vermarktung,* 4., überarb. Aufl, Schäffer-Poeschel, Stuttgart.

van Aken, J.E. (2005), “Management Research as a Design Science: Articulating the Research Products of Mode 2 Knowledge Production in Management”, *British Journal of Management*, Vol. 16 No. 1, pp. 19–36.

VDMA (2015), “Mechanical engineering – figures and charts 2015”, available at: http://www.vdma.org/documents/105628/7657821/MbauinZuB2015.pdf/9b789a8c-ef20-4f8d-a6fc-d6268d2c09e5 (accessed 14 March 2016).

VDMA and McKinsey (2014a), “Erfolgsmuster und Trends in der deutschen Antriebstechnik. Handlungsansätze für mehr Wachstum und Profitabilität”, Eine Detailanalyse der Studie „Zukunftsperspektive deutscher Maschinenbau“, available at:

http://www.vdma.org/documents/105628/6563034/Zukunfstsperspektive+deutscher+Maschinenbau+-+Auswertung+Antriebstechnik.pdf/84956959-badd-4adf-82c2-e0578545d4e4 (accessed 2 October 2015).

VDMA and McKinsey (2014b), *The future of German mechanical engineering*.

VDMA and McKinsey (2014c), "Zukunftsperspektive deutscher Maschinenbau. Erfolgreich in einem dynamischen Umfeld agieren", available at: http://www.mckinsey.de/sites/mck_files/files/zukunftsperspektive_maschinenbau.pdf (accessed 2 October 2015).

Velomobile (2013), "Velomobile Media Sales of NuVinci Continous Variable Planetary Transmission", available at: http://velomobilemedia.com/nuvinci.htm (accessed 12 February 2014).

Verburg, R.M., Ortt, J.R. and Dicke, W.M. (2005), *Managing technology and innovation: An introduction*, Routledge, London, New York.

Vieweg, H.-G. (2012a), "An introduction to Mechanical Engineering: Study on the Competitiveness of the EU Mechanical Engineering Industry. Final Report", available at: ec.europa.eu/DocsRoom/documents/12329/attachments/1/translations/en/renditions/native.

Vieweg, H.-G. (2012b), "An introduction to Mechanical Engineering: Study on the Competitiveness of the EU Mechanical Engineering Industry. Summary", available at: ec.europa.eu/DocsRoom/documents/12329/attachments/2/translations/en/renditions/native.

Walter (2013), "Walter wins Innovation Prize", available at: http://www.walter-tools.com/en-gb/press/press_lounge/Pages/emo-award-2013.aspx (accessed 12 November 2014).

Wang, Z.Y. and Rajurkar, K.P. (2000), "Cryogenic machining of hard-to-cut materials", *Wear*, Vol. 239 No. 2, pp. 168–175.

Warentest, S. (2013), "Fahrradtechnik im Überblick - Fahrradschaltungen im Überblick - Special - Stiftung Warentest", available at: http://www.test.de/Fahrradtechnik-im-Ueberblick-In-die-Gaenge-kommen-1791218-1791324/ (accessed 13 February 2014).

Webster dictionary, "Mechanical Engineering", available at: http://www.merriam-webster.com/dictionary/mechanical%20engineering (accessed 14 March 2016).

White, M.A. and Bruton, G.D. (2007), *The management of technology and innovation: A strategic approach,* Student ed, Thomson/South-Western, Mason, OH.

Wittenberg, R. and Cramer, H. (2000), *Datenanalyse mit SPSS für Windows: Mit zahlreichen Tabellen, UTB für Wissenschaft*, Vol. 1841, 2., neubearb. Aufl, Lucius und Lucius, Stuttgart.

Wittenberg, R., Cramer, H. and Vicari, B. (2014), *Datenanalyse mit IBM SPSS Statistics: Eine syntax-orientierte Einführung, UTB*, Nr. 4225, UVK-Verl.-Ges., Konstanz.

Wohlfeil, F. (2015a), "Radical Technological Innovation: Case Study of Cryogenic Machining by 5ME", *KIT Scientific Working Papers No.* 29.

Wohlfeil, F. (2015b), "Radical Technological Innovation: Case Study of the Friction Disc by SKF", *KIT Scientific Working Papers No.* 42.

Wohlfeil, F. (2015c), "Radical Technological Innovation: Case Study of the P1.18 Bicycle Transmission by Pinion", *KIT Scientific Working Papers No.* 28.

Wohlfeil, F. (2015d), "Radikale technische Innovationen in der deutschen Antriebstechnik: Handlungsempfehlungen zur erfolgreichen Umsetzung", *KIT Scientific Working Papers No.* 39.

Wohlfeil, F. and Terzidis, O. (2014), "Critical Success Factors for the Strategic Management of Radical Technological Innovation", Bergamo, Italy.

Wohlfeil, F. and Terzidis, O. (2015a), "A Critical Success Factors Model for Radical Technological Innovations", Budapest, Hungary, available at: http://conference.ispim.org/files/budapest_proceedings/documents/669625219_Paper.pdf.

Wohlfeil, F. and Terzidis, O. (2015b), "Strategic Approaches for the Realization of Radical Technological Innovations within the Manufacturing Industry", Pisa.

Wohlfeil, F., Terzidis, O. and Hellmann, L. (2015), "Radical Technological Innovation–Comparison of a Critical Success Factors Framework with Existing Literature", *World Academy of Science, Engineering and Technology, International Science Index 105; International Journal of Social, Behavioral, Educational, Economic, Business and Industrial Engineering*, Vol. 9 No. 9, pp. 3060–3068.

Wouters, M.J.F. (2009), "Customer Value Propositions for Technology Commercialization: Investigating the Feasibility of a Real Options Approach. Conference Publications", available at: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5373513 (accessed 15 March 2013).

Wragg, M. (2012), "Pinion P1.18 Gearbox: First Ride - Pinkbike", available at: http://www.pinkbike.com/news/Pinion-Gearbox-First-Ride.html (accessed 30 January 2014).

Yakubovich, K. (2014), *Process Model for Technology Commercialization: Master Thesis under the supervision of F. Wohlfeil and O. Terzidis*, Karlsruhe.

Yin, R.K. (2009), *Case study research: Design and methods,* 4th ed., Sage Publications, Los Angeles, Calif.

ZIV (2013a), "Statistik Informationen für das Jahr 2012 – Präsentation des ZIV", available at: http://www.ziv-zweirad.de/public/pk_2013-ziv-praesentation_20-03-2013_ot.pdf (accessed 27 February 2014).

ZIV (2013b), "ZIV-Jahresbericht 2013", available at: http://www.ziv-zweirad.de/public/ziv_jahresbericht_2013.pdf (accessed 27 February 2014).