A Comprehensive Approach for the Empirical Investigation of Success Factors in Product Development

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Abstract

The outcome of product development projects depends on a multitude of different factors, deriving not only from technical challenges, but also from aspects like human behavior or complex organizational environments. Empirical research studies have become increasingly important in verifying which of these Potential Success Factors contribute most to successful product development. Many studies have focused on certain aspects of the design process, such as the individual designer or design teams. These have contributed greatly to a better understanding in Engineering Design Research. Comprehensive studies, viewing the product development process holistically with all its influencing factors, are rare. However, additional information can be obtained from comprehensive investigations. In addition to understanding which of the Potential Success Factors show an actual correlation to Design Success - then considered Success Factors - it can also be investigated how these Success Factors depend on each other. Such dependencies provide information about causalities and subsequently lead to a set of Dominant Success Factors. These not only influence the outcome of product development projects significantly, but also cause other Success Factors to change, which is why they need to be given the first and most attention by engineering management.

This dissertation illustrates the framework of an empirical approach, which supports the comprehensive investigation of Success Factors in product development. The approach was applied to 44 gas turbine component development projects of varying complexity. The collected data was analyzed using statistical methods, which provided information about the reliability of the results. Following the proposed approach with its two analysis steps lead to the identification of the following four Dominant Success Factors, which distinguished successful from less successful development projects: Priority of Project; Skills and Experience of Project Lead; Complexity and amount of Innovation of Project; Awareness of Lessons Learned and State of the Art Technology Knowledge. The remaining factors, not identified as dominant, are considered Supplementary Success Factors, as they can help to leverage Design Success. However, the research work clearly shows that the Dominant Success Factors contribute most and have to be seen as the foundation for successful product development. Engineering management can use the results of this work for an improved project risk management, especially in the early stages of product development.

Zusammenfassung

Das Ergebnis von Produktentwicklungsprojekten hängt von einer Vielzahl verschiedener Faktoren ab, welche nicht nur aus technischen Herausforderungen, sondern auch aus anderen Aspekten, wie etwa des menschlichen Verhaltens oder komplexer Organisationsumgebungen, bestehen. Empirische Forschungsstudien wurden im Laufe der Zeit immer wichtiger, um zu verifizieren welche dieser Potenziellen Erfolgsfaktoren am meisten zur erfolgreichen Produktentwicklung beitragen. Viele der durchgeführten Studien fokusierten auf bestimmte Bereiche des Entwicklungsprozesses, zum Beispiel dem Entwickler als Individuum oder Entwicklungsteams, und haben entscheidend zum besseren Verständis im Forschungsbereich Engineering Design Research beigetragen. Ganzheitliche Studien, die den Produktentwicklungsprozess holistisch, mit all seinen Einflussfaktoren, betrachten, sind selten zu finden. Jedoch, können gerade aus diesen ganzheitlichen Untersuchungen zusätzliche Information gewonnen werden. Außer dem Verständnis welche der Potenziellen Erfolgsfaktoren einen Zusammenhang zu Entwicklungserfolg zeigen - dann als Erfolgsfaktoren identifiziert - können zudem Abhängigkeiten der Erfolgsfaktoren untereinander untersucht werden. Derartige Abhängigkeiten geben Aufschluss über kausale Zusammenhänge und führen letztlich zu einer Gruppe von Dominanten Erfolgsfaktoren. Diese beeinflussen nicht nur die Ergebnisse von Produktentwicklungsprojekten signifikant, sondern verursachen zusätzlich die Änderung anderer Erfolgsfaktoren, weshalb sie die bevorzugte und höchste Aufmerksamkeit der Entwicklungsleitung erhalten müssen.

Diese Dissertation beschreibt das Grundgerüst einer empirischen Methode, welche die ganzheitliche Untersuchung von Erfolgsfaktoren in der Produktentwicklung unterstützt. Die Methode wurde auf 44 Komponentenentwicklungsprojekte von Gasturbinen, mit variierender Komplexität, angewandt. Die gesammelten Daten wurden mit Hilfe statistischer Verfahren ausgewertet, was Auskunft über die Verlässlichkeit der Resultate gab. Die Anwendung der vorgeschlagenen Methode mit ihren zwei Analyseschritten führte letztlich zu den vier folgenden Dominanten Erfolgsfaktoren, durch welche sich erfolgreiche von weniger erfolgreichen Entwicklungsprojekten unterscheideten: Priorität des Projekts; Fähigkeiten und Erfahrung des Projektleiters; Complexität und Innovationsanteil im Projekt; Bewusstsein über Gewonnene Erkenntnisse und aktuellen Stand der Technik. Die verbleibenden Faktoren der Studie, die nicht als dominant indentifziert wurden, werden als Ergänzende Erfolgsfaktoren betrachtet, da sie durchaus unterstützend zu besserem En-

twicklungserfolg beitragen können. Allerdings zeigen die Forschungsergebnisse deutlich, dass die Dominanten Erfolgsfaktoren den höchsten Beitrag leisten und daher als Fundament für erfolgreiche Entwicklungsprojekte angesehen werden müssen. Führungskräfte von Entwicklungsabteilungen können die Ergebnisse dieser Arbeit zur Verbesserung von Projektrisikomanagement, vor allem in frühen Stadien von Entwicklungsprojekten, verwenden.

Contents

List of Figures

List of Tables

List of Symbols

x_i	Potential Success Factor
Y	Design Success
d	Total amount of data points required for an empirical study
m	Sample size of projects for an empirical study
H_0	Null-Hypothesis
μ_{Low}	Mean of data sample group rated Low for a Potential Success Factor
μ_{Medium}	Mean of data sample group rated Medium for a Potential Success Factor
μ_{High}	Mean of data sample group rated High for a Potential Success Factor
SS_{total}	Total sum of squares
SS_{within}	Sum of squares within the sample groups of a Potential Success Factor
$SS_{between}$	Sum of squares between the sample groups of a Potential Success Factor
y_{ij}	Any data point in any data sample group
$\bar{y}_i$	Mean of any data sample group
df	Degrees of freedom
df_{within}	Degrees of freedom for SS_{within}
$df_{between}$	Degrees of freedom for $SS_{between}$
MS_{within}	Mean of squares within the sample groups of a Potential Success Factor
$MS_{between}$	Mean of squares between the sample groups of a Potential Success Factor
F	F ratio derived from variance analysis of means
p	Probability value
H	H ratio derived from variance analysis of ranks
n_i	Number of data points in the ith sample group
$\bar{R}_i$	Mean of the sum of the ranks in the ith sample group
$\bar{R}$	Mean of the sum of the ranks of N
N	Total number of observations in all data sample groups combined

χ^2	Chi-Square distribution
O_i	Observed count for each compared sample group
E_i	Expected count for each compared sample group

1 Motivation

Managing engineering development projects has evolved into an ever more complicated task. The increased complexity of products and the global set-ups of companies challenge designers and engineering managers to understand and stay focused on the factors that contribute the most to successful product design. Engineering Design Research is the field concerned with understanding what factors of the design process contribute more to successful outcomes than others. While the subject was originally based on theories, empirical studies have become increasingly involved (Ahmed, 2007) to help indentify these factors by providing 'real world' data.
Reviewing the current state of Empirical Engineering Design Research reveals that there are areas that require more focus and provide room for improvement. These areas are elaborated in the following Problem Statement. Througout the text, design projects and development projects are synonymous.

1.1 Problem Statement

Many research activities about various isolated parts (Eppinger et al., 1994; Mehalik and Schunn, 2006) of the product development process, such as the role of the individual designer (Frankenberger et al., 1998) or human behaviour in general (Lindemann, 2003), have taken place and produced fruitful results in Empirical Engineering Design Research. However, investigating only partial aspects of the design process does neglect the consideration of potential dependencies to other influencing factors (Ernst, 2002), which might be more dominat. Such a scenario would mean that the studied factors were only 'symptoms', which were caused to change by other factors not considered in the study. Only a complete view on the design process, with all its influencing factors, provides this information. Such comprehensive or holistic (Schregenberger, 1998) studies, viewing designers from an integrated perspective within their complex organizational context, are rather rare (Mehalik and Schunn, 2006; Schregenberger, 1998).
Another observation, which can be made on many existing empirical studies, is that a judgement on the reliability of results cannot be made, due to limited amounts of data and a lack of applying rigorous statistical techniques (Ernst, 2002). Oftentimes only a handful - or even only one - development project is part of an empirical study. The

outcome of such studies does not permit for the generalization of results, which would allow the definition of general measures for improving the success rates of product development projects. It is the most challenging part for academia in the field of Empirical Engineering Design Research, to obtain sufficient and reliable data from the industrial domain (Blessing and Chakrabarti, 2009).
Lastly, it can be found that many empirical industry studies do not provide a clearly defined theoretical framework (Horváth, 2004). A missing theoretical foundation results in an increased risk for a lack of comprehensiveness and undetected causal relationships among the influencing factors (Ernst, 2002).

In summary, the following three areas can be identified as lacking in the existing Empirical Engineering Design Research studies:

- Comprehensiveness: Consideration of all the factors potentially influencing the outcome of a product development project.
- Reliability of Results: Collection of sufficient data and use of appropriate statistical techniques to identify significances.
- Theorectical Framework: A foundation to support comprehensiveness and the identification of causalities for the determination of the most significant and dominant Success Factors.

This dissertation outlines an empirical research work in the industry, where these three problem areas are addressed, which also marks its contribution to the current state of the art research in the field. At first, a general approach is developed to support the holistic investigation of Success Factors in industrial product development projects. This approach is referred to as the Comprehensive Approach in this dissertation. A refined set of necessary characteristics for the Comprehensive Approach is elaborated in the Literature Review Chapter. Following the development, the Comprehensive Approach is tested by applying it to a sample of product development projects performed in an industrial context.

1.2 The Product Development Process

Engineering design is the process of mental creation of a product (Pahl et al., 2007), which can then be physically realized in a subsequent manufacturing process. The need for continuous mental creation derives from market and customer demands for ever more user-friendly, cost-effective and environmental friendly products. Hence, product development plays a vital role for society and its continuous advancement. Equally important, it is essential for the economic health and competetive edge of technology firms. This becomes obvious when considering the fact that up to 75% percent of a product's costs are committed during - and especially in the early stages of - the design process, where most of the mental creation occurs. Figure 1.1 shows this paradox of committed versus actually incurred costs. It means that only 25% of the costs remain influenceable for reduction by the downstream activities, such as product optimization and lean manufacturing. After decades of focus on perfectionizing manufacturing processes, many companies have recognized the enormous potential for cost-effectiveness in the development process already. Morgan and Liker discovered, from their investigation of Toyota's Development Process, that

> there is only so much waste that you can squeeze out of production before the engineering of the product and processes becomes a critical constraint. Indeed, product and process development can have an even bigger impact on lean enterprise than lean manufacturing. (Morgan and Liker, 2006, p.1)

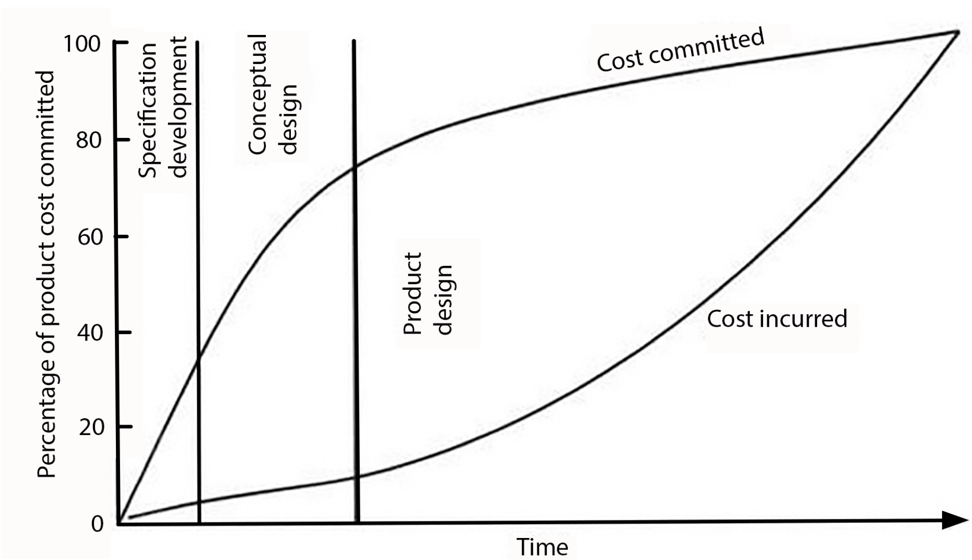

Figure 1.1: Committed costs during product development process (Ullman, 2003)

Besides the ever more important focus on product costs itself, designers have to create products that provide value for customers. Value reflects a customer's "desire to retain or obtain a product" (Neap and Celik, 1999, p.181). Such a desire exists if customers perceive that costs, usability, quality and aesthetic appeal (for consumer products) are in an acceptable relation for them. Design teams have to consider all of these areas, combine them and translate them into physical solutions. This broad range of boundaries and requirements turn the product development process into a multi-faceted activity, starting with abstract, creative stages and converging towards concrete, science-based solutions.

During this activity, design teams are confronted not only with the challenge of designing products that provide value to customers, but also have to keep an eye on external factors, such as stakeholders within the company, legal requirements or environmental constraints. Due to this complexity, it has shown to be beneficial to organize this activity systematically into subsequent steps, which became known as the product development process. Different schools in defining this process have evolved. The overall goal, however, has always been the same, to provide design engineers with a scheme on how to organize the development activity in order to increase the chance of a successful outcome.

1.2.1 Systematic Approach

Pahl and Beitz were one of the first to study a systematic organization of the development process, starting in the early second half of the 20th century. In their classic work 'Engineering Design: A Systematic Approach' (Pahl et al., 2007), they propose splitting the product development activity into four main phases, which they refer to as:

1. Product planning and clarifying the task
2. Conceptual design
3. Embodiment design
4. Detail design

Figure 1.2 shows a process map of the Systematice Approach. In the first phase, they recommend clearly determining and specifying the task and the desired outcome of the development project. For new product development, this starts with market analysis, but also with an evaluation of the company situation, to ensure the resources and knowledge are available. The customer and product requirements are then defined in a requirements list, which is nowadays in most companies known as the Produt Design Specification (PDS). The completed list, agreed on by the stakeholders of the development project, marks the end of the first phase and starts off the second phase. Conceptual design is a highly creative activity, where virtual requirements are translated into principle solutions. Since this is the time in the development process where the highest impact on cost, usability, quality and innovation can be made, the ideas that engineers produce in this phase are an important driver for a product's and company's success. Being aware of this importance, Pahl and Beitz aimed to provide a systematic that would guide designers in this phase, without hampering their creativity. This is done by abstracting the problem into function structures for the essential problems. Then ideas are generated to solve these problems of sub-functions, using different types of creativity techniques. The solutions for the sub-functions are then evaluated and combined into concept variants. At the end of the conceptual design phase, the most promising concept variants remain, which are subjected to a more detailed evaluation in the embodiment design phase. The third phase starts with studying the feasibility of the concept variants. First calculations and layouts, if necessary tests, are carried out to determine if the solutions, which were found in the conceptual phase, are technically feasible. An economic assessment, as well as any other external boundaries (e.g. legal requirements), needs to be part of this evaluation, so that the development team can determine the go-forward concept variant to be developed into a detailed design solution in the fourth phase. The objective of the detail design phase is to finalize the design and create all the necessary documentation, allowing manufacturing to transform the mental creation into a physical product. Manufacturing is recommended to be involved from the embodiment design phase at the latest to initiate the manufacturing process development in parallel, so that production can start with the completion of the design process.

On a more detailed level, each of the four phases consists of different stages. Pahl and Beitz recommend following these stages in sequence and provided various methods to support the designer in these stages. In a simulated empirical study in the lab, Pahl gave a design problem to engineers applying the systematic approach and engineers who did not. His conclusion was that, although it takes them longer to come up with initial solutions, engineers using the methodology were able to design a better product in an overall shorter development cycle (Pahl, 1992).

The Systematic Approach is best known and applied in Germany and Central Europe.

1.2.2 Quality Function Deployment

Quality Function Deployment (QFD) was developed in Japan by Akao (Akao, 1990) in the 1960's. It found its first successful application in the Mitsubishi Heavy Industries Kobe Shipyard in 1972 and has since been globally known and applied. The method is an adaption of Total Quality Management Tools (TQM) (Cohen, 1995) and aims to provide a structure for guiding the product development process from the customer voice to the control of production. It spans wide into both areas, before the actual design work and after. The tools used are quality tables, which are also known as Houses of Quality. The process is organized into four main phases, each systematically elaborated with one or more quality tables. In the first phase, the customer needs and desires are determined and translated into specific product requirements. After that, functional solutions are elaborated for these requirements in the second phase. In the third phase, the functional solutions are translated into actual design components and processes are developed. Finally, the design is transitioned into production, where the last phase is also used to control production processes. Figure 1.3 shows the four phases of QFD.

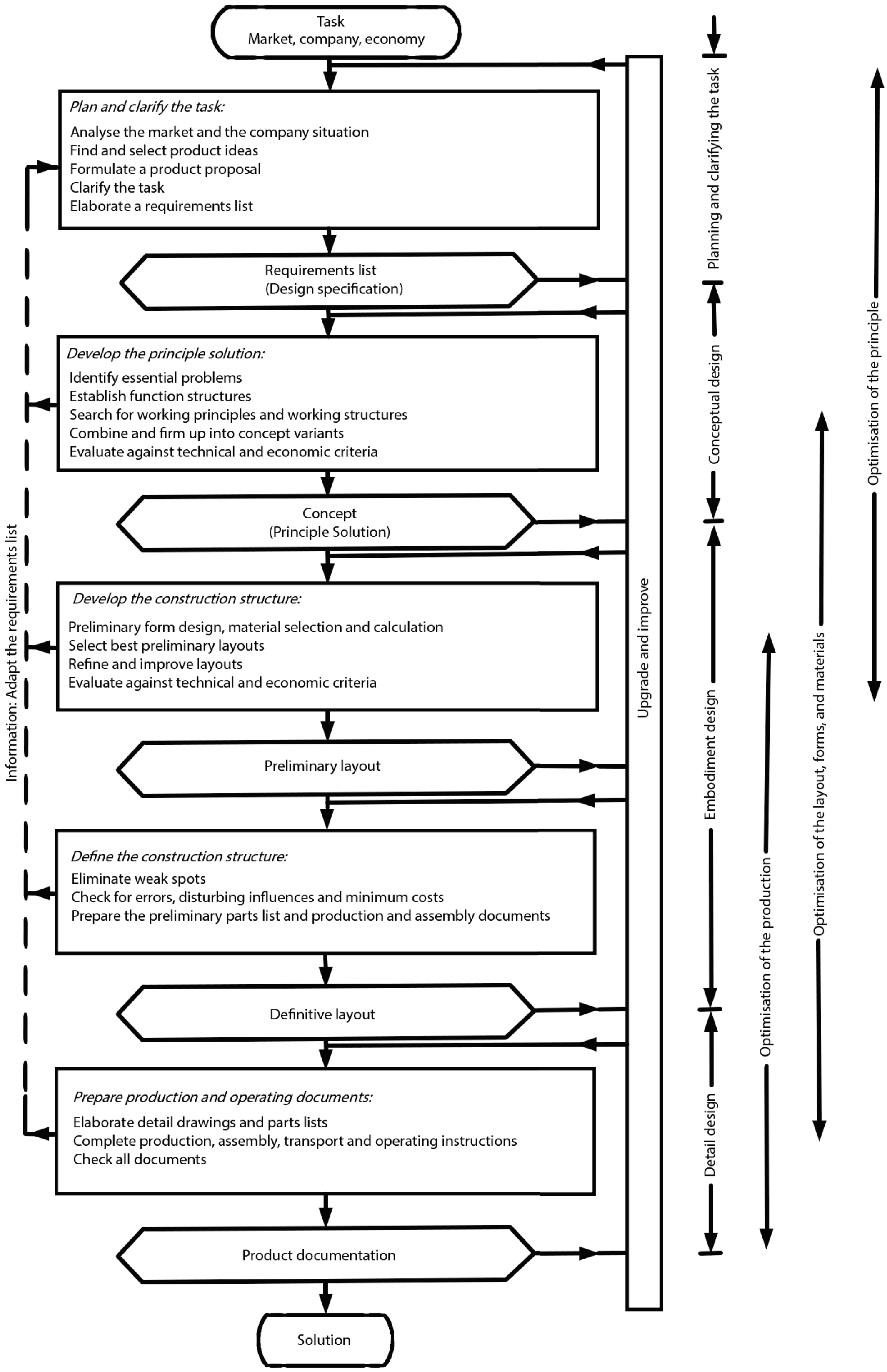

Figure 1.2: Process map of the Systematice Approach by Pahl and Beitz (2007)

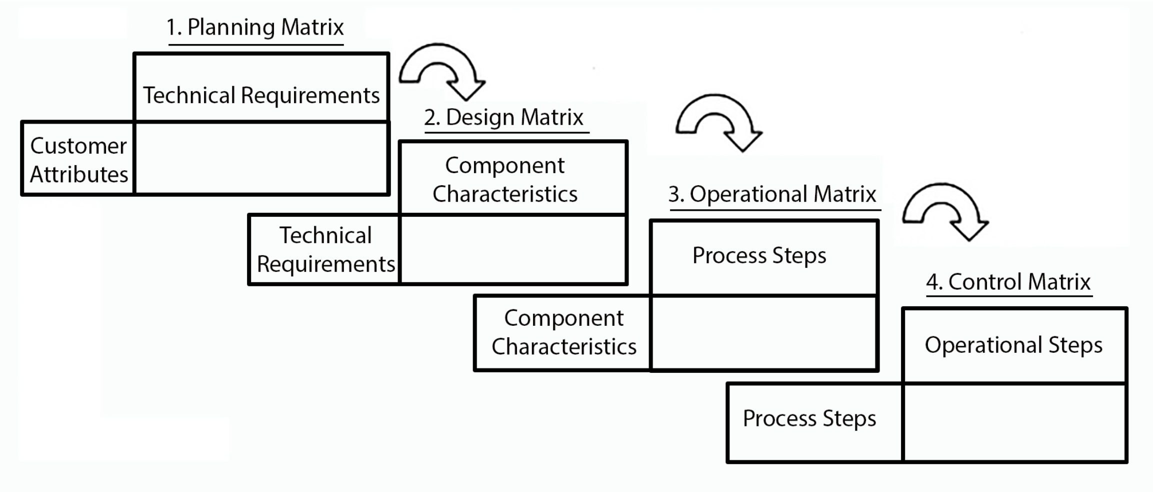

Figure 1.3: The four phases of Quality Function Deployment (Yang et al., 2003)

1.2.3 Design for Six Sigma

The Motorola Company came up with Six Sigma in the 1980's, aiming to improve the quality of its products significantly. Many companies, especially in North America, adapted this methodology. The name is derived from statistics nomenclature, where sigma stands for standard deviations of a normal distribution of data points. Being able to control six standard deviations would mean that a process produced only 3.4 defects per one million possibilities, which is the goal when applying Six Sigma. The core approach of the methodology is to identify cause-effect relationships of defects quantitatively. The central parameter is variation. If the varying parts of a process can be detected with help of statistical tools, then measures can be implemtented to reduce the variation and in that way the process becomes more robust. The typical Six Sigma process improvement consists of a five step process: Define, Measure, Analyze, Improve and Control (DMAIC). While the DMAIC process proved to be suitable for error correction and waste reduction in processes, it was recognized that in order to sustain almost defect-free quality, focus needed to shift upstream to the development process as well (Brue and Launsby, 2003). This lead to the development of Design for Six Sixma (DFSS), a derivative of the Six Sigma methodology with its own process. DFSS is not so much an invention of new design methods, but a 'tool box' of mostly established design and quality tools, including parts of QFD and TQM. DFSS represents a process that provides design teams with the guidance of using recommended methods at the right time in the design phase, similar to the intend of Pahl's and Beitz' Systematic Approach. Different styles of DFSS have evolved over time, depending on the specific design task. The most popular DFSS style is the IDOV (Identify, Design, Optimize and Validate) process. Similar to the Systematic Approach and QFD, it suggests splitting the design process into four phases:

1. **Identify**: Analyze the market and determine customers CTQs (Critical To Quality

requirements).

2. **Design**: Translate CTQs into alternative concept solutions.

3. **Optimize**: Use statistical and simulation tools to predict performance of concepts. Select most robust design solution that meets CTQs.

4. **Validate**: Finalize design and verify that completed design meets customers expectations.

The aforementioned three design methodologies are examples of established approaches which have been developed in Germany, Japan and North America, respectively. More schools have evolved over the last half century. To mention is Pugh's (1991) approach Total Design, or Ullman's (2003) book The Mechanical Design Process. Ehrlenspiel propagates an intergrated approach (Ehrlenspiel, 2009), emphasizing the importance of collaboration between engineering, manufacturing, sales, procurement and controlling throughout the development process. His approach includes elements from Simultaneous Engineering, Quality Function Deployment and Target Costing.
Although the authors use different terminologies and propose varying tools for certain tasks in the development process, they all have in common that they recommend splitting the design process into four phases. Starting with a clear definition of the product requirements, it is demanded to maximize the solution space by generating as many alternative solution concepts as possible in the next steps. These concepts are then evaluated and systematically down-selected, so that in the last phase, the most suitable design solution remains and is finalized. Figure 1.4 shows this concept graphically using the terminology from the Systematic Approach.

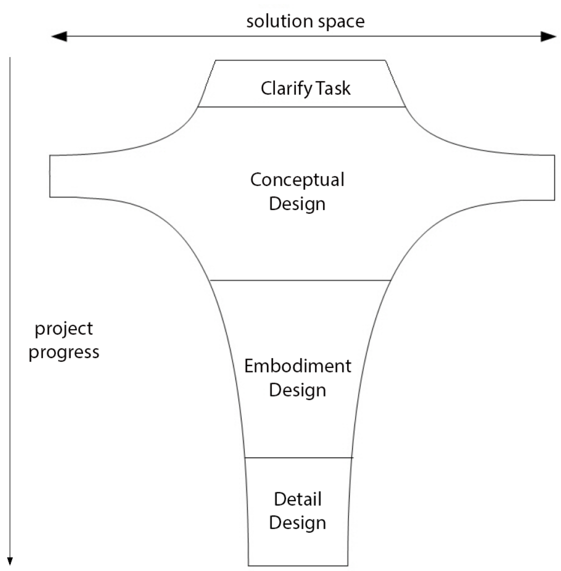

Figure 1.4: Common layout of design methodologies

For most companies, the completion of a new product development does not end the engineering process. After successful completion of the development, products need to be monitored and maintained, if necessary upgraded over time, until their discontinuation. For this reason, the product development process is oftentimes embedded into the product life cycle process, which spans from the idea of a new product until its disposal. Figure 1.5 shows this relationship.

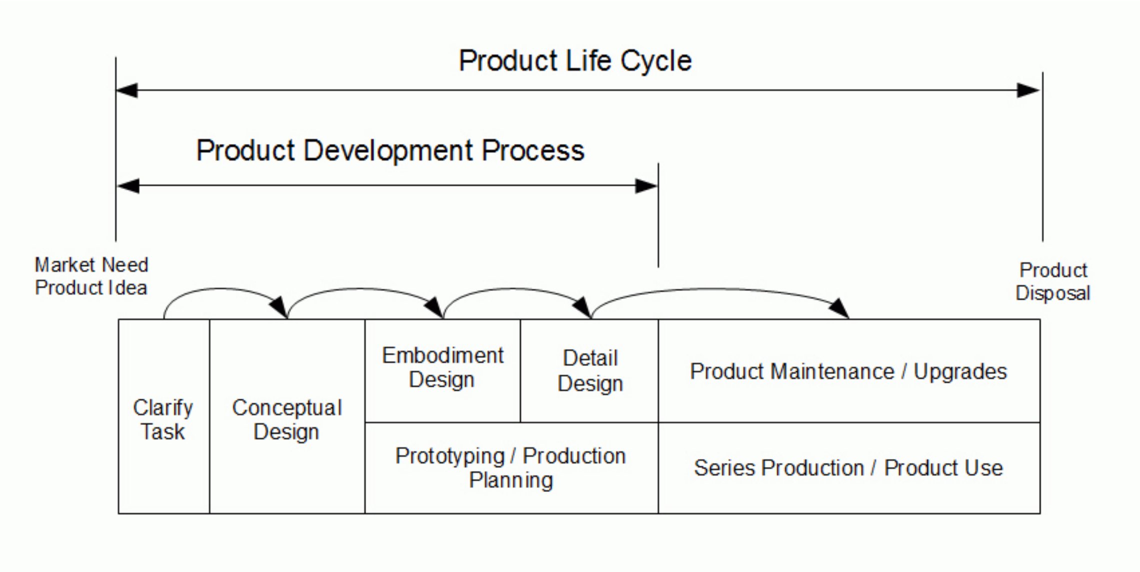

Figure 1.5: Role of the development process in the product life cycle

1.3 Factors influencing Design Success

The central function of the product development process in the life cycle of a product and the above mentioned complexity of the development activity itself, give an indication of the multifold of factors to be considered that potentially influence the outcome.
Dixon locates the work of design teams in the center of two intersecting streams (Figure 1.6), one being technical, the other cultural. On the technical side, design engineers need a broad knowledge of the natural sciences, engineering sciences and manufacturing technologies. Their solid technical background and experience are important factors in accomplishing their work successfully. While these influencing factors are more related to and learnable by the individual within the engineering domain, the cultural factors result mainly from external or less controllable influences. An artistic and creative mindset is likely to be more of a personality trait than learnable. The economic situation might be dictated by customers, competitors or management targets and support. Sociological factors derive from the central position the engineering department has within a company, but also from the interaction of globally distributed design teams, where many engineers

find themselves these days. Political factors might be specific to the product and its exposure to society, but also refer to legal requirements, e.g. environmental or customs regulations.
All these cultural and technical factors have an impact on the successful outcome of a development project. But they do not do that independently. At least some of them are related, likely through causal dependencies.

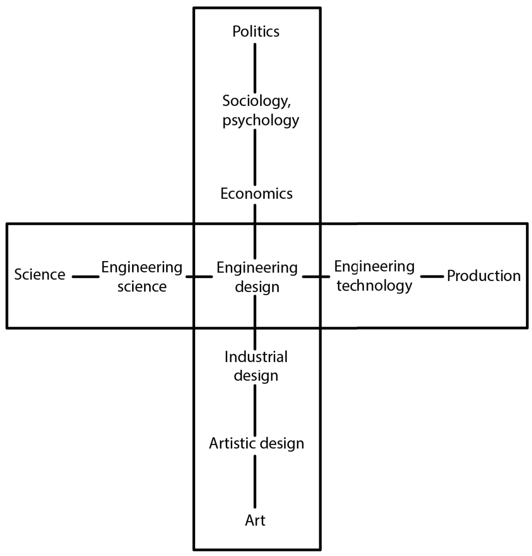

Figure 1.6: The central activity of engineering design (Dixon, 1966)

1.4 Engineering Design Research

While the classic engineering sciences - mechanics, dynamics, materials, thermodynamics etc. - have a history back to the 18th century, Engineering Design Research is a fairly young scientific field, which developed from the middle of the 20th century. With the increased complexity of engineering products and organizational structures, it evolved as a science with its own body of language, ”related but not identical to other sciences” (Blessing and Chakrabarti, 2009, p.3). Unlike most other sciences, it is rather difficult to draw the boundaries to other research fields. The aforementioned, multifolded influencing factors, result in a fuzzy area of investigation (Horváth, 2004). Figure 1.7 shows the current scope of interest in Engineering Design Research, according to Horvárth.
It is the ultimate goal of Engineering Design Research, to gain a better understanding of the design process in all its complexity and to develop and validate methods to improve the current situation in design (Blessing, 2002).
Since the beneficiaries of study results are companies in the private sector, Engineering Desing Research efforts rely on collaboration with the industry. This circumstance, paired with the broad scope of influencing factors, from the arts to the 'hard' sciences,

leads to challenges which are very unique to this research field. Eckert et al. describe these challenges as:

> subject to tensions between conflicting needs and goals:
>
> - between the need for valid, well-grounded research results, and the need for industry supported research to have immediate practical applications;
> - between the academic need to produce reportable results quickly from projects with limited resources, and the industrial need for powerful, reliable, validated tools and techniques;
> - between the need for large research groups to exploit their resources to make major advances, and the need to allow isolated researchers to make effective contributions; item between the need for students to achieve intellectual independence in their own research, and research leaders to achieve larger-scale, longer-term results;
> - between the need for students to develop skills in different aspects of applied research and their need to focus to achieve results in a reasonable time. (Eckert et al., 2003)

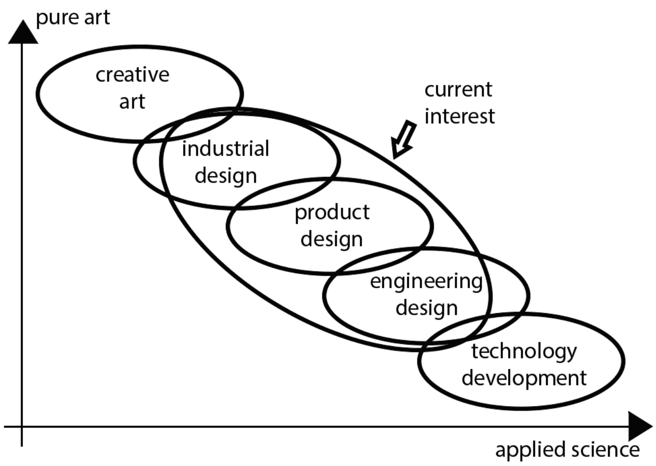

Figure 1.7: Area of interest in Engineering Design Research (Horváth, 2004)

Aurisicchio and Wallace investigated the competencies and conditions required for conducting empirical design research successfully. They concluded

> that for a research project to be successful, a researcher has to have knowledge of the design domain under investigation, the topic of study, the research process and the collaborating company. (Aurisicchio and Wallace, 2007, p.397)

The author of this dissertation spent five years as a design engineer and technical project lead in the collaborating company's engineering department, prior to conducting this research.

It has to be distinguished between different types of Engineering Design Research studies. The difference is defined by the characteristics researchers have selected. Some characteristics can be freely chosen, while others are forced upon the researcher by constraints, such as available object to be observed, amount of samples to be studied, or time frame available for the research project. The characteristics of Empirical Engineering Design Research studies are elaborated in detail in the Literature Review Chapter.

1.5 Research Questions

The motivation for the research effort described in this dissertation can be summarized in the following three research questions:

- Research Question I: How do the characteristics of an Empirical Engineering Design Research study need to be set to obtain comprehensiveness?
- Research Question II: Which of all the influencing factors can be proven to have a significant and dominant influence on Design Success?
- Research Question III: What can engineering management do to increase success rates of development projects?

The answer to question one provides the framework for the Comprehensive Approach. Both, the first and the second answer are contributions to the state of the art in Engineering Design Research. They provide proposals for complementing current practices with a theorectical framework, which allows for a more rigorous focus on comprehensivenes and reliability of results. From the answer to the second question, recommendations for future research activities are derived. The answer to the third question will be particularly beneficial to engineering managers working in the industry, by providing concrete measures on how to increase the successful outcome of product development projects.

1.6 Research Object and Observed Process

For the empirical study, the research object was defined by the company and the product under investigation. The company is a global player in the field of energy systems, specialized in large scale power generation equipment. The product studied are Heavy Duty Gas Turbines, which are utilized in power plants. The gas turbine business employs close to 4000 people, about a third of these are employed in engineering functions.

Different models of gas turbines are in the company's product portfolio, covering a power output range between 5-375MW. Besides the casing and the rotor, gas turbines consist of three major components: compressor, combustion system and turbine (Figure 1.8). Stationary gas turbines have become a significant part of the energy mix in many countries over the last 20 years. Their low emission levels, high efficiency, fuel and operational flexibility have been recognized as beneficial; especially in the developed countries, where power companies have to fulfill ever more stringent emissions requirements, face higher fuel costs and increasinlgy inbalanced power grids, caused by a growing portion of renewable energy sources. This demand lead to enormous research efforts to improve efficiencies, reduce emission levels and extend the life times of components. While the largest gas turbine in the world had a power output of around 100MW only 25 years ago, it is now close to 400MW. This rapid and ongoing increase is only possible by continuously increasing turbine inlet temperatures, which require advancements, especially in materials, cooling and combustion technologies. For this reason, the combustion and turbine component are in the focus of research and development activities and experience a high rate of innovation and increasing complexity. The scope of this empirical study was on development projects within these two components. In total 50 projects of varying complexity and innovative content were analyzed, where 44 remained at the end, providing valid data for the quantitative analysis. Out of these 44, 21 were combustion system, 23 turbine component development projects.

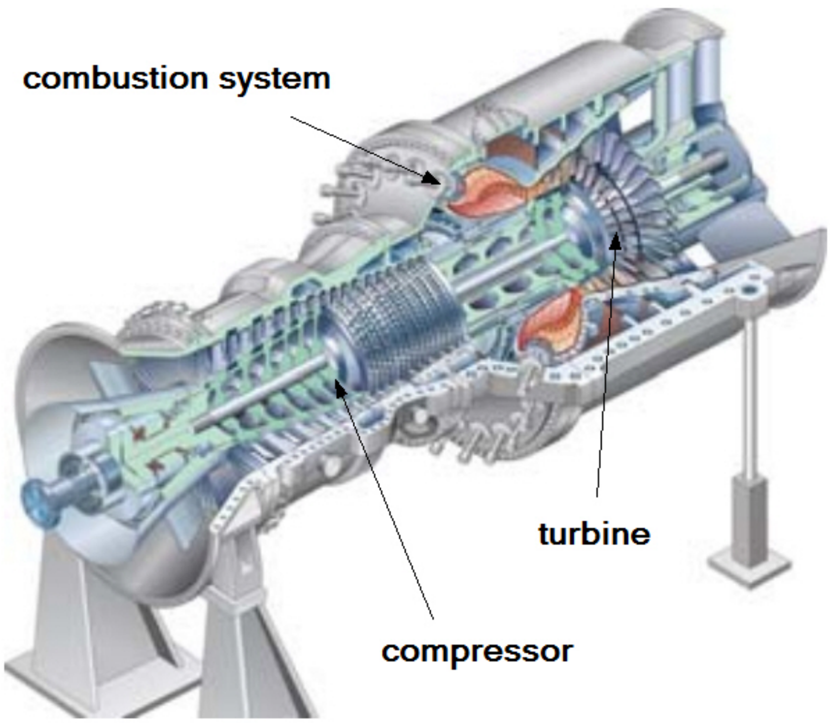

Figure 1.8: Main components of a gas turbine (Siemens, 2013)

The observed process was defined by the portion of the product life cycle (see Figure 1.5) which was investigated. The company has developed its own product developement process. Figure 1.9 shows the process, with a total of nine phases (green arrow shaped boxes) and eleven review gates (R0-R10). The phases are organized in five clusters (grey boxes). Due to the complexity of the products and the associated stretched testing and validation intervals, it extends far beyond the actual design process itself. This specific product development process could almost be seen as covering the complete product life cycle. However, this is not the case, as eventually the developed and sold products go into ownership of the company's service business, which then offers maintenance and upgrades for several more decades.
Although organized and grouped a little different between the clusters and particular phases, the four phases which most design methodologies have in common can still be recognized. They are referred to as: Strategic Product Planing (first cluster), Conceptual Design (first phase in second cluster), Basic Design (second phase in second cluster), Final Design (first phase in fourth cluster). These are complemented by separate Sales Preparation (after the Basic Design Phase), Procurement, Manufacturing & Assembly and Validation Phases, after the design has been finalized. The observed process of this study spans from after the Product Planning Phase (past R1 Review) until completion of commissioning and trial operation. Strategic Product Planing is excluded, as it is driven by the marketing and strategy department. At the end of this cluster, a Product Development Specification (PDS) has been developed for a new generation gas turbine. Specific product requirements for the components have to be derived from this PDS in the Conceptual Design Phase of each component development project.

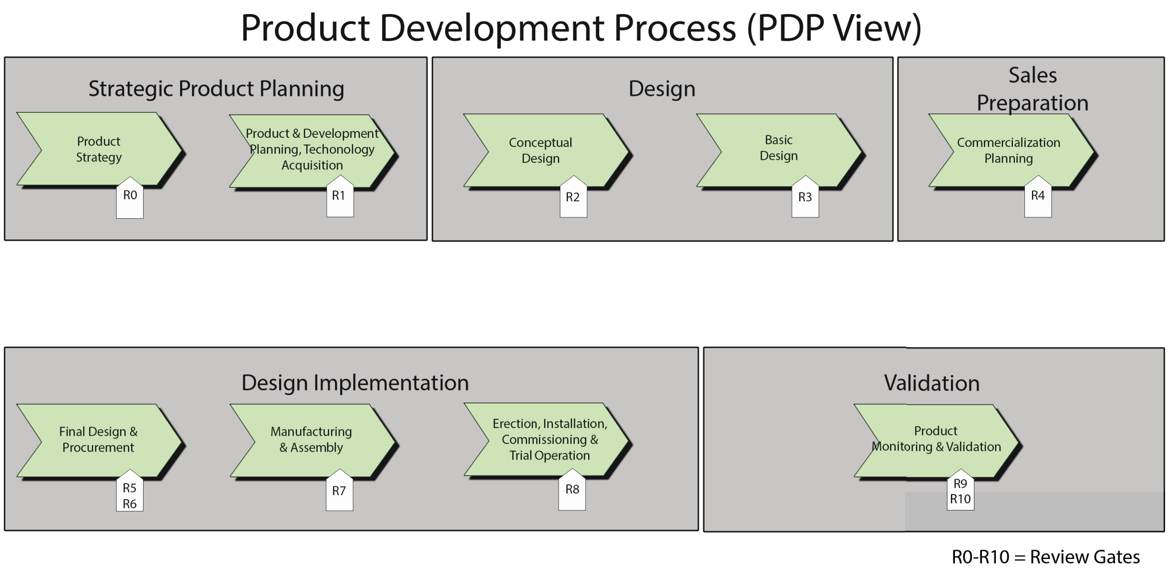

Figure 1.9: Product Development Process in company of study

Collected Data

The data for the influencing factors was collected for the time between the beginning of Conceptual Design and completion of Final Design (R5 Review) for each project. The success measurement for each development project was collected at the time of completion of the Erection, Installation, Commissioning & Trial Operation Phase. In that way each developed component in the study has gone through the manufacturing process and the initial testing period. This end of the observed process was chosen to allow equal comparison between each of the 44 projects, as some had just passed this phase (R8 Review), while other developed components already had years of operating experience.

Variation in Process

The company specific product development process provides a guideline that does not apply to each project with all its phases. While the development of a new product generation demands that each process step is followed, it is not mandatory for component development projects, which happen more frequently as part of product upgrades over their life cycle. This flexibility is intentionally provided to reduce administrative effort and hampering of design teams. Design teams may chose to pass through all design review gates (R2+R3+R5), only two of them (R2+R5 or R3+R5), or hold only the last and always mandatory design review (R5 Review), weighing risk against justified effort. The resulting variability in the process is considered in the study as being one of the influencing factors.

1.7 Dissertation outline

After a brief historic introduction of Engineering Design Research, past research efforts are analyzed and characteristics of comprehensive studies elaborated in Chapter 2. The theoretical framework of the Comprehensive Approach is illustrated in Chapter 3. Definition and measurement of Design Success are explained in Chapter 4, including the collection of the data. This is similarly shown for the Potential Success Factors in Chapter 5, including the validation of the collected data. Chapter 6 is concerned with the introduction of the analysis methods and data anlysis itself, where the results are interpreted in this chapter as well. The interpreted results are reviewed in Chapter 7, where their applicability is discussed and recommendations to engineering management, as well as for further research activities, are provided. Chapter 8 summarizes the work of this dissertation.

2 Literature Review and Research Needs

Designing products has a long history in the different fields of engineering. But it was not until "well into the second half of the 20th century" (Blessing and Chakrabarti, 2009, p.2) that researchers would become interested in systematically investigating the product development process itself. At first, phases of experiential and intellectual design research dominated the research activities. In the experiential phase, senior developers documented their experiences in product design. At that time, there was no link to a theoretical framework or methodology, which later became the interest of researchers in the intellectual phase. In the 1980s, the focus shifted slowly to empirical studies (Wallace and Blessing, 2000). In the following decade, a series of experiments were performed - mainly in the laboratory with small sample sizes of professional designers or engineering students - with the aim to understand the role of the designer in the development process. Ullmann, Dietterich and Stauffer (1988) developed a model of the mechanical design process by analyzing audio and video protocols of the design work of five mechanical designers. Dylla (1991) investigated design strategies of individual designers in the early development stages. Pahl (1992) studied the traits of good problem solvers by observing designers of different skill sets and educational backgrounds. Fricke (1996) observed designers and analyzed their work to find the factors for best success in the design process.

Many more of these types of studies were performed in this period, at the end of 20th century. Their results contributed greatly in understanding the product development process, especially the role of the individual designer. However, as these studies were conducted in the laboratory under simulated conditions, they missed to view the engineers wihtin their organizational context. Impacts of influencing factors resulting from the environment in an industrial company, where engineers actually work, could not be verified. Subrahmanian described the sparseness and need of studies on a higher level, as "design very seldom takes place in actual practice only at individual levels" (Subrahmanian, 1992, p.4). Schregenberger pointed out, that in order to understand the complete product development process, comprehensive or holistic (Schregenberger, 1998) studies, would have to be carried out within an industrial environment. Indeed, since the 1980s,

an increased interest in empirical studies with 'real world' data can be observed (Ahmed, 2007). Cantamessa (2003) found that industrial involvement is benefical to empirical design research, but also indicated a lack of research methodology, which can be found quite frequently in empirical projects. Figure 2.1 shows a high level timeline of the phases in Engineering Design Research. It has to be noted that the phases cannot be clearly separated, but that they rather overlap chronologically. As aforementionted, the empirical studies can be divided into two main categories, referring to their environments: *laboratory* versus *industrial*. Due to their reflection of 'real world' situations and data, industrial studies - being the most complex kind - have the potential to deliver the most reliable results on success factors of product development projects (Ahmed, 2007; Aurisicchio and Wallace, 2007; Schregenberger, 1998; Subrahmanian, 1992). The scope of this literature review and the described research work focuses on this category.
In the following, an overview of Empirical Engineering Design Research studies performed in the industry, is given. They are referred to as empirical industry studies. The different types of empirical industry studies with their characteristics are introduced. It is illustrated, what results were obtained by past studies. The research approaches and methodological frameworks of these efforts are discussed, revealing the gaps and areas of improvement, which were addressed in this research work.

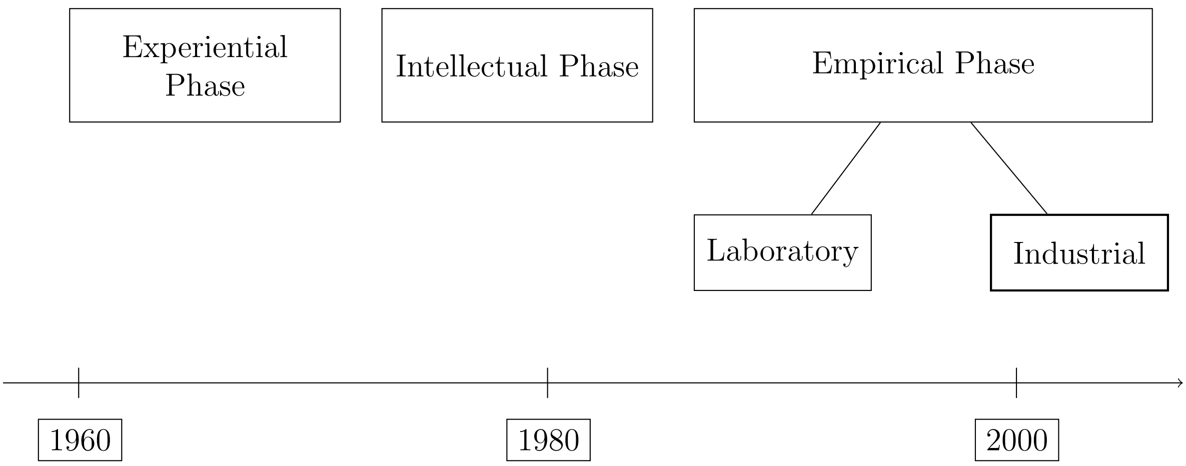

Figure 2.1: High level timeline of Engineering Design Research

2.1 Characteristics of Empirical Industry Studies

Different types of empirical industry studies have to be distinguished. The distinction derives from the characteristics that are selected for the type of study. Some characteristics are given to the researcher by constraints such as: access to data, available resources or timeline of the study. Table 2.1 gives an overview of the most significant characteristics, which distinguish the different types of empirical industry studies from each other. The table is adapted from Blessing and Chakrabarti (2009), in that only the characteristics significant for empirical industry studies are listed. Characteristics needed for simulated studies (role of reseearcher, time constraint, duration, setting, findings and notes) are not shown in the table and are not part of the later discussuion.

Table 2.1: Characteristics of empirical industry studies, adapted from (Blessing and Chakrabarti, 2009)

Characteristic	**Options**
Aim, research question, hypothesis	The aim of the research project and of the study, main research question and hypothesis, Success Criteria and/or Measured Success Criteria.
Study process (nature of study)	Controlled versus natural.
Theoretical basis	Paradigms, methodologies, theories, views, assumptions that guided the researcher.
Unit(s) of analysis	The element(s) for which findings are reported and about which to draw conclusions that are intended to be generalized.
Data collection method	The method(s) used, such as direct observation using video, participant observation, diary keeping, archival research, questionnaire, interview.
Observed process	Starting point and required deliverables of the observed process: e.g., specification as starting point, layout drawing, prototype or product as deliverable.
Task	Type and complexity of task.
Number of cases	Number of data sets collected.
Case size	Number of persons, product elements, employees, etc., within each case.
Participants	Level and type of experience, background, size of organisation, etc.
Object	Description of the design object, company, project or documents analyzed.
Coding and analysis method(s)	Methods used to process, code and analyze the data, e.g., use of pre-determined coding schemes or not, and statistics applied.
Verification method(s)	Methods used to verify the results.

Blessing and Chakrabarti refer to characteristics also as dimensions. Since the characteristics of studies are mainly independent, the terminology 'characteristics' is used throughout this dissertation instead of dimensions. This is also to avoid confusion with the dimensions of success defined later on. Aurisicchio and Wallace (2007) also refer to the characteristics defined by Blessing et al. (1998), but propose - instead of what is defined as *nature of study* by Blessing and Chakrabarti (2009) - to add the characteristic *process*, which can be either *controlled* or *natural.* It is referred to as *study process* in the following, to avoid confusion with the characteristic *observed process.*

Understanding the characteristics supports the identification of areas of improvement on existing empirical industry studies. Each characteristic is briefly discussed in terms of how their selection impacts the outcome of a study.

Aim, research question, hypothesis: The aim of the study is the first characteristic to be defined. It reflects the motivation and need for the research effort. By formulating the research question, some of the other characteristics are determined and the type of study is being narrowed down. The domain of intererst - which is usually the development department in Engineering Design Research - is known with the aim, as well as the unit of analysis within the domain.

Study process (nature of study): The two options are *controlled* or *natural.* A study process is controlled when one ore more variables are held constant. Are all variables allowed to vary freely, it is natural (Aurisicchio and Wallace, 2007). In a controlled study, researchers adjust the natural situation in order to be able to focus on certain aspects. As a result of the created constraints, they likely influence the results - consciously or subconsciously. Examples for such studies are researchers attending a certain stage in the development process and asking questions, or video taping the work. The influence from the adjustment of the situation does not exist in a natural study. Here the researchers stay in the background and only observe and investigate 'real world' events. Examples for natural studies are document research or interviewing engineers after they completed a design project. Natural empirical industry studies are the most complex kind of study (Aurisicchio and Wallace, 2007). The data collection and validation process can turn into an extensive enterprise. But if valid data in sufficient quantity can be obtained, high quality results - reflecting reality in engineering design - can be expected. As discussed later in section 4.3 and 5.3, valid data exists if the sample size shows a representative distribution of the population and if sufficient data points exist for the categories of each influencing factor, in order to be able to apply statistical methods.

Theoretical basis: A theoretical framework is necessary for any kind of research work. It provides guidance during the elaborating process and helps to ensure that the steps of a study converge towards the desired aim, which has been defined at the beginning. With a defined theoretical framework, it becomes obvious what kind of data has to be obtained. Defining the theoretical framework includes deciding which methods should be utilized, but also assumptions that need to be made. Assumptions might have to be redefined as a study progresses.

Unit(s) of analysis: The unit of analysis directly derives from the research question.

It can vary from a small, detailed scale to a large scale. Examples of a unit of analysis (listed with increasing scale and complexity) are: behaviour of the individual designer, project teams, design phases, product development process. Defining the unit of analysis is a condition to begin with and already determines the options for the method of data collection. Many studies found in the literature focus on units of analysis of a smaller scale, such as the behaviour of individual designers (Frankenberger et al., 1998; Lindemann, 2003; Pahl, 1992) or design teams (Frankenberger and Auer, 1997). They have contributed greatly in understanding these units. The high frequency of studies on these smaller scale units of analysis can be explained by their ability to compromise on constraints, such as limited research windows or access to industry data. Empirical industry studies, focusing on the overall product development process in a holistic manner, can rarerly be found (Mehalik and Schunn, 2006; Schregenberger, 1998).

Data collection method: Many methods of data collection are possible. Some examples are: observation, interview, questionnaires, archive or product analysis. By having defined the characteristics research aim, study process, theoretical framework and unit of analysis, the usable methods for data collection are already narrowed down. The goal of a study needs to be to gather as much data as possible to allow for a generalization of results. On the other hand, bias needs to be kept to a minimum. The latter criteria calls for a data collection method where the researcher does not interact with the participants of the observed process, as can be done by researching archives or completed projects. However, significant amounts of data can best be obtained from direct interaction with participants, e.g. through questionnaires. In general, a trade off between the amount of data and bias has to be found. Some studies use a combination of data collection methods.

Observed process: Although not declared specifically in all studies found in literature, this characteristic is important to know. It indicates the validity of the results with respect to the domain and the aim defined at the beginning. An observed proccess can be as detailed as a single stage in the development process, for instance idea generation in the conceptual design phase. But it can also be from the product requirement specification until completion of validation or even consider the complete product life cycle. The researcher has to clearly state what the observed process of the study is, in order to bring the results into perspective.

Task: The task being studied has an influence on the generality to be interpreted from the results. If the task is specific to a certain industry, the results might only be representative for this specific area. The complexity of the task, but also the innovative content of the task are important to know. A task might be complex, but have little problem solving or unknown technology involved. The outcome might still be successful, even if some success factors were not met. Ideally, design tasks with varying complexity and amount of new technology are investigated for understanding how these variables relate to the outcome, but also how they depend on other factors influencing Design Success. Therefor, including a sufficient number of cases into the scope of a study is essential.

Number of cases: An important characteristic which determines the potential for generalization and the ability to verify the results. The more cases can be investigated, the better applicable become quantitative methods, such as descriptive statistics (used to describe the sample size being studied), or ideally inferential statistics (used to extend the studied sample size to make universal projections on the population). Here is where many studies are limited by a lack of access to industry data.

Case size: The amount of employees, departments or interfaces involved in the task. As with the Task, this characteristic should be evaluated for the relationship to other factors influencing the design process. In order to do so, a sufficient number of cases is necessary.

Participants: Depending on the research question and the unit of analysis, information about the participants needs to be known. This information can be objectively measurable data, such as years of experience or educational background. But it can also be more complex, on an abstract level, especially when it comes to traits related to personality. Again, in an ideal study, sufficient and varying data about the participants is collected and analyzed. The participants of the study (e.g. the person answering a questionnaire) might be different than the participants of the observed process.

Object: The object brings the unit of analysis, observed process and task into perspective. Knowing the product, company or area of industry, supports the determination of how general the results can be considered. Depending on the research question, the validity of the results depend upon this characteristic. For instance, if the aim of a study is the understanding of the design process in a global environment, the size and global set-up of the company studied has to be known.

Coding and analysis method(s): In order to remove as much bias as possible from a study, quantitative data should be the preferred type of data. Some factors are easier to quantify than others. For instance, project durations, budgets, team sizes etc., can be obtained from archives in a straightforward, objective manner. Others, especially when it comes to investigating the human side, are more difficult to define objectively. In these areas, researchers can utilize methods for quantification from other academic fields, for instance the social sciences, where such tools have been developed due to the need.

Verification method(s): The use of advanced (inferential) statistical methods provides tools for the verification of results, such as significance levels and probabilities of repeatability. The determination of dependencies between factors of significance can serve as an additional method for verification of results. In general, verification should not be reduced to analysis of results, but also considered in earlier steps. After all, statistical analysis methods strictly follow the rule of 'garbage in, garbage out'. The quality of the data input needs to be assured upstream, from the very beginning of the research work. Verification means having sound methods for research set-up, research execution and post-processing.

2.2 Review of different Types of performed Studies

A multifold of empirical industry studies can be found in the Engineering Design Research literature within the last three decades. The majority of them were conducted through questionnaires and surveys, due to the ability of obtaining large amounts of data in a fairly straightforward manner. Giving a complete overview within this literature review is impossible. Hence, four different studies are introduced, representing common types of studies with varying characteristics. The pros and cons, in terms of quality and reliability of the results, are discussed for each. Through that, preferable characteristics for a comprehensive empirical industry study are elaborated.

2.2.1 Hales: Analysis of the engineering design process in an industrial context

Hales (1987) conducted one of the first empirical studies in the industry over a longer term. The object of this study was the development of a coal gasification system, with up to 37 people being involved into the development process. The observed process spanned over 36 month, from the initial planning stage until near completion of the project, when the company decided to stop the project. Aim of this single case study was the understanding of factors influencing the design process, in particular with respect to the use of a systematic design approach, which was introduced for this development project. The Systematic Approach (Pahl et al., 2007) provided the theoretical framework, but also determined the units of analysis, which were the stages of the design process. Due to this intervention - controlling the design methodology to be utilized - into the work of the designers, the study process was controlled. The data was collected on a weekly basis through observation, audio taping, diary notes and design reports. Main findings of the study were: a list of factors likely to influence the design process; the design process follows overlapping phases, which, if not forecasted and managed properly, will lead to cost and time overrun; and less than a quarter of the overall engineering time was spent on the use of methodological techniques.

Pros of this study type: The adavantage and contribution of Hale's study is the observation of a large development project in a 'real' environment over almost all stages of the development process. The different types of data, collected on a weekly basis from many participants, provided a large amount of information to be evaluated. In general, bias can be reduced by collecting data form many participants rather than a few or even one.

Cons of this study type: The fact that this research was based on a single case, raises the question on how general these results can be recognized. From a statistical point of view, a sample size of one does not allow for determining the confidence of the result. It cannot be known, if all the factors identified to influence the design process do so in a general manner and could hence repeatedly be observed on other development projects. The results might just be specific to the studied object and people involved. In addition, the observed process did not include the building and testing of the product. The question, if the use of a systematic approach lead to an adequate product, which fulfilled the expected product requirements, could not be answered.

2.2.2 Ehrlenspiel: Problems in Development and Design

This survey-based study was performed by Ehrlenspiel (2009) in 1991/92. In total, 300 participants with a design or engineering management background were asked for their feedback. The participants all worked in engineering companies with 500-2000 employees, so the object of the study were medium sized companies. Aim of the study was to understand the role of issues in product development and their resulting negative impact on the business as a whole. A set of potential problem factors - grouped in three problem areas: organizational; process related; technical-economical - was provided in the survey. The participants were asked to rank them on a scale from 0 to 4. The results of the study are shown in Figure 2.2. Only the mean value is reported for each pre-defined, potential problem factor.

This type of study is a natural study in that participants were not influenced in their actual design work. The theoretical basis goes back to assumptions on what problem factors of the development process can potentially be. The unit of analysis was the complete product life cycle. The task and complexity of the cases is not known.

From the representation of the results, the author identified cost issues, time constraints, unclear definition of objectives and the control of the design process as the most significant problem factors. What is interesting about the factors cost issues and time constraints, is, that these are effects rather than causes. There must have been specific reasons, which must have existed before and eventually lead to time and cost issues. One can think of a lack of simultaneous development, or low management support, just to give two examples of what can be found in literature, to cause missed deadlines and budget overruns in development projects.

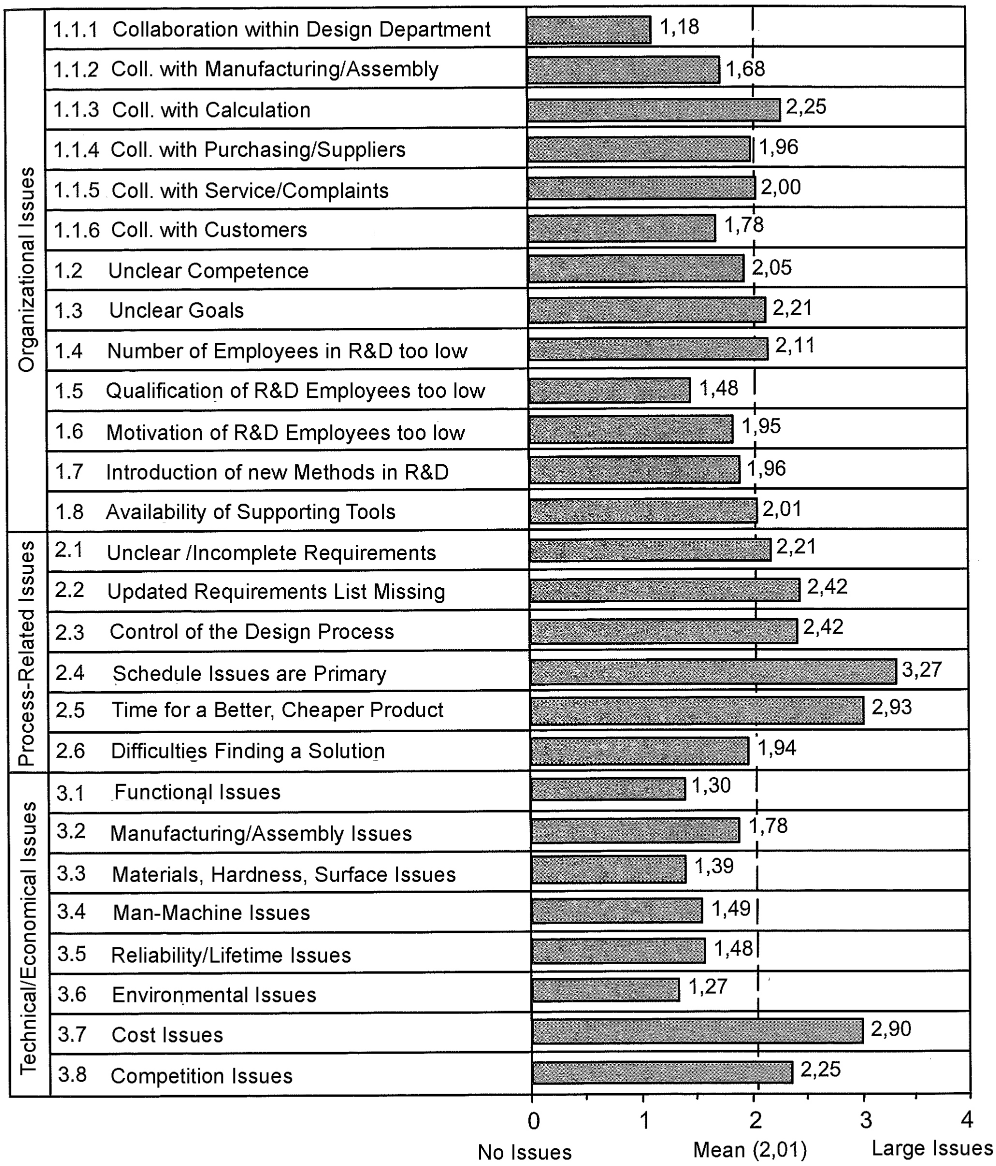

Figure 2.2: Result of Ehrlenspiel's survey study, translated from (Ehrlenspiel, 2009)

Pros of this study type: A sufficient amount of data was collected in this study (300 data sets from participants of different engineering companies), allowing for the use of quantitative analysis methods. Due to that, the results can be considered as being general in nature and representative, at least for medium sized companies.

Cons of this study type: Only a most basic statistical evaluation - the mean value for each problem factor - is presented in the result summary (Figure 2.2) of the study. With only the mean value being known, the confidence of the results cannot be predicted. A high variance in distribution in the answers could still exist for each individual problem factor, which could, for instance, go back to the different industries where the participants were from. Illustrating the data distribution in addition to the mean, as an example, would give a much clearer picture about the reliability of the survey result. Another source of inconsistency is in the way the survey was designed. The problem areas and problem factors were given to the participants. It is not explained how these were determined and where they came from. There might be other influencing factors on the design process, which were not asked, hence the comprehensiveness of the study is to be questioned. It can also be recognized, that some of the asked for problem factors are causes while others are effects, resulting from causes. As discussed before, cost and time issues are more likely to be symptoms, triggered by other factors. These circumstances raise questions about the soundness of the theoretical framework and the assumptions made for the study, which can frequently be observed in such types of studies (Cantamessa, 2003).

2.2.3 White and Fortune: Current practice in project management - an empirical study

White and Fortune (2002) conducted a survey for determining influencing factors on project management. Aim of the study was not just the determination of the factors that are most critical to project success, but also what methods and tools are most successful in supporting the project management process. The questionnaire was designed in a way in that potential success factors were given for choice, but also in that the particiants were asked to add factors they thought are most important for project success. In addition, the participants were asked to list disturbances and side-effects they experienced during project work. The mixture of questions resulted in data that allowed for answering several research questions. The unit of analysis of this study was the project management process from kick-off to project completion. 236 valid data sets were collected. Different industries were represented in the study. Two thirds of the participants worked for companies with 1000 employees or more, the rest for companies with 100-1000 employees. The study process was natural in that the participants were not controlled in their actual project management activity. A theoretical framework existed in the methodological way the questionnaire was designed to allow for answering different research questions. In the first step the participants were asked to list the three most important dimensions to measure success. As was to be expected, these were answered as: meet client's requirements, completed within schedule, completed within budget. What is interesting in this study, is that 41% of the studies were reported as being finished completely successfully. 85% of the projects were ranked with a six or seven on a 1-7 scale, as shown in Figure 2.3. This unusually high success rate - in contrast to findings of many surveys in literature (White and Fortune, 2002) - is likely related to bias, as 82% of the participants reported to have managed the projects themselves.

The three factors found by White and Fortune to have the most significant impact on the project success were:

1. Clear goals/objectives

2. Support from senior management

3. Adequate funds/resources

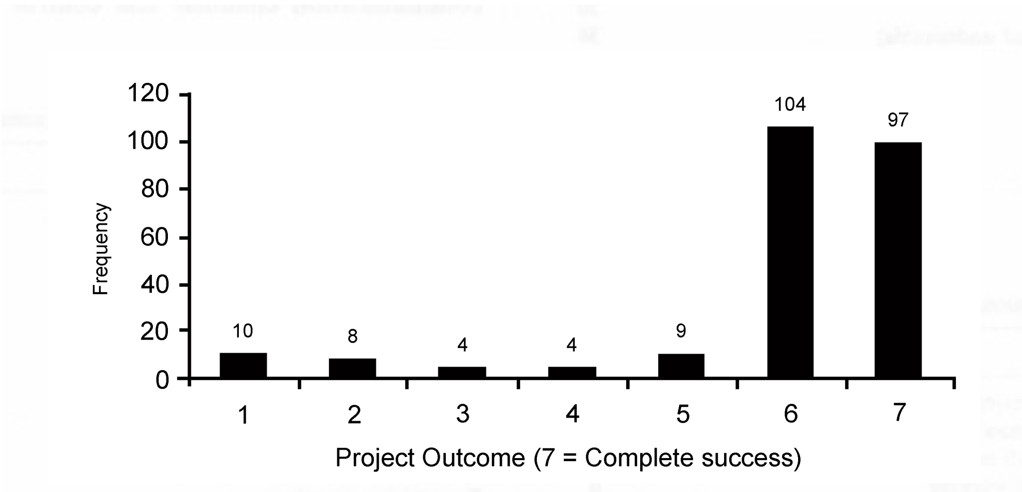

Figure 2.3: Success reported in White and Fortune's empirical study

Pros of this study type: As with many survey studies, enough data was collected to allow for the use of quantitative evaluation methods. The questionnaire did not only provide pre-determined questions, but also open questions. Open questions were, when the participants were asked to describe any other influecing factors they can think of. This helped in identifiying factors the researchers might have not thought of when preparing the survey.

Cons of this study type: The success rate was reported very high for almost all of the projects. These positive results are likely to be linked to the fact that 82% of the participants were the project managers themselves. Bias apparently plays a significant role with this method of data collection. Another problem, with only highly successful projects being reported, is, that it cannot be proven what really distinguishes successful from less successful projects. The success factors identified through the survey were believed to have contributed to the project success. However, if less successful projects lacked these exact factors is not known, as little is known about projects with low success from the survey results. Mehalik and Schunn (2006) have found in a meta-analysis of 40 empirical studies that, although factors influencing success are extensively researched, few studies have examined what impacts the design process negatively. What is also not shown, is how the factors found are related to each other. For instance, it would be of interest to know how and in what direction the success factor 'clear goals/objectives' changes, when the factor 'support from senior management' changes. Knowing such dependencies can help identifying causal relationships of factors.

2.2.4 Ahmed: Understanding the knowledge needs of novice designers in the aerospace industry

In this study Ahmed and Wallace (2004) investigated how unexperienced designers gain knowledge about the design process from their experienced peers in an industrial environment. Aim was to understand the knowledge needs and awareness of their own knowledge of novice designers. The research consisted of two parts, with the second part being this study. It built up on the first part in which Ahmed, Wallace and Blessing (2003) observed experienced and unexperienced designers to study the difference in how they approach design tasks. Unit of analysis were novice designers, which were defined as being young engineers with less than 2.5 years of work experience. Experienced designers were defined as having more than 10 years of work experience in the engineering field. The study process was controlled, as the participants had a pre-defined scope and were aware that the conversations were recorded. The data was collected through audio-recorded interview sessions, which the novice designers held with the experienced designers. Using discourse analysis, the recorded qualitative data was then analyzed. Discourses were the interactions between the novice and experienced designers. Discourse analysis is a central tool in the social sciences (Potter, 2004), utilized to conceptualize language with the goal of finding explaining patterns. In the case of this study, for example, five different patterns of query and response were defined through which the novice designers gathered information from the experienced designers, as shown in Figure 2.4. The number of queries and responses fitting in one of these patterns were then counted from the recorded data. This step meant a conversion of qualitative data into quantitative data, allowing for the use of descriptive quantitative methods. In the next step each pattern was cross-checked against different query topics the novice designers had asked about and which were counted as well. Figure 2.5 shows an example for the pattern 'rephrased or irrelevant queries' checked against the topics of queries. The experience of the teams - each consisting of two novice designers, except of Team C, where one of the two members had 8 years of work experience - increased from A to C. In this example from the study, the researchers concluded that the less experience designers have, the more they are interested in how the product or technology works. However, the more experience they gain in their professional career, the more their focus shifts, e.g. to how processes in the company work.

Pros of this study type: The researchers attempted to translate the qualitative recorded data into quantitative data. They did so by using discourse analysis, a method from the social sciences, where translating highly qualitative data into quantitative data is a common research challenge. Hence, supportive tools were devloped over the years. Having quantitative data to work with, conclusions can be made more objectively, e.g. by using basic descriptive statistics. In this case a bar diagram was used to illustrate frequencies for query/response patterns against different topics the novice designers asked about.

Patterns	Team A	Team B	Team C	Percentage of all queries
Experience of each trainee	2 months	8 months	18 months	
	9 months	8 months	96 months	
Explicit question and answer	10%	29%	27%	35%
Rephrased or irrelevant queries	17%	8%	7%	10%
Additional information provided	18%	35%	21%	29%
Statements	28%	8%	32%	16%
Confirming queries	27%	20%	13%	21%

Figure 2.4: Patterns of query and responses for gathering information

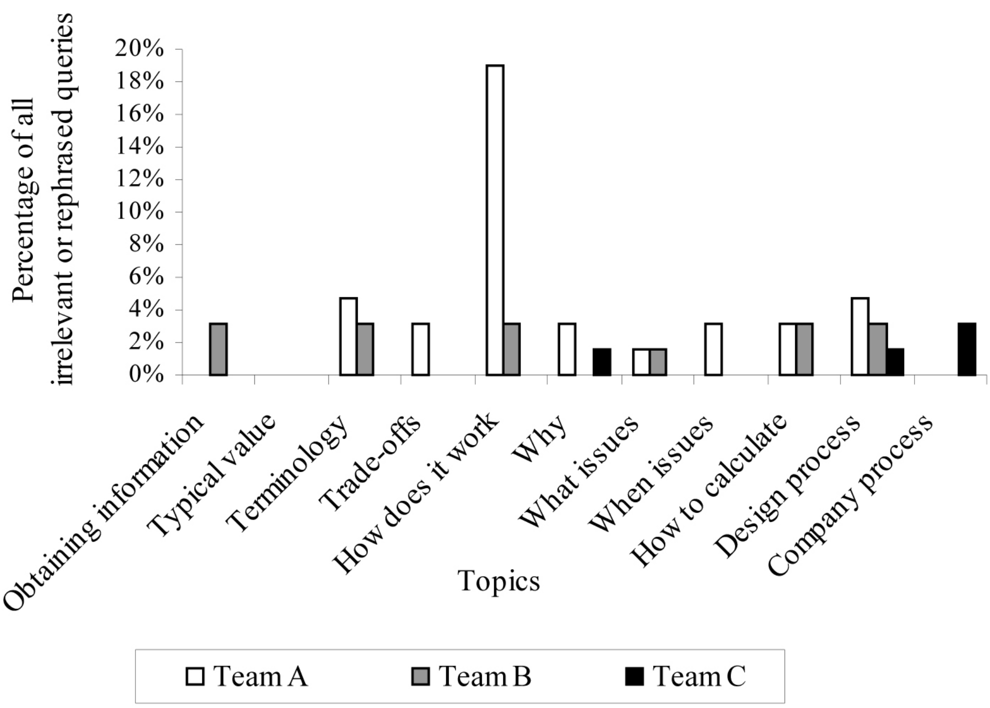

Figure 2.5: Cross-check of patterns against topics of queries

Cons of this study type: Again, as in Hales' study, a small sample size was investigated in the study. The question remains how representative the data of the three teams (with two participants each) is. The definition of what a novice and what an experienced designer is appeared to be broad and neglected the consideration of individual traits, preferences and skills, factors that might strongly influence the results. Another important aspect to recognize is, that although the data was quantified for use of descriptive methods, no criteria for distinction were defined. The results were still fairly freely interpreted from the visualized bar charts. A beforehand defined criteria, on when a factor was considered as distinctive, would have been desirable in order to avoid this room for interpretation in the results. Using more advanced statistics provides such criteria through significance levels and probabilities of repeatability. Therefore, sufficient sample sizes are essential.

2.3 Meta-Analyses on Success Factors

Beyond individual empirical research projects, studies reviewing and summarizing the results of empirical studies have been performed. The results of these meta-analyses provide a valuable overview on the reoccurrence and frequency of success factors found in individual empirical research efforts. Such reviewing studies can be found in Engineering Design Research, but also in related higher level fields, like the NPD (New Product Development), Innovation and Management Science. Three meta-analyses, with considerable sample sizes, are discussed in the following.

Ernst: Success factors of new product development: a review of the empirical literature

In this review of the empirical literature, Ernst (2002) summarized the findings of empirical studies on success factors of NPD. The studies were based on questionnaires to industrial companies and provided significant sample sizes (n = 18-1400) in most cases. A total of 52 studies where reviewed, all performed in the time between 1974 and 1999. The author developed five categories and assumed the determined success factors would fit in any of these. Ernst summarized his findings as follows:

- NPD process: Presence of a formal or informal new product development process to support a clear technical and commercial planning, and provide ongoing control of the project progress.
- Organization: Dedicated, multi-disciplinary project teams. Skills and know-how of Project Lead plays significant role.
- Culture: No significant results found, topic "has not been adequately researched to date" (Ernst, 2002, p.32).
- Role and commitment of senior management: Recognition of the value of new product developments has positive effect on product success.
- Strategy: Only weak evidence, suggesting that long-term, strategic NPD planning yields higher success.

The selection of the categories relates to the domain of interest, which was the management of NPD in this meta-analysis. A more limited view on the product development department as domain of interest would have likely suggested a different categorization. The measurements of success of the investigated studies varied between the dimensions: commercial success, technical succes and on time delivery.

Mehalik and Schunn: What Constitutes Good Design? A Review of Empirical Studies of Design Processes

Mehalik and Schunn (2006) reviewed 40 journal-published, empirical studies. The authors were looking for elements which are reported to be associated with good and effective design pratice. The reviewed studies where performed between 1986-2003, most of them in the years around the turn of the century. The publications on success factors in product design were found in a variety of journals from different areas (see Table 2.2).

Table 2.2: Journals represented in Mehalik's and Schunn's meta-analysis

International Journal of Human-Computer Interaction	10
Design Studies	8
Cognitive Science	3
International Journal of Man-Machine Studies	3
Behaviour & Information Technology	2
International Journal of Human-Computer Studies	2
International Journal of Technology and Design Journal of Technology and Design Education	2
Journal of Engineering Design	2
Applied Ergonomics	1
Ergonomics	1
Human-Computer Interaction	1
International Journal of Intelligent Systems	1
Journal of Applied Psychology	1
Learning and Instruction	1
Proc Instn Mech Engers	1
Thinking and Reasoning	1
Total	40

Around half of the studies consisted of design tasks in the engineering fields (mechanical, electrical, structural, civil, automotive, and other types of engineering). Software development projects comprised about 40% of the studies, the rest were studies from non-engineering fields, such as architecture or marketing. In 60% of the studies, the subjects were engaged in real design tasks. The remaining studies were based on artificial studies or a combination of aritificial and real. The focus of the majority of the studies was on the earlier design stages, which explains why the findings show more detailed factors than the higher level studies. The three most significant success factors detected were:

- Explore problem representation (refers to how designers go about identifying and defining the design task or problem)
- Use interactive/iterative design methodology
- Search the space (explore alternatives)

Schimmoeller: Success Factors of new Product Development Processes

Schimmoeller (2010) reviewed eleven publications on success factors of new product development projects from in between 1975 and 2003. Among the reviewed publications where not solely empirical studies, but also articles on the topic, mostly with a view from innovation management. The review scope was limited, in that the aim was to verify, if successful development projects have three commonly suggested (Schimmoeller, 2010) key success factors in common:

- Cross-functional teams
- Support of upper-management
- Organizational structure

By organizational structure, the author was referring to an integrated product development process, supporting the development steps, communication within the company, documentation and tracking of project progress. The dimensions for measurement of success were defined as: product performance, speed to market and development costs. The reviewed publications provided some evidence that all three factors play a role. The factor of most significance, with the most frequent citation, was found in the management support, particularly with respect to speed to market.

In total the three meta-analyses provide findings of 103 empirical studies and publications on success factors of the product development process. It has to be noted that this sample size represents an accumulation of different types of studies with varying characteristics. In addition, variance existed in the domains of interest and observed processes. Schimmoeller's and Ernst's reviews focused on a higher organizational level and found as common success factors:

1. Need for a product development process
2. Multi-disciplinary teams
3. Skill set and know-how of project lead

4. Support of (upper-)management

Mehalik and Schunn reviewed studies of a more detailed level, mainly focusing on the early design stages as unit of analysis. Their findings add three success factors on a design work level to the list:

5. Define the task/problem

6. Use design methodology

7. Search for alternative solutions

These three are all elements which can frequently be found recommended in the classic engineering design literature (Ehrlenspiel, 2009; French, 1999; Pahl et al., 2007; Pugh, 1991; Ullman, 2003).
From the introduced meta-analyses, one can recognize that the Comprehensive Approach needs to take Potential Success Factors of different organizational levels into consideration, from management down to detailed design tasks. The seven factors, together with the findings of the introduced empirical industry studies, serve as input for the later process of determining all the Potential Success Factors and are complemented by the factors found from a review of the product development literature.

2.4 Research Needs

The four research works introduced in section 2.2 provide a representative cross-section through existing types of empirical industry studies with varying charactersitics. Their pros and cons revealed the consequences on the results, that come with the way certain characteristics are chosen. From the cons, the research needs for comprehensive empirical industry studies can be derived. These can be summarized as follows:

- Study process (nature of study): Primarily controlled studies can be found. They were characterzied by the researcher directly being involved into the research or at least controlling some parameters. Controlled studies promote the chance for bias and are also likely to alter the behaviour and habits of participants. Natural studies avoid any interaction between researchers and the observed process with its participants and do in that way produce the closest to 'real world' results.

- Theoretical basis: The theoretical framework of studies is in many cases missing or not obvious. A missing framework results in two effects. First, the comprehensiveness of the studies are to be questioned. This case can be observed when a limited amount of factors are investigated and it is not explained how they were derived and what assumptions were made. Second, the causality of the results is to be questioned. Factors considered in a study and assumed to contribute to success are oftentimes linked in relationships of cause and effect. Some factors are actual causes, others might just be symptoms which result from other causing factors. Without a sound framework to distinguish between cause and effect, results might be misleading with respect to causality. Blessing and Chakrabarti (2009) defined a Design Research Methodology that provides engineering design researchers with a process framework, which partially addresses comprehensiveness and causality. They aknowledge that industrial data is difficult to obtain for academic researchers and developed their methodology to be used for small sample sizes and support the making of necessary assumptions on dependencies.

- Data collection method: The way the data is collected should support the quantification to allow for the best possible objective analysis. It should also support the collection of sufficient data. The influence of participants and chance for bias should be considered as well, when making this choice.

- Observed process: The exact observed procees is not always known for studies. Especially the end part, where the outcome of the design process is validated, e.g. through a commissioning or testing phase, can be found to be missing quite frequently. A representative study should take the outcome of the observed process into consideration.

- Number of cases: A small number of cases is not suitable if study results are aimed to be generalized, which research efforts usually aim for. A sufficient amount of cases is essential in order to verify the confidence of the results and draw general conclusions.

- Participants: This is the primary source of bias and the researcher needs to be aware of it. Ideally the participants of the observed process are not influenced during the study. This can be done, for instance by analyzing projects after they have been completed. The participants of the study might be different from the participants of the observed process, which is desired in order to reduce bias. Study participants asked to rate the outcome of a project they were not involved, are likely to give a more objective answer, than would be the case if participants are asked to rate projects they managed or were involved themsleves. In addition to the participants, researchers themselves can be a source of bias, especially when they have to interpret data or convert qualitative into quantitative data themselves. And similar to the participants, if they were involved in the studied projects themselves. To minize the researchers bias, they ideally only collect already quantified data (e.g. documented team sizes, project time lines, budgets) and gather data that needs to be converted from neutral sources, e.g. by interviewing stakeholders that have or had no personal bond to the investigated projects. In addition to that, researchers can increase or reduce bias by the way they collect data, e.g. through the types of questions or quantification scales (Blessing and Chakrabarti, 2009; Landy and Barnes, 1979). For that reason, researchers should run trial runs with their defined questions and quantification scales to get an understanding of how comfortable and neutral participants are likely going to be with their answers.

- Coding and analysis method(s): Quantitative methods are desirable. Most studies in literature show the conversion to and use of quantitative data. However, the methods used to analyze the data cannot always be found to be suitable. If only basic descriptive statstics are applied, hard criteria are missing, which support the researcher in deciding which factors are significant and which are not. Ernst reported in the findings of his meta-analysis of empirical studies that

  > studies frequently do not give reliability coefficients. Because these data are missing, it is not possible to make a judgement on the reliability of the constructs. Here one must encourage scholars to apply more rigorous statistical techniques in empirical studies and one should introduce minimum reporting standards in publications. (Ernst, 2002, p.33)

  The use of advanced (inferential) statstics can help to overcome this shortcoming, as clear criteria are provided by significance level and probabilities. In fact, a more rigorous application of advanced statistical methods can be observed within the last few years, e.g. in Olechowski et al. (2012) or Welo et al. (2013). In order to be able to apply methods of inferential statistics, the right kind of data needs to be available and collected, as discussed in section 3.2.

- Verification methods: Utilizing advanced statistics provide objective indicators, such as confidence intervals and probability of repeatability. In addition, the verification of dependencies (e.g. through multiple variable regression) and their direction of change, can support the determination of causal relationships. Ernst also noted in his findings that

  > Only in the past few years have some authors begun to conduct empirical research of success factors on the basis of reliable measurement for the dependent and the independent variables. (Ernst, 2002, p.33)

2.5 Characteristics of the Comprehensive Approach

The discussed research needs lead to a set of desired characteristics, as shown in Table 2.3. These characteristics are regarded as best suited for a comprehensive empirical industry study. It is the aim in this research, to be aligned with this 'ideal' type in the best possible manner. This attempt is referred to as the Comprehensive Approach. As can be seen in Table 2.3, some of the characteristics are assumed to be influencing factors (Task, Case Size and Participants). These have to be evaluated for their cause-effect relationships together with the population of influencing factors, which are systematically determined. In the next chapter, the theoretical framework is explained. Background on framework related characteristics, such as data anlysis and data collection methods, are presented in this chapter as well.

Table 2.3: Characteristics of the Comprehensive Approach

Characteristic	**Options**
Aim, research question, hypothesis	Find factors which distinguish successful from less successful development projects.
Study process (nature of study)	Natural.
Theoretical basis	Framework supporting identification of cause-effect relationships. Systematic consideration of all influencing factors to ensure comprehensiveness.
Unit(s) of analysis	Product development process, holistic view.
Data collection method	Investigation of completed projects. Collect and quantify data from project reports and interviews. Success to be rated by participants not involved in the design projects themselves.
Observed process	Product development process from planning phase to product validation.
Task	Varying cases of complexity to verify cause-effect relationships.
Number of cases	As many as possible.
Case size	Varying case sizes to verify cause-effect relationship.
Participants	Varying experience, skills, personalities to verify cause-effect relationships.
Object	Global industrial companies.
Coding and analysis method(s)	Advanced (inferential) statistics.
Verification method(s)	1.) Derives from use of advanced statistics (probability of repeatability). 2.) Determine dependencies between found Success Factors.

3 Framework of the Comprehensive Approach

A sound methodological framework is the basic condition for any research activity. Different viewpoints and approaches can be found in any scientific field. However, in Engineering Design Research "a rather fragmented, if not a chaotic, picture" (Horváth, 2004, p.155) can be found, certainly attributed to the complexitiy of engineering design, consisting of a multifaceted combination of science and human behaviour. Dixon describes the objective of engineering design research to be the search for "theories that can be tested by formal methods of hypothesis testing" (Dixon, 1987, p.145). Antonsson pointed out that "EDR [Engineering Design Research] often lacks a clear hypothesis and testing method" (Antonsson, 1987, p.153). It was the aim in this research to develop a framework, representing a clear theory, which can be verified with methods of hypothesis testing. The underlying assumption of this theoretical framework is that the product development process can be viewed as a matter of cause and effect, as shown in the Cause-Effect-Diagram (Ishikawa-Diagram) in Figure 3.1.

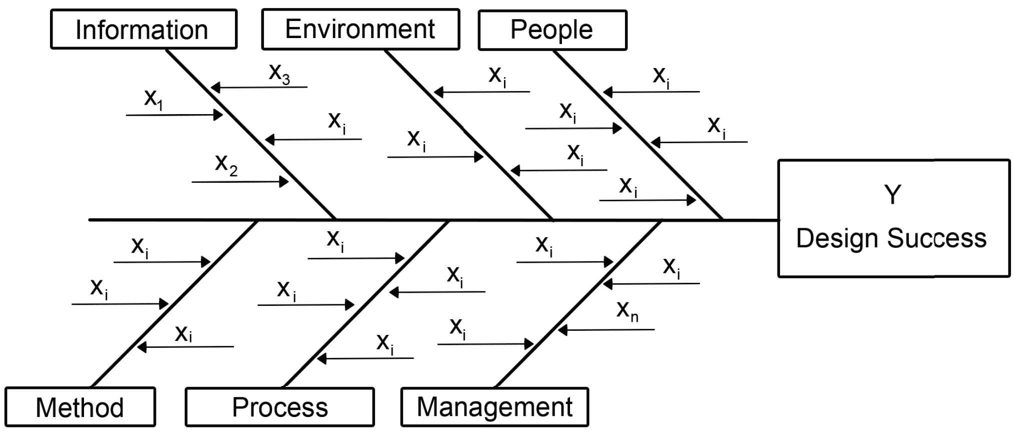

Figure 3.1: Cause-effect relationship in product development

The nature of any process is that it transforms certain input parameters (x_i) into a desired output (Y). In theory, by knowing all the input parameters (causes) and by knowing the transfer function $f(x_1...x_n)$ of the process, it is possible to predict the output (Y), as shown in Figure 3.2. However, the transfer function is not known and determining it is precisely the objective of Engieering Design Research. In other words, Engineering Design Research is interested in knowing which of the input parameters correlate to the output, and knowing dependencies between input parameters.

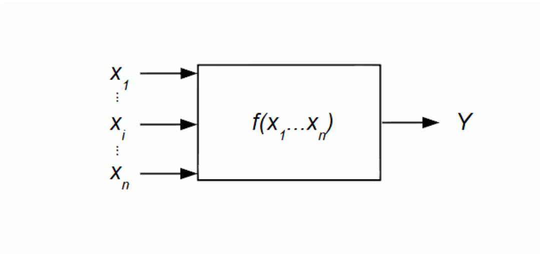

Figure 3.2: Transfer function of product development process

The transfer function can be developed if the input and output parameters are known. Sample data for both these factors can be obtained from real world development projects. Then the transfer function can be developed by performing hypothesis testing with methods of inferential statistics. This approach of converting a practical problem into a statistical problem, finding the transfer function from collected actual input and output data, and converting the statistical solution back into a practical solution; is in analogy to the Six Sigma theory, as shown in Figure 3.3.

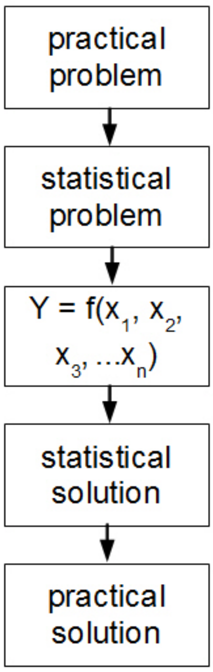

Figure 3.3: Theory behind the Six Sigma approach (Brue and Launsby, 2003)

The concept of the hypothesis test is, to separate the independent variables (causes = Potential Success Factors) from the dependent variable (effect = Design Success), then test each independent variable for a significant correlation to the dependent variable (Figure 3.4), using methods of inferential statistics. The significant input parameters identified can then be considered Success Factors. However, this analysis step does not provide the full picture. It is possible that some of the Success Factors are dependent on each other. For instance, Success Factor A could be caused to change by Success Factor B. The first analysis step would show a relationship to Design Success for both factors, because Success Factor B causes Success Factor A to change whenever it changes itself. In such a case Success Factor B would be dominant over Success Factor A, but it would not be obvious. In order to reveal such kinds of dependencies, a subsequent, second analysis step is required. This second analysis step can be performed again, with statistical methods for hypothesis testing. Its sole aim is to show dependencies between the Success Factors that were determined in the first analysis step. The methods which were used for the two analysis steps in this study are discussed in the Data Analysis Chapter. Only after both these steps were performed, could the results be interpreted and the Dominant Success Factors be filtered out. Ernst pointed out that this second and essential analysis step can seldomly be found in empirical studies (Ernst, 2002). The process map in Figure 3.5 illustrates the theoretical framework of the Comprehensive Approach. The first step is the definition of the research objective (What is the effect of interest?), which in the case of this study was Design Success. After that, the cause-effect relationship needs to be established. In the next step, the effect (Design Success) needs to be defined and quantified. As explained in more detail in the Defining Design Success Chapter, domain and dimensions of the effect need to be known to allow for a clearly defined scope. Similarly to the effect, all the causes (Potential Success Factors) need to be determined, grouped and quantified. It is shown in the Potential Success Factor Chapter that these steps are necessary to limit the amount of data to a manageable size, without sacrificing comprehensiveness. With the effect and the causes quantified, the two analysis steps can be performed, which results in the Dominat Success Factors. Knowing these, allows for the introduction of suitable measures for increased Design Success.

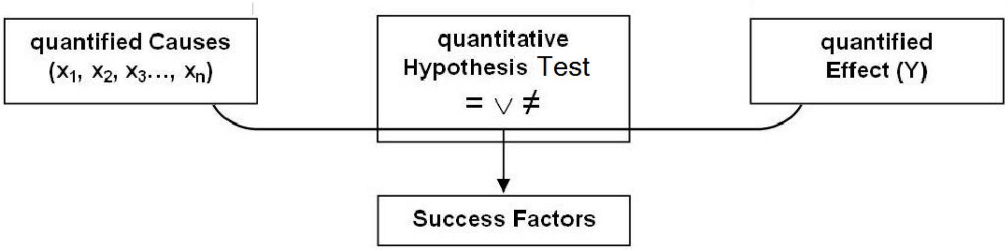

Figure 3.4: Concept of hypothesis test

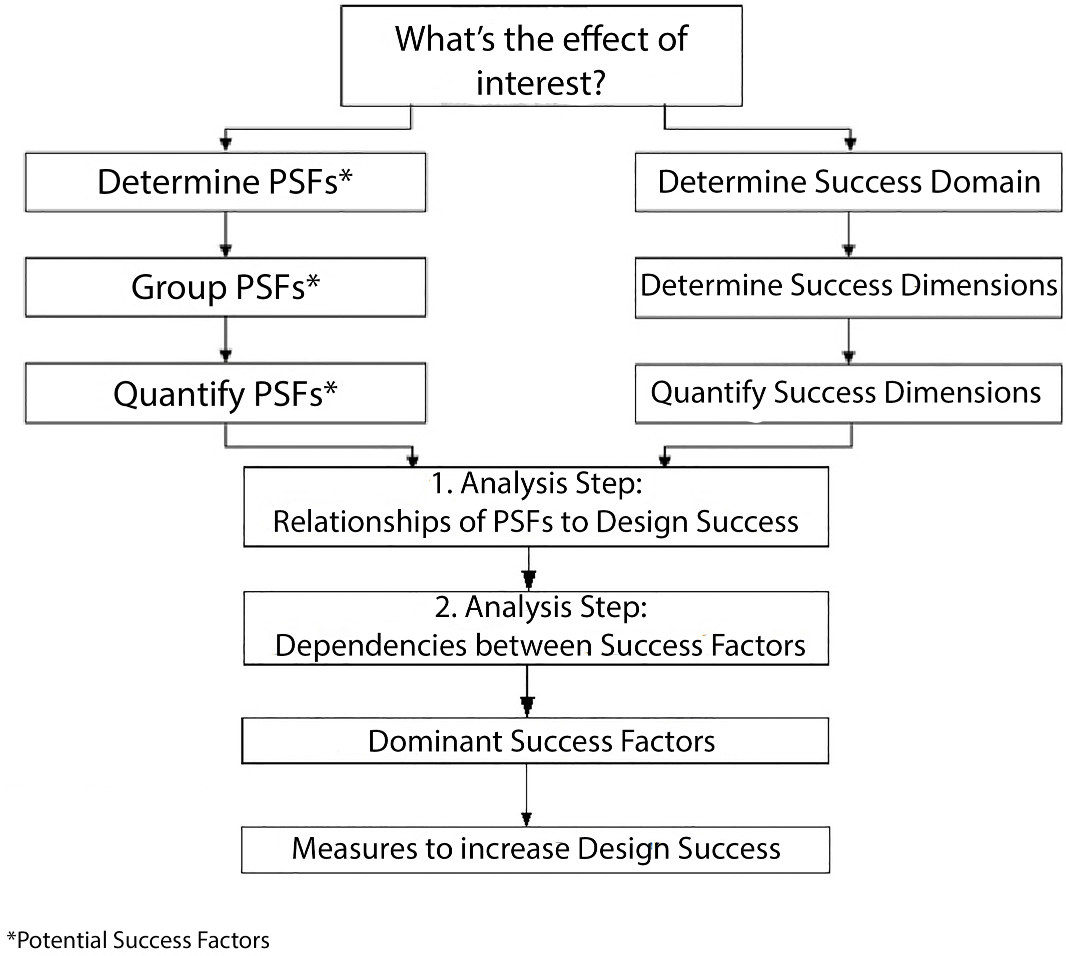

Figure 3.5: Process map of the Comprehensive Approach

The most critical requirements for the successful implementation of this framework are the following:

- Clear definition of what Design Success (Y) is and how it is quantitatively measured.
- Determination and quantification of all Potential Success Factors (x_i).
- Use of robust statistical methods, which provide a measure for confidence of the results.
- Collection of sufficient 'real world' sample data to allow for the use of these statistical methods for hypothesis testing.

3.1 Link to Design Research Methodology

Recognizing the aforementioned lack of theoretical foundations in Engineering Design Research, Blessing and Chakrabarti (2009) defined an overall framework for research in engineering design in their book *DRM, a Design Research Methodology.* They recommend to split the research process into four stages:

- Research Clarification (RC): Formulate Research Goal. Define what part of the engineering design process shall be improved.
- Descriptive Study I (DSI): Obtain understanding what factors influence the area of interest, e.g. by conducting literature reviews (Review-based) or empirical studies (Comprehensive).
- Prescriptive Sudy (PS): Develop measures to improve the situation, based on the findings in DSI.
- Descriptive Study II (DSII): Verify effectiveness of the developed measures, e.g. by conducting empirical studies.

The framework provides flexibility in that not each stage has to be followed for specific research projects, depending on the research question and scope of the project. In total, the DRM framework results in seven possible research types (Figure 3.6). The approach and empirical study outlined in this dissertation falls under the second type. The first two stages (RC+DSI) are addressed in their full entirety, while the third stage (PS) is only addressed in an initial state, which are recommendations for engineering management on what factors need more focus in development projects. The Comprehensive Approach complements the DRM framework in that it provides a more in depth and rigorous process for conducting a comprehensive study in the DSI stage.

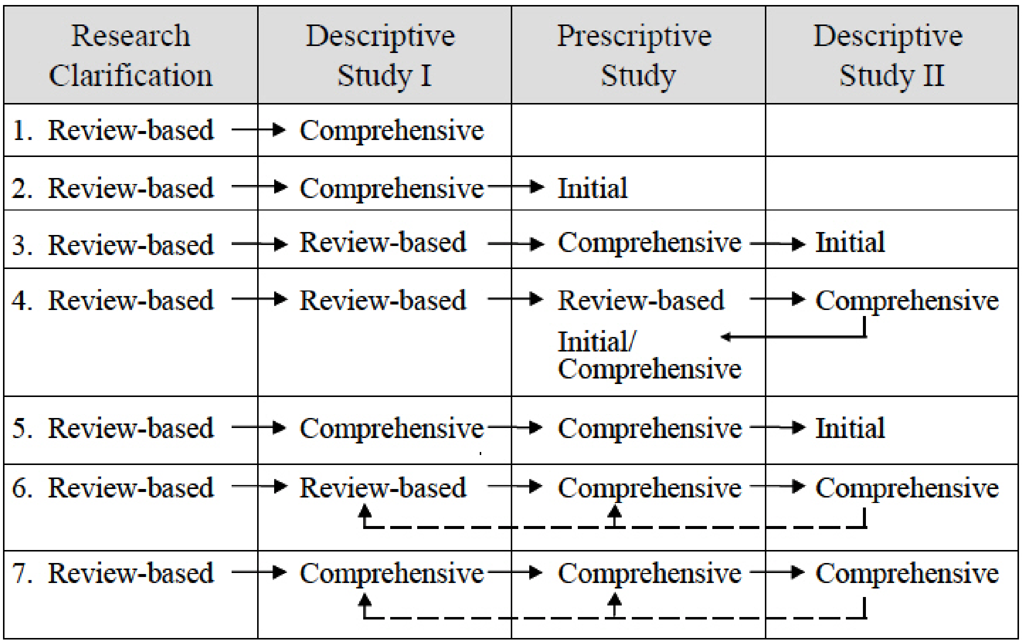

Figure 3.6: Seven possible types of studies in the DRM framework

3.2 Statistical Methods

In this section, only a broad overview of statistics and the terminology related to this research is given. For a more detailed view on the subject, it is referred to the extensive literature available.
Statistics can be divided into two main fields: *Descriptive Statistics* and *Inferential Statistics*. The first field is concerned with describing the nature of an existing set of data, by using for instance graphical illustrations, such as Histograms or Box Plots. The latter field is concerned with extrapolating the pattern of data samples of limited size to a population and, in addition, providing levels of confidence for this extrapolation. The confidence is a measure for the probability, an observed pattern could repeatedly be seen, when drawing different samples from a population. The multifold scenarios in all areas of science, where extensive - or even infinite - amounts of population data exist, made it necessary to come up with this 'mathematical shortcut'. Many different kinds of statistical methods exist. Selecting the most suitable method for a problem is dependent on two main factors:

1. Types of data available
2. Distribution of the available data

Data Types in Statistics

Four different types of data have to be distinguished:

- Nominal: Data divided into categories which are neither in a certain order, nor have any relationship. An example would be male versus female, or parts separated into categories by color. Changing the order of the categories does not change the nature of the data.
- Ordinal: Data points which have ranks on a scale. The ranks might be represented by numbers (usually integer), or descriptions (e.g. negative, neutral, positive). The distance between the ranks might not be equal and can usually not be determined.
- Interval: Variables which are measured on an interval scale are uniform on the scale. Mathematical operations can be applied, but ratios are not meaningful. A typical example for interval data is the Celcius scale. Temperatures can be added or subtracted and the results are valid. However, it cannot be claimed that 40C is twice as hot as 20C, as 0C is not an absolut zero point.
- Ratio: Similar variables than interval data, but with meaningful ratios. A typical example is the Kelvin temperature scale. Unlike on the Celcius scale, it is valid to

claim that a temperature of 600K is twice as hot as a temperature of 300K, since an absolute zero point exists at 0K.

The first two types (nominal and ordinal) are common whenever qualitative data is translated into quantitative data, e.g. data obtained through surveys. Suitable statistical methods for these data types have especially been developed in the social sciences. These are the types of data usually seen in Engineering Design Research. Interval and ratio data on the other hand, are more commonly found in the areas where 'hard data' can be obtained, for example in the natural sciences or economics.

Distribution of Data

The second important criterion for the selection of a statistical method is the distribution of the sample data. Parametric tests are used under the assumption that the data follows a normal distribution. In case it is found that the data is not normally distributed, non-parametric methods have to be used. Table 3.1 gives an overview of suitable tests for different kinds of comparisons.

Table 3.1: Paramteric vs. non-paramteric statistical tests (Burke, 1998)

Types of comparison	**Parametric methods**	**Non-parametric methods**
Differences between independent groups of data	t-test for independent groups	Wald–Wolfowitz runs test Mann–Whitney U test Kolmogorov–Smirnov two-sample test
	(ANOVA/MANOVA)	Kruskal–Wallis analysis of ranks Median test
Differences between dependent groups of data	t-test for dependent groups	Sign test Wilcoxon's matched pairs test McNemar's test χ^2 (Chi-square) test
	ANOVA with replication	Friedman's two-way ANOVA Cochran Q test
Relationships between continuous variables	Linear regression Correlation coefficient	Spearman R Kendall Tau
Homogeneity of variance	Bartlett's test	Levene's test, Brown and Forsythe
Relationships between counted variables		Coefficient Gamma χ^2 (Chi-square) test Phi coefficient Fisher exact probability test Kendall coefficient of concordance

3.3 Data Collection Methods

Varying methods for data collection are available in the social sciences and can be applied for problems in Engineering Design Research. They can be divided into the main groups: observation, experiments, case studies, analyzing documents, questionnaires, interviews (adapted from Blessing and Chakrabarti (2009)). Each of these groups have subsidies, sometimes a combination of methods is applied to research problems.
The criteria of comprehensiveness and high reliability of results for the Comprehensive Approach, narrow the options for suitable data collection methods. The requirement for 'real world' data from development projects in an actual industrial setting prevents the use of experiments or case studies. Observational studies are time consuming and only allow for the collection of one or very few cases. Blessing and Chakrabarti called it "impossible or very difficult" (Blessing and Chakrabarti, 2009, p.255), to collect data from multiple cases in industrial studies. However, the use of statistical methods for data analysis demands data from multiple industrial studies. The following three methods remain, in permitting the collection of data from multiple industrial cases:

- Interviewing
- Questionnaires
- Analyzing documents

The quality of the data is an important aspect which needs to be considered carefully. Especially when information is directly received from humans, or even participants of the design projects investigated, bias is unavoidable (Donaldson and Grant-Vallone, 2002). The goal in empirical research needs to be, the reduction of chances for bias to a minimum. The way in which the data is collected is an essential part of this. Although questionnaires provide the most amount of data with the least amount of effort, they bear a lot of uncertainty, as oftentimes little is known about the participants, their background and involvement in the investigated projects. Interviewing and analyzing documents gives researchers more control on this factor and are hence the better quality sources for data collection with respect to bias.
Still, researchers need to be aware of two aspects of bias. At first, they need to prevent self-report bias as much as possible, as participants - as well as researchers, if they were involved in study objects themselves - tend to answer in "socially desirable ways" (Donaldson and Grant-Vallone, 2002, p. 247). This is because participants usually want to look as good as possible, or they sense the possibility that their employer could have access to the data they provided (Donaldson and Grant-Vallone, 2002). White and Fortune experienced such optimistic self-reporting (see Figure 2.3) in a study where 82% of the participants were directly involved in the projects they were asked about. To avoid this

aspect of bias, data can be collected from sources that know the project well enough, but do not have a direct involvement. These could be stakeholders of studied projects or managers of the participants.

Secondly, researchers need to chose and prepare the data collection in a way that limits bias from a rating error perspective. They can do so by formulating questions in a neutral manner that do not direct participants towards a desired answer (Blessing and Chakrabarti, 2009). For data quantified on a scale, it helps to provide definitions along the quantification scale, giving the participants anchor points that are more informative for decision making than simpley numbers (Landy and Barnes, 1979). In order to get an understanding of the potential for bias, researchers should run test trials of the defined questions and quantification scales with one or a few participants. This will give them the chance for correction, if they sense that trial run participants struggle with making solid judgements and to test the fitness of the purpose (Aurisicchio and Wallace, 2007).

4 Defining Design Success

Success in product development cannnot be defined in an one-dimensional measure (Griffin and Page, 1993; Prabhakar, 2008; Suomala and Jokioinen, 2003). In Engineering Design and Innovation Management Research, the triad (Schimmoeller, 2010), also referred to as the 'iron triangle' (Gericke, 2011), is oftentimes used:

- Development of products that fulfill defined Product Requirements
- Meeting Development Timeline
- Stay within Development Budget

These three dimensions for measuring Design Success are widely accepted as the best practice (Kerzner, 2010). White and Fortune (2002) found, in a survey to 995 project managers in different companies, that these dimensions are recognized significantly more important than any others (Table 4.1).

Table 4.1: Rated importance of dimensions for measuring success (White and Fortune, 2002)

Criteria	Sum of re-coded ranking	Sums ranked
Meets client's requirements	970	1
Completed within schedule	850	2
Completed within budget	766	3
Meets organisational objectives	188	4
Yields business and other benefits	86	5
Causes minimal business disruption	71	6
Meets quality/safety standards	48	7
Other criteria	20	8

Conversely, it can be found that the triad is critized as being "too simplistic" (de Wit, 1988, p.166). De Wit recognizes the three dimensions, but considers these dependent on the objective of the development project. Objectives vary by types of projects, throughout the life cycle, view from management hierarchy and stakeholders involved. He demonstrates different success criteria during the life cycle of a oil field development project, due to varying objectives in different project phases (Table 4.2).

Table 4.2: Changing success criteria with varying objective (de Wit, 1988)

Phases	Primary objective
Exploration	Find oil in large enough quantity for development
Development	Develop the oil field in the most economic manner
Production	Maximize daily production and optimize total oil recovery

In order to account for the objective, it is necessary to define the domain, in addition to the dimensions of success. By domain, it can be referred to the different departments in an organization. Depending on the department under consideration, the dimensions of success vary. For instance, the marketing or service departments have different success criteria than the engineering department. Having defined the domain of interest for a research project, the dimensions result from the metric this department is measured against in the organization (Figure 4.1). In the case of Engineering Design Research, the domain of interest is the development department, which leads to the three success dimensions: product requirements, timeline and budget.

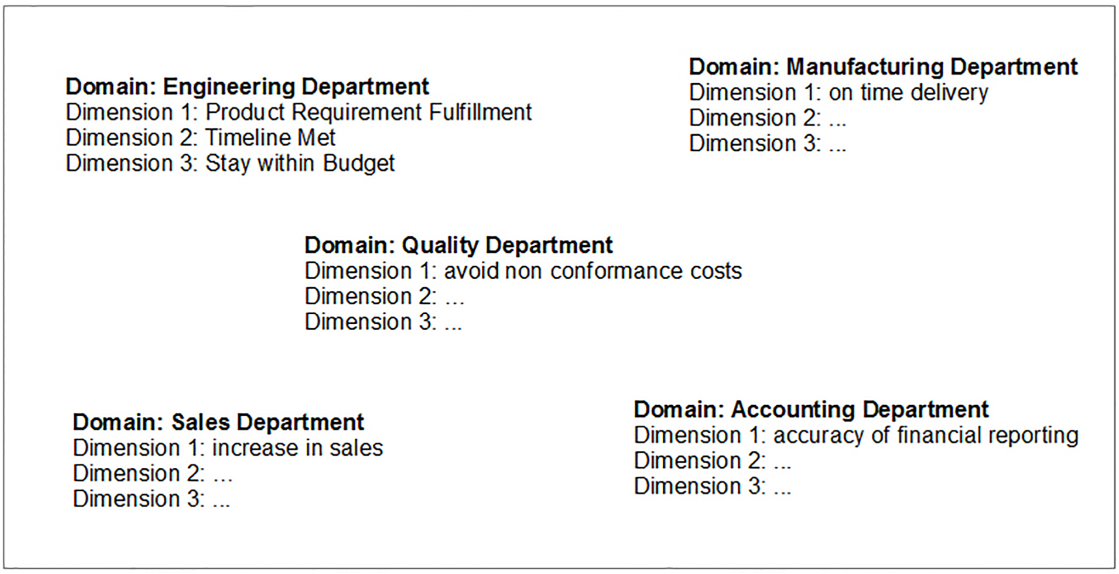

Figure 4.1: Examples of domains and their success dimensions

4.1 Success Dimensions of the Comprehensive Approach

For the empirical study, it had to be decided which of the three success dimensions is of most interest and serves as the primary dimension. Defining a primary dimension is inevitable, as pursuing all three dimensions in one study with one set of data leads to one of the following two issues:

1. In order to determine the factors for design success statistically, a good distribution of data from highly successful projects, to projects of low success, has to be considered (ideally normally distributed to allow for the use of parametric statistical methods). If only successful or only unsuccessful projects are investigated, the findings cannot be seen as verified, as the opposite was not proven. Finding a good distribution of projects on the success scale with respect to one dimension of interest is doable. However, finding a sample size of projects that includes a representative sample distribution in three different dimensions is very unlikely. At least it would require extensive amounts of data, more than is possbile in the course of a doctoral research.

2. The three dimensions are not necessarily on the effect-side, but can also switch to the cause-side. This is especially true for products which have development cycles of several years. Development budgets in companies are typically determined and distributed on a yearly basis. A development project which is planned for several years can be impacted by funding cuts during that duration. In this case, the third dimension 'Stay within Development Budget', which was thus far considered to be an effect, would now become a cause that impacts the first two dimensions.

The primary dimension was chosen to be 'Product Requirement Fulfillment'. 'Timeline Met' was chosen as secondary dimension. The correlation of Success Factors to this secondary dimension is investigated indirectly through the first dimension, as shown in the Data Analysis Chapter. This verification is necessary, as otherwise the question, if any project can be accomplished successfully if there was just enough time spent and resources invested, remains open. The third dimension 'Stay within Development Budget' turned out to be a cause and is investigated under the Potential Success Factor 'Resources provided / Project Stability'.

4.2 Primary Success Dimension

An additional advantage of chosing the fulfillment of product requirements as primary dimension is that this factor can be easily measured on at least an ordinal scale. For this

research it was decided to measure success on a scale from one to ten. This would even allow a direct translation to success rates between zero and a hundred per cent.
For the attempt of quantifying originally qualitative data (perception of success), it was important to define anchors on the rating scale using clear descriptions. This helped to recognize the reasons behind the decision, guiding interviewees towards a rational judgement rather than an unspecified rating anywhere on the scale (Landy and Barnes, 1979). Table 4.3 shows the success quantification scale for the primary dimension 'Product Requirement Fulfillment', with descriptions on two point intervals. In this case, Product Requirement represented a combined measure, not only including functional and quality aspects, but also legal and cost considerations. The interviewees were asked to use the end customer's perception of and reaction to the developed product, with respect to these dimensions, as a reference for their overall judgement.

Table 4.3: Quantification scale for primary dimension 'Product Requirement Fulfillment'

10	Product fulfilled all product requirements as specified and worked "out of the box".
9	
8	Minor problems with functionality/quality and fulfillment of product requirements; minor rework/adjustments required during commissioning phase; minor costs occured for customer and/or company from rework.
7	
6	Noticeable problems with functionality/quality and fulfillment of product requirements; moderate rework/adjustments required during commissioning phase; moderate costs occured for customer and/or company from rework.
5	
4	Large problems with functionality/quality and fulfillment of product requirements; large amount of rework/adjustments required during commisioning phase; high costs occured for customer and/or company from rework.
3	
2	Very large problems with functionality/quality and fulfillment of product requirements; product only worked after fundamental changes/redesign; excessive costs occured for customer and/or company.
1	
0	Product failed to function; repair not possible or with extensive efforts; development program terminated before completion.

The other source of bias in success measurement is self-report bias (Donaldson and Grant-Vallone, 2002). This occurs when participants, involved in the projects themselves, are asked to rate success (Blessing and Chakrabarti, 2009; White and Fortune, 2002), as described in section 3.3. To avoid this 'pitfall', the success ratings for the projects in this study were provided by the stakeholders of the project. In the case of this study, these were internal customers, such as the Product Line Management or Service Department. On the cause side (Potential Success Factors), managers and team members (if managers didn't have the knowledge) were interviewed for missing information, or information which could not be retrieved directly from the engineering database, such as the average experience of project teams. The clear definition of success on a scale and the separation of success rating from persons involved in the projects themselves, is expected to have greatly helped in minimizing the chance for bias in the data. However, it has to be recognized that a certain amount of bias remained, which is inherent to any translation of qualitative into quantitative data.

4.3 Data Collection for Primary Success Dimension

Collecting the data for success from the stakeholders of the projects meant interviewing actual persons in the organization. The stakeholders were managers in the Product Line Management and Service Departments. These departments served as customers of the investigated development projects in that they provided the funding to the engineering department for execution and were the recepients of the final product. Hence, they had a special interest in the on time delivery of a specified product, within a provided budget. In total, nine managers were asked to judge the success of the projects using the rating scale shown in Table 4.3. A trial run was performed with one manager at first to allow for a 'fine tuning' of the descriptions on the scale. This trial run showed that using a descritpion anchor on every second step on the scale was sufficient. In general, this held true for all participants during the actual data collection. In cases they were indecisive about two descritptions, they chose a rating value in between.

In the end, 44 projects remained which provided valid data (see section 5.3) and were used for the study. After collecting the success data for all these projects, the next step was to understand the distribution of the data. Figure 4.2 shows the distribution of the 44 projects over the sucess scale from one to ten. It can be seen that the distribution is not even. For the projects rated between four and ten, the data is close to normally distributed. In addition, four projects of zero success are found on the scale. These are projects which were terminated before completion. No projects were found between the scale points zero to four. This pattern suggests that the organization had measures in place to terminate projects, before they lead to 'catastrophic' results. The resulting gap in the data meant that the desired even, or normal distribution of data points on the scale was non-existent. However, as elaborated in the Data Analysis Chapter, suitable statistical tools exist for such uneven distributions of data; and are used for the analysis.

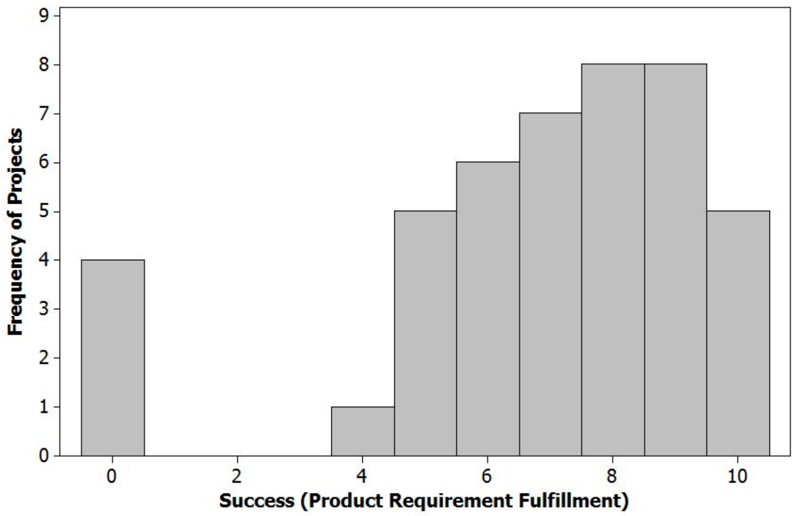

Figure 4.2: Design Success of 44 investigated projects

4.4 Secondary Success Dimension

Defining success in terms of the project timeline is different than for the product requirements. On the one hand, the data is already in quantitative form, as the completion dates of the projects can be retrieved from the engineering database. On the other hand, the question on how these dates could be translated into a success scale, provided different possible answers. For instance, if a project met the timeline, it should have been considered as high success. But what about projects which were completed beyond the target date? Due to this unclarity with respect to a reference, it was decided that the best way to define this success dimension is with categories for 'timeline met' and 'timeline not met'. As the investigated projects have typical cycle times of several years, a tolerance band of plus and minus one month was accepted as timeline met. For the later evaluation against the primary dimension, the four projects with zero success were left out, as these projects had been terminated before completion. A third category 'timeline exceeded' could have possibly been defined, but it was already known from the data collection process, that none of the 44 projects were completed ahead of the target date.
The data for meeting or missing the completion dates was directly retrieved from the engineering database, where target and actual completion dates were recorded. The anlysis against the primary success dimension is shown in the Data Analysis Chapter.

5 Potential Success Factors

The causes that ultimately lead to the effect in product development, sum up to an extensive amount of data. As shown in Figure 3.1, the Potential Success Factors can be found to fit into one of the six categories: Information, Environment, People, Method, Process and Management. A comprehensive review of the product development literature, journals and meta-anlyses on succes factors in engineering desing, as well as feedback from the interviewed project leads and engineering managers, lead to a total of 63 causes (x_n) in the six categories, for the domain development department. The Comprehensive Approach demands the quantification of all of the causes in order to perform a hypotheses test against the effect (Design Success). This means that for a sample size of 44 projects (m) and two (primary and secondary) success dimensions (y_k), the resulting amount of required data points (d) is

$$(n + k) * m = d \tag{5.1}$$

or

$$(63 + 2) * 44 = 2860.$$

This number illustrates a major reason why comprehensive studies are so difficult and are rarely conducted. The effort for collecting and evaluating data of that many causes would be extensive and beyond the time frame of typical studies, such as a doctoral research. A more manageable amount of data would result, if there was a way to reduce the amount of Potential Success Factors systematically.

5.1 Reduction of Potential Success Factors

A systemtatic reduction of the data size on the cause-side demands that the comprehensiveness of the approach must not be sacrificed. With respect to this demand, a simplification can be justified (Wörz and Göhlich, 2012) using the following two considerations:

1. The results of an Empirical Engineering Design Research study are intended to be of practical use for engineering managers and development project leads working in the industry. Keeping this in mind, the data set can be reduced to the Potential Success Factors that can be influenced and measured, for instance Team Size or Team Composition. Managers are certainly interested in results that suggest measures of how to form productive teams. Conversely, certain Potential Success Factors, for instance *creativity*, are difficult to controll or be influenced by engineering management or project leads, when setting up a development project. In addition, it needs to be assured that there is a way to quantitatively measure such a cause. In psychology, there is not yet a clear common understanding or way of measuring creativity (Gausemeier et al., 2000). While it is oftentimes acknowledged as a personal trait, some researchers consider it a result of situational circumstances and environments (Amabile, 1996). Therefore, the first reduction in the data relates to the 'practicality' of the Potential Success Factors.

2. Instead of quantifying each cause, it is reasonable to combine certain causes into groups, which can then be quantified as one measure. For instance, in the literature, aspects of performing conceptual design are oftentimes mentioned as factors leading to Design Success, such as: breaking problems into sub-functions, use of creativity techniques for solution finding, finding many alternative solutions, etc. A higher level category or cause, where all these single causes fit, can be defined as 'Conceptual Design performed'. By defining one quantitative scale for such a higher level cause, it is possible to evaluate if and to what extent it contributes to successful product design. Figure 5.1 shows the concept of this iterative approach.

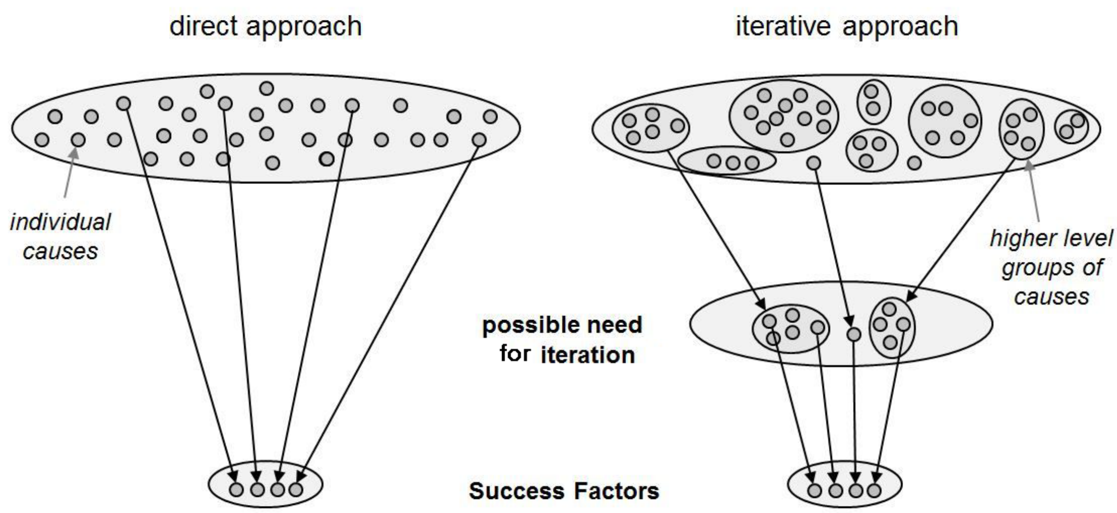

Figure 5.1: Iterative approach for reduction of data points

Applying these two criteria leads to a reduction in the determined Potential Success Factors from origianlly 63 to 18. This means that, applying formula 5.1 again, the number of data points has been reduced from 2860 to

$$(18 + 2) * 44 = 880.$$

A reduction to less than a third of the originally required data points was achieved, by retaining the comprehensiveness of the study - with respect to information necessary for engineering management. Applying the iterative approach might result in the need for a second iteration, as shown in Figure 5.1. Still, the overall required data points are reduced, as some groups of higher level causes can be expected to be eliminated in the first iteration. An additional advantage of this approach is that the extensive research effort of a comprehensive investigation of Success Factors in product development can be split clearly into separatable stages. The time constraint of this research work permitted only to focus on the first iteration. However, the results presented in this dissertation can provide the ground work for future researchers, to focus in more detail on the determined Success Factors, especially if they are groups of higher level causes.
Figure 5.2 shows the 18 remaining Potential Success Factors in the Ishikawa Diagram, after the systematic reduction. The six categories (Methodology, Management, People, Process, Information and Environment) were derived from categorizing the 18 causes with help of the Affinity Diagram Procedure (Cohen, 1995).

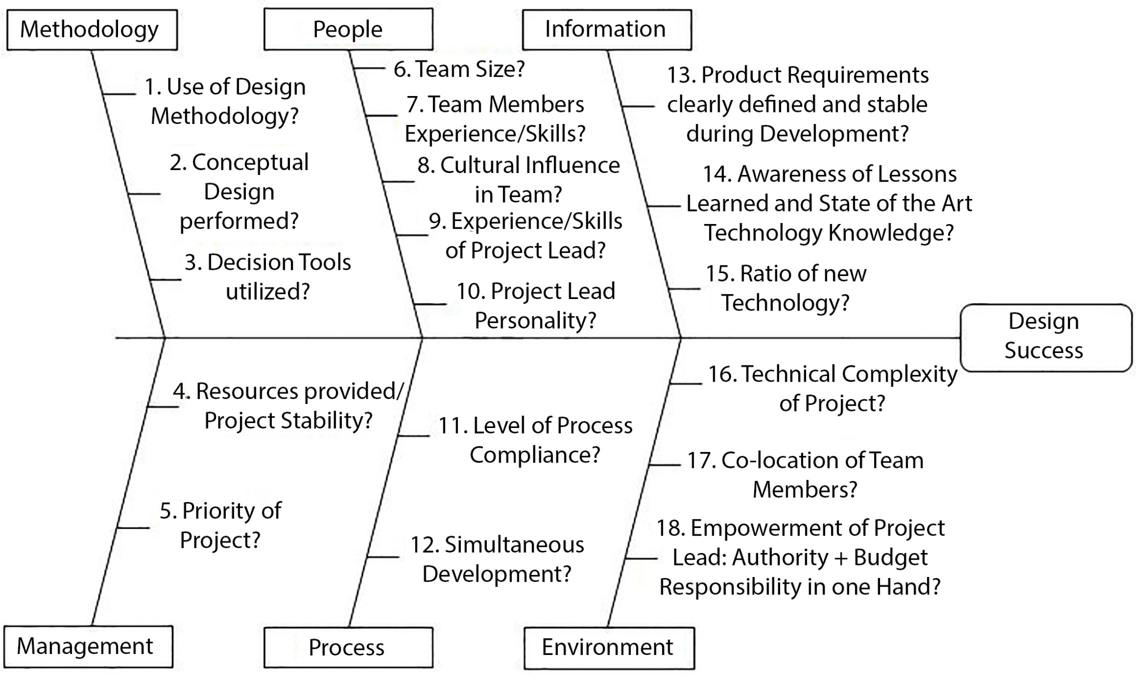

Figure 5.2: Remaining Potential Success Factors after systematic reduction

5.2 Quantification of Potential Success Factors

In order to allow for the collection of quantitative data (as described in 5.3), the 18 remaining Potential Success Factors had to be clearly defined on rating scales. The factors were defined as either ordinal data in three groups, or nominal data in two groups. The suitable use of these scales resulted from trial runs with some participants in the company. For the factors measured in three groups it was originally intended to apply a five point Likert type scale, with the categories: Very Low, Low, Moderate, High, Very High. However, it was recognized that this scale provided difficulties in deciding between Very Low or Low and High or Very High. The concern for too much noise in the data using the five categories lead to the decision to only use three: Low, Medium and High. It was confirmed during the data collection that the interviewees were able to respond comfortably to these three categories. The same 'trial and error' approach was applied to the factors which ended up to be measured in two categories.
In the following sections, the 18 Potential Success Factors and their respective rating descriptions are explained.

5.2.1 Use of Design Methodology

The rating scale definitions for this Potential Success Factor are shown in Table 5.1. Applying design methodologies is widely found to be an important factor for success in the product development domain (Krause et al., 2006; Lindemann, 2009; Mehalik and Schunn, 2006; Schregenberger, 1998). Pahl and Beitz define methodology as "concrete course of action...to achieve general and specific goals" (Pahl et al., 2007, p.10). Different methodological movements evolved in the industrialized countries in the scond half of the 20th century. These methodologies might appear different on a detailed level, but they all have in common that they regard the product development process to consist of four main phases (with varying terminology): *Definition of Task; Conceptual Design; Basic Design; Detail Design*. The methods themselves vary within these phases, but the aim is always the same: to provide design engineers with the appropriate tools to master the particular challenges of each respective phase.

Table 5.1: Rating definitions for 'Use of Design Methodology'

High	Design methodology used completely or mostly throughout the development process
Medium	Design methodology used occasionally or at different stages of the development process
Low	Design methodology used rarerly or not at all during the development process

5.2.2 Conceptual Design performed

Being usually - but not necessarily - part of an overall methodology, the Conceptual Design Phase is emphasized by some authors as crucial for successful product development (French, 1999; Pahl et al., 2007; Ullman, 2003). In this phase, a series of stages are proposed to be performed. The most common of these are: breaking the system or problem into sub-systems; generate multiple solution ideas for the sub-systems using different (creativity) techniques; systematically down-select to the most suitable solutions; evaluate solutions on a system level before moving on to basic design. The definitions for rating to what extent coneptual design was utilized in the investigated projects, is shown in Table 5.2.

Table 5.2: Rating definitions for 'Conceptual Design performed'

High	Conceptual design with all or most of its stages performed
Medium	Partial stages of conceptual design performed
Low	Very little or no conceptual design performed

5.2.3 Decision Tools utilized

Table 5.3 shows the rating scale definitions for this Potential Success Factors. Similar to conceptual design, the systematic application of decision tools can be, but is not necessarily applied as part of an overall design methodology. Instances can be found where the decision making process almost solely determines the progress of a development project. Morgan and Liker found that one of Toyota's cornerstones of success in the design process, is the use of engineering checklists throughout the development cycle to support decision making. This can lead to cases were decisions have to be postponed due to incomplete information in the decision checklists. As a result, Morgan and Liker claim that "delaying decisions at Toyota leads to faster overall product development" (Morgan and Liker, 2006, p.65).

Table 5.3: Rating definitions for 'Decision Tools utilized'

High	Decision tools utilized consequently in each or most stages of the development process
Medium	Decision tools utilized in some stages of the development process
Low	Decision tools rarely or not at all utilized during the development process

5.2.4 Resources provided / Project Stability

This Potential Success Factor includes internal, as well as external influences, meaning it varies based on decisions made outside of the engineering department. Although engineering management distributes resources within its domain, upper-level management decisions can change the course of action in a way - e.g. by changing the product strategy or cutting the budget - that engineering management has no other choice than to reallocate resources. Especially on products with development cycles of several years, this impact on product stability can occur frequently as research and development budgets usually are evaluated and redistributed at least once a year. By setting a strategy and vision that supports the stable execution of development projects over the whole cycle, upper-management is believed to have a significant impact on the outcome of development projects (Ehrlenspiel, 2009; Gausemeier et al., 2009; Schimmoeller, 2010).

Table 5.4: Rating definitions for 'Resources provided / Project Stability'

High	Throughout project: no or very minor changes in budget or core team member commitment to project
Medium	Throughout project: moderate changes in budget or core team member commitment to project
Low	Throughout project: large or complete changes in budget or core team member commitment to project

5.2.5 Priority of Project

Table 5.5 shows the rating scale definitions for this Potential Success Factors. The project's priority refers to the status the develoment project has within the engineering domain. Due to the amount of tasks being executed in a global engineering organization, engineering management has to set priorities on which projects to give more attention than others. The priority setting derives from the need to balance different stakeholders interests, such as upper-managment directive, internal or external customers. Fricke and Shenbar point out that

> Division and assignment of resources, prioritization, and customized management style, which have little relevance in relation to single projects, are shown to play a major role in the success of multiproject management. (Fricke and Shenbar, 2000, p.258)

Table 5.5: Rating definitions for ’Priority of Project’

High	Project had high priority in the engineering department
Medium	Project had medium priority in the engineering department
Low	Project had low priority in the engineering department

5.2.6 Team Size

One would assume that the size of a development team is a function of other factors, such as the complexity of the project. Such relationships would have to be verified if the Team Size showed to be related to the successful outcome of projects. In the first step, however, it was only of interest if smaller teams caused a different effect than larger teams did. The impact of teams on project performance can most commonly be found in the literature under the collective term ’Team Composition’ (Ernst, 2002; Schimmoeller, 2010). However, bundling this factor into a one-dimensionsal measure appeared to be difficult. It was actually an allocated projection in the Potential Success Factors: ’Team Size’, ’Team Members Experience / Skills’, ’Cultural Influence in Team’ and ’Simultaneous Development’. Team sizes vary with the industries and products. The size definitions for small, medium and large project teams were derived from typical team size conventions (rule of thumb) used for gas turbine component development projects.

Table 5.6: Rating definitions for ’Team Size’

High	Team consisted of 13 or more core team members
Medium	Team consisted of 6-12 core team members
Low	Team consisted of 1-5 core team members

5.2.7 Team Members Experience / Skills

Similar to Team Size, the requirements for experience level and skill set of the team members varies, depending on the industry and product. Engineering management might accept teams with less average years of experience for the development of software or consumer goods - this might even be desired, for staying connected to the trends of the market - than for complex physical products, such as power plants or airplanes, which require very experienced teams (Lindemann, 2009). The development of gas turbines demands highly specialized skill sets, which explains the relatively ’stretched’ rating definition intervals chosen for the three categories, shown in Table 5.7. The skill set is related to work experience in this case, as close to all engineering team members enter the gas turbine development domain possessing related advanced engineering degrees.

Table 5.7: Rating definitions for 'Team Members Experience / Skills'

High	Average team experience of 15 or more years in gas turbine development
Medium	Average team experience of 8-14 years in gas turbine development
Low	Average team experience of 7 or less years in gas turbine development

5.2.8 Cultural Influence in Team

It showed to make sense to measure this Potential Success Factor binominal, dividing teams with members of one culture from teams with members of more than one culture, as shown in Table 5.8. Defining more categories on an ordinal scale, e.g. measuring amounts of cultures involved, wouldn't have provided valuable information, as a change in group dynamic usually occurs between culturally homogeneous and culturally heterogeneous teams (Thomas, 1999). It would have also meant that the distances between the categories was highly unproportional, which would have made the use of quantitative methods difficult. Dividing between no cultural influence and any cultural influence provides the highest level evaluation, suitable for a first analysis step. If the factor was found to be of significance, it could be investigated in more detail in a subsequent step.
Baumgärtner and Blessing (1999) studied project-related differences in the design practice of two different cultures (Italy vs. Germany). They found that the differences lie oftentimes in soft factors which are not always obvious. The research proposed that although things are done in a different way, they can still lead to the same success. Finally, the authors recongized a trend to more common practices in executing development projects between cultures, as more and more companies are forced into international collaborations or take-overs.

Table 5.8: Rating definitions for 'Cultural Influence in Team'

High	Core team members from more than one culture
Low	Core team members from one culture

5.2.9 Experience / Skills of Project Lead

Project leads and their personalities are believed to play an important role in successsful design work (Ehrlenspiel, 2009; Pahl et al., 2007). As it showed impossible to combine the complexity of this influence into one factor, it was divided into two Potential Success Factors, one measuring the experience and skills, the other measuring personality traits. Table 5.9 shows the definitions for categories on experience and skill levels of project leads.

Table 5.9: Rating definitions for 'Experience / Skills of Project Lead'

High	High degree of technical and project lead experience; has lead several similar development projects in respective technical area and environment before
Medium	Moderate degree of technical and project lead experience; has lead few similar development projects in respective technical area and environment before
Low	Low degree of technical and project lead experience; has not lead similar development projects in respective technical area and environment before

5.2.10 Project Lead Personality

Measuring personality types has traditionally been an area of interest in psychology. Different models have been developed over time. The Myers-Briggs personality test has been established as the most used evaluation (Quenk, 2009). Founded on Jung's model of typology (Jung, 1971), the test is a standard instrument in assessment and recruiting centers. The model suggests that a humans personality can be defined by four basic categories with pairs of opposite traits: Introverted vs. Extroverted; Sensing vs. Intuitive; Thinking vs. Feeling; Judging vs. Perceiving. While this model might not directly be applicable to traits of successful project leads, three - to these personality dimensions related - traits can be found in the literature (Ehrlenspiel, 2009; Pahl, 1992; Pahl et al., 2007):

a) Communication

b) Decision Making

c) Risk Awareness

The opposites were defined for the rating, as shown in Table 5.10. Although no person can be located clearly on one or the other end of these scales for the traits, the interviewed managers were, in general, able to make a judgement using these definitions.

Table 5.10: Rating definitions for 'Project Lead Personality'

	10a: Project Lead Personality - Communication
High	Strong/active communicator
Low	Subtle communicator
	10b: Project Lead Personality - Decision Making
High	Quick decision maker
Low	Takes time to make decisions
	10c: Project Lead Personality - Risk Awareness
High	Continuously/often evaluates risks and corrects course of project if necessary
Low	Rarerly/never evaluates risks and corrects course of project if necessary

5.2.11 Level of Process Compliance

Processes are essential in large organizations (Morgan and Liker, 2006) to define clear responsibilities, coordinate activities and ensure the adequate flow of information. The product development process in the company of the study consists of different review and quality gates over the complete lifecycle of a product (Figure 1.9), starting with a Product Requirement Specification Review and ending with a Field Validation Review after several years of operation of the product. In the area of engineering design, three process steps are required to be completed with a review when developing a new gas turbine:

1. Conceptual Design Review: review of usually two to three alternative solutions, which were elaborated in this phase on a high level and shall be pursued in the basic design phase.

2. Basic Design Review: review of the basic design work, including analysis, feasibility studies and prototype tests. The design team presents the proposal for a go-forward solution and the respective technical justification.

3. Final Design Review: review of the detailed and completed design work, including product definitions (drawings and bill of materials). A successful Final Design Review results in the product release for production.

For component development projects (e.g. combustion system upgrades) however, it is not a requirement to follow all these three process and review steps. This is done conciously to allow for flexibility in the process. The design team itself is allowed to make the call on how many reviews are required, weighing complexity and risk against justified process effort at the beginning of each project. All component development projects have to have a final review conducted upon completion of the Final Design Phase. The rating scale definitions shown in Table 5.11 measure the level of process compliance in how many of these reviews were conducted.

Table 5.11: Rating definitions for 'Level of Process Compliance'

High	All three design process steps (Conceptual, Basic and Final Design) followed and completed with official reviews
Medium	Two out of three process steps followed and completed with official reviews
Low	Only final process step (Final Design) completed with official review

5.2.12 Simultaneous Development

The rating definitions for this Potential Success Factor were aligned with the design phases (Conceptual, Basic and Final Design) of the product development process (Table 5.12). Simultaneous development is the concept of shortening development cycles by performing as many design tasks in parallel as possible, rather than sequential (Krause et al., 2006). This means developing and evaluating concepts in parallel, building prototypes early and - most importantly - involving downstream stakeholders (manufacturing and suppliers) from an early stage on. In an ideal case, good coordination does not only lead to shorter development time, but also improves quality by supporting the detection of 'downstream issues' early on. Evaluating this factor against the success dimension 'Timeline Met' it was found that projects where simultaneous engineering was utilized from the beginning had a higher chance of being completed on time.

Table 5.12: Rating definitions for 'Simultaneous Development'

High	Integration of manufacturing and suppliers from the Conceptual Design Phase on
Medium	Integration of manufacturing and suppliers from the Basic Design Phase on
Low	Integration of manufacturing and suppliers in the Final Design Phase

5.2.13 Product Requirements clearly defined and stable during Development

A clear understanding and definition of product (customer) requirements is one of the most commonly found conditions for success in product development. Any of the classic literature sources about engineering design refer to it with emphasis (Akao, 1990; Ehrlenspiel, 2009; Pahl et al., 2007; Pugh, 1991; Ullman, 2003). An additional potential influnce on success, which was found from interviews with engineering managers and project leads, is the 'transient' change of product requirements over the course of a project. It was reported that issues occured, in cases where the requirements were not continuously checked and if necessary updated.

This factor is somewhat specific to the object of the study. Power companies (customer) usually hire purchasing engineers with many years of design experience in power generation products. Unlike on consumer products, the chance for significantly missing the customers needs is low. The customer's purchasing engineers know and define almost exactly what they need, which determines the product requirements of a new gas turbine. The component development team has to translate these overall requirements into product requirements for the components. Researching different projects in the engineering database showed that some projects had the requirements clearly defined in the project charters, while others didn't. For the projects that showed clear definitions, it was determined through interviews if there were any transient changes in the product requirements during the project, which were not recorded. If both the conditions - clear definition and stability of requirements - were fulfilled, the Potential Success Factor was rated High. If one of them was not fulfilled, it was rated Low. Table 5.13 shows the rating definitions for the specification and stability of product requirements.

Table 5.13: Rating definitions for 'Product Requirements clearly defined and stable during Development'

High	Product requirements clearly defined, continuously checked and updated during development project
Low	Product requirements not clearly defined, or continuously checked and updated during development project

5.2.14 Awareness of Lessons Learned and State of the Art Technology Knowledge

Poor knowledge transfer, from internal or external (competitors or the scientific community), can be found to have a negative impact on success in new product development (Knudsen, 2007; Lindemann, 2009). Many different things have oftentimes been tried out over the years within a company and valuable lessons have been learned. These might not be well documented. Especially when teams of younger engineers are in charge of projects, they might face issues which could have been prevented, if it was known what was done in the past. The same is true for knowledge about what has been done in the technical field external to the company, which can be referred to as 'State of the Art Technology'. The rating definitions are shown in Table 5.14 for this Potential Success Factors.

Table 5.14: Rating definitions for 'Awareness of Lessons Learned and State of the Art Technology Knowledge'

High	No issues occurred due to lack of awareness of lessons learned or state of the art technology knowledge
Low	Issues occured due to lack of awareness of lessons learned or state of the art technology knowledge

5.2.15 Ratio of new Technology

Unlike the Potential Success Factor 'Awareness of Lessons Learned and State of the Art Technology Knowledge', this factor measures the amount of new technology that has not been used or developed before. It is basically a measure of how much innovation is involved in the development project. Some projects require a low amount of innovation, for instance routine upgrades of existing products with plenty of operating experience. Others require the use of completely new design solutions and technologies, such as when the company wants to take a leap by developing a product with the aim to excel current competitor's products significantly. Table 5.15 shows the rating definitions for this Potential Success Factor.

Table 5.15: Rating definitions for 'Ratio of new Technology'

High	Development of product with high amount of new technology compared to other development projects executed in department
Medium	Development of product with medium amount of new technology compared to other development projects executed in department
Low	Development of product with low amount of new technology compared to other development projects executed in department

5.2.16 Technical Complexity of Project

The technical complexity is a measure for the size of the project, the amount of people involved and the interfaces that have to be considered. Complex projects can be expected to have a higher need for state of the art technology knowledge or innovation. But this does not necessarily have to be the case. A project might involve a lot of resources due to its size, but it might in its nature be more of a routine task, which has been done before and is mostly known. This does not exclude problem solving activities, e.g. finding solutions to work around geometric contrainst, but it won't require completely new technologies. For this reason, this factor needs to be measured separately from the two formerly introduced Potential Success Factors 'Awareness of Lessons Learned and State of the Art Technology Knowledge' and 'Ratio of new Technology'. In order to provide a basis for judgement, the population of component development projects in the gas turbine development department served as reference for defining what low, medium or high complexity meant. Having a reference was necessary, as otherwise interviewees would have had trouble to decide how the projects should be rated. Table 5.16 shows the definitions for the measurement of a project's complexity.

Table 5.16: Rating definitions for 'Technical Complexity of Project'

High	High technical complexity in comparison to other projects in department. High amount of: changes and developments that involve problem solving; interfaces to disciplines within and outside of component
Medium	Moderate technical complexity in comparison to other projects in department. Moderate amount of: changes and developments that involve problem solving; interfaces to disciplines within and outside of component
Low	Low technical complexity in comparison to other projects in department. Low amount of: changes and developments that involve problem solving; interfaces to disciplines within and outside of component

5.2.17 Co-Location of Team Members

A rapid increase in the use of global teams can be observed in technology firms (McDonough et al., 2001). Van den Bulte and Moenaert (1998), as well as Kahn and McDonough (1997), found evidence of improved R&D performance in their investigation of the effect of co-location. The company's engineering department in this study was distributed over six locations on three continents (Europe, North-America, Asia). Due to that, many project teams consist of core members being in different locations. The difference to the Potential Success Factor 'Cultural Influence in Team' is, that team members from different cultures can still be co-located. On the other hand, teams consisting of members from one culture could potentially be distributed over more than one location. In other words, co-location measures the geographical separation of project teams, not the composition. The rating definitions are shown in Table 5.17.

Table 5.17: Rating definitions for 'Co-Location of Team Members'

High	Core Team Members all in one location
Low	Core Team Members distributed over two or more locations

5.2.18 Empowerment of Project Lead: Project and Budget Responsibility in one Hand

Project leads in engineering are responsible for delivering a specified product at a certain time, within the allocated budget. While they always own technical responsibility for the project outcome, budget ownership might be in other hands in the company, e.g. Product Line Management or Marketing. Empowerment means that project leads have the technical responsiblity, but are also awarded with the authority to manage the development budget, without having to get permissions for any project related expenses from other institutions in the company. Ehrlenspiel (2009) considers this kind of project lead empowerment as crucial for Design Success. Table 5.18 shows the rating definitions for the Potential Success Factor 'Empowerment of Project Lead: Project and Budget Responsibility in one Hand'.

Table 5.18: Rating definitions for 'Empowerment of Project Lead: Project and Budget Responsibility in one Hand'

High	Project and budget responsibility in one hand (project lead)
Low	Project and budget responsibility in different hands

5.3 Data Collection and Validation for Potential Success Factors

The data points for the Potential Success Factors were collected from the engineering review database in the first step. The project charters and the archived review documents

provided information about: timeline, budget, resources provided, methodologies, design tools used, team sizes, location of core team members, level of process compliance and definition of product requirements. Missing information in the database was gathered from interviews with engineering managers, project leads or team members of the respective projects. Information about team members and project leads skills/experiences, project lead personalities, priorities, complexity, amount of innovation and awareness of lessons learned were directly obtained by interviewing engineering or project managers. Most of these data points were collected from single sources, due to the limited availability of the interviewees. Only a few cases, where interviewees expressed to be uncertain about a rating, required an inter-rater reliablility check. This was done by interviewing a second source with sufficient project knowledge. The ratings coincided for these few instances.
From the original 50 projects considered for investigation, 44 provided the complete set of data. For the other six projects, it was not possible to obtain all data points. The reason was insufficient documentation in the review database, or missing sources for interviews. It was decided to remove these incomplete data sets from the study and continue with the remaining 44 projects. The alternative would have been to interpolate the missing data. However, this technique bears risks (Kitchenham and Pfleeger, 2003), especially when cross-checking of dependencies among the causes is desired to be performed.

Before the actual analysis, the data matrix of the 44 projects and 18 Potential Success Factors was screened for the distribution of the data. In order to be able to identify singificant influences on Design Success, each Potential Success Factor had to show variance in the categories (Low, Medium or High) for the 44 projects. Potential Success Factor that did not show this variance had to be considered constant and were not suitable for the analysis. In order to determine when a Potential Success Factor was considered constant, a criteria was needed. As explained in the later Data Analysis Chapter, the analysis method (Kruskal-Wallis Method) used for the first analysis step requires a minimum of five data points per category. The five data points were used as the treshold. For the Potential Success Factors which were measured in three categories (Table 5.19), it was required that at least two of the categories showed more than five data points. If this condition was fulfilled, the data was used for the analysis. The second Potential Success Factor 'Conceptual Design performed' is such a case. The 44 projects showed only a low or medium level of conceptual design performed. However, both categories showed sufficient projects (low = 27, medium = 17). This data could be used to determine if there was a significant difference in impact on the succesful outcome between projects where a low versus a medium level of conceptual design was applied.
Of the Potential Success Factors measured in three categories, 'Use of Design Methodology' and 'Resources Provided / Project Stability' harmed the criterion of more than five data points in at least two categories. These had to be considered constant and their

significance could not be determined. Although these two factors were not involved in the further analysis, it was still possible to draw some conclusions.

First constant Potential Success Factor: Use of Design Methodology

Almost all of the projects showed only a low application of design methodologies. It could not be determined if this factor belonged to the Dominant Success Factors. However, it was known that this factor was not the only dominant factor. If such had been the case, there wouldn't have been variation in the success of the 44 projects as it is seen (Figure 4.2). The variance in the success data indicated that there are other (at least one)

Table 5.19: Amount of data points in each category for Potential Success Factors measured in three categories

Potential Success Factors	Low [n]	Medium [n]	High [n]
1 Use of Design Methodology?*	40	4	-
2 Conceptual Design performed?	27	17	-
3 Decision Tools utilized?	15	22	7
4 Resources Provided / Project Stability?*	1	4	39
5 Priority of Project?	9	18	17
6 Team Size?	7	27	10
7 Team Members Experience / Skills?	6	26	12
9 Experience / Skills of Project Lead?	1	20	23
11 Level of Process Compliance?	20	14	10
12 Simultaneous Development?	9	20	15
15 Ratio of new Technology?	13	14	17
16 Technical Complexity of Project?	13	13	18

*to be considered as constant

Dominant Success Factors. Although it could not be proven if it is a Dominant Success Factor, it has to be concluded that more use of design methodology could have elevated the success rate of projects, as the literature commonly suggests this positive relationship (Krause et al., 2006; Lindemann, 2009; Mehalik and Schunn, 2006; Schregenberger, 1998).

Second constant Potential Success Factor: Resources Provided / Project Stability

The fact that 39 out of 44 projects had good project stability showed that a lack of resources was not an issue in the company. In addition, it showed that upper-level and engineering management made it a priority to keep projects stable and frequent reallocation of resources low. Similar to the use of design methodology, it was not possible to determine if this factor belonged to the Dominant Success Factors. But, contrary to the

Table 5.20: Amount of data points in each category for Potential Success Factors measured in two categories

Potential Success Factors	Low / No [n]	High / Yes [n]
8 Cultural Influence in Team?	19	25
10a Project Lead Personality - Communication?	30	14
10b Project Lead Personality - Decision Making?	30	14
10c Project Lead Personality - Risk Awareness?	28	16
13 Product/Customer Requirements clearly defined and stable during Development?	13	31
14 Awareness of Lessons Learned and State of the Art Technology Knowledge?	7	37
17 Co-Location of Team Members?	7	37
18 Empowerment of Project Lead: Project and Budget Responsibility in one Hand?	7	37

first constant factor, it had to be concluded that Design Success would have likely been lower, if this factor was not constantly high.

The Potential Success Factors which were measured in two categories did not show any data cell with less than five data points (Table 5.20). The last three factors (14, 17 and 18) had each had seven projects in the Low categoy and 37 projects in the High category. This pattern suggested that these factors were directly related, meaning that the seven projects in the Low catogory represented the same projects for all three Potential Success Factors, and the 37 projects in the High category the same projects for all three Potential Success Factors, respectively. Looking at the data revealed that there was a difference in projects for these three factors (Appendix A) and the similar data points in the categories were just coincidence.

6 Data Analysis

The objective of analyzing the data quantitatively was at first to understand which of the Potential Success Factors showed a relationship to Design Success - then identified as Success Factors. Secondly, it was of interest to understand if and how the Success Factors identified depended on each other. The dependencies, if any existed, would be beneficial for determining causal relationships. These two objectives were addressed in two subsequent analysis steps using suitable statistitical techniques for each.

6.1 First Analysis Step: Search for Success Factors

The first analysis step was aimed at detecting relationships between successful product design and each of the Potential Success Factors. One statistical method for testing the dependency of multiple independent variables on a dependent variable is multiple linear regression. However, this method demands the dependent variable (in this case Design Success) be normally distributed (Garson, 2012). As Figure 4.2 shows, this is not the case for the collected data. Alternatively, a hypothesis test can be applied for each independent variable (the Potential Success Factors) against the dependent variable (Design Success). The statistical methods used for hypothesis testing are introduced in this chapter.
The Null-Hypothesis states that there is no significant difference between the sample groups of each Potential Success Factor:

- Null-Hypothesis for two sample groups: $H_0 : \mu_{Low} = \mu_{High}$
- Null-Hypothesis for three sample groups: $H_0 : \mu_{Low} = \mu_{Medium} = \mu_{High}$

The finding of a significant difference would necessarily lead to a rejection of the Null-Hypothesis. This case would mean that there was enough evidence in the data to believe, that what was seen can be repeated on a different sample from the same population, although with a certain chance of error. The significance level as a criteria, and the related chance for error, is provided by methods of inferential statistics. Using methods of inferential statistics demands caution when it comes to types and distribution of the data.

6.1.1 ANOVA for Hypothesis Test

It was intended to perform the hypothesis test using the ANOVA (ANalysis Of VAriance) method. The ANOVA is a technique, particularly friendly to experimental data, for comparing the means of two or more sample groups (Sirkin, 2006). The sample groups are the categories (Low, Medium or High) for each Potential Success Factor, where the means for each group results from the independent variable, the rating of success. Due to the evaluation of one independent variable, this test is also referred to as the One-Way ANOVA. Using the ANOVA, the goal would be to understand if there were a significant difference between the sample groups, considering the means and their variances. The measure of significance is the p-value (from probability value). The p-value is a dimensionless factor in the range of 0 to 1. It represents the probability that a difference in sample groups is due to chance. The p-value can be derived if the F distribution - which results from the F ratio - is known. The F ratio is determined by the variance within the sample groups in relation to their degrees of freedom, and the variance between the sample and their degrees of freedom. The variances can be expressed by the sum of squares, where the total sum of squares (SS_{total}) is the sum of squares within (SS_{within}) the sample groups and the sum of squares between ($SS_{between}$) the sample groups:

$$SS_{total} = SS_{within} + SS_{between} \tag{6.1}$$

Assuming k sample groups and n data points within each sample group, SS_{within} can be written as

$$SS_{within} = \sum_{i=1}^{k} \sum_{j=1}^{n} (y_{ij} - \bar{y}_i)^2 \tag{6.2}$$

with y_{ij} being any of the n data points in any of the k sample groups, and $\bar{y}_i$ being the mean of each of the k sample groups. Knowing the overall mean of all sample points $\bar{y}$, $SS_{between}$ can be written as

$$SS_{between} = \sum_{i=1}^{k} n(\bar{y}_i - \bar{y})^2 \tag{6.3}$$

which leads to

$$SS_{total} = \sum_{i=1}^{k}\sum_{j=1}^{n}(y_{ij} - \bar{y}_i)^2 + \sum_{i=1}^{k} n(\bar{y}_i - \bar{y})^2. \tag{6.4}$$

With 6.2 and 6.3 and the degrees of freedom (df) for SS_{within} and $SS_{between}$

$$df_{within} = n - k \tag{6.5}$$

and

$$df_{between} = k - 1 \tag{6.6}$$

the variances can be expressed as the mean of squares within the groups

$$MS_{within} = \frac{SS_{within}}{df_{within}} \tag{6.7}$$

and the mean of squares between the groups

$$MS_{between} = \frac{SS_{between}}{df_{between}}. \tag{6.8}$$

The F ratio results as

$$F = \frac{MS_{between}}{MS_{within}}. \tag{6.9}$$

The F distribution is a non-symmetric, right skewed curve. Its shape depends on the degrees of freedom $df_{between}$ and df_{within}. The total area under the curve is always 1. Looking at 6.9, it becomes obvious that the significance in difference between sample groups increases with an increasing $MS_{between}$ and a decreasing MS_{within}. Hence, larger F ratios signify a higher probability that the sample groups do not come from the same population and a higher likelihood that the Null-Hypothesis has to be rejected. At what point it has to be rejected, depends on the chosen α-level. The α-level is the remaining chance for error. If the F ratio lies within the α-level (grey area under the curve in

Figure 6.1), the Null-Hypothesis has to be rejected. Every value of the F ratio has a p-value associated with it. The p-value stands for the probability of chance in the data and can directly be evaluated against the chosen α-level. In case the p-value is smaller than the α-level, the Null-Hypothesis has to be rejected. Figure 6.1 shows an example of a F distribution for α=0.05, with the critical value for the F ratio and the associated p-value for $df_{between}$=2 and df_{within}=12. In this case a F ratio of less than 3.89 would suggest that the sample groups come from the same population and that the data had to be considered random. On the other hand, for a F ratio of larger than this value, a significant difference in the sample groups would be the conclusion, as the probability of chance was less than the chosen significance level.
It is common practice in scientific studies to regard differences in sample groups as significant, if the p-value is < 0.05. This would mean that the chance of error is less than 5%. Or, in other words, one would have a 95% confidence to reject the Null-Hypothesis and would only expect a different result in one out of 20 tests, if repeatedly testing different samples from the same population. The significance level might be chosen more (e.g. 0.01) or less (e.g. 0.1) stringently, which is dependent on the sensitivity and potential impact of the results. For empirical studies in the medical or pharmaceutical area, significant levels that are usually chosen are more conservative (smaller), as severe harm could result from a wrongly rejected Null-Hypothesis. In this research, a significance level of equal or smaller than 0.1 was chosen. The reasons for this limit are elaborated during the discussion of the analysis results.

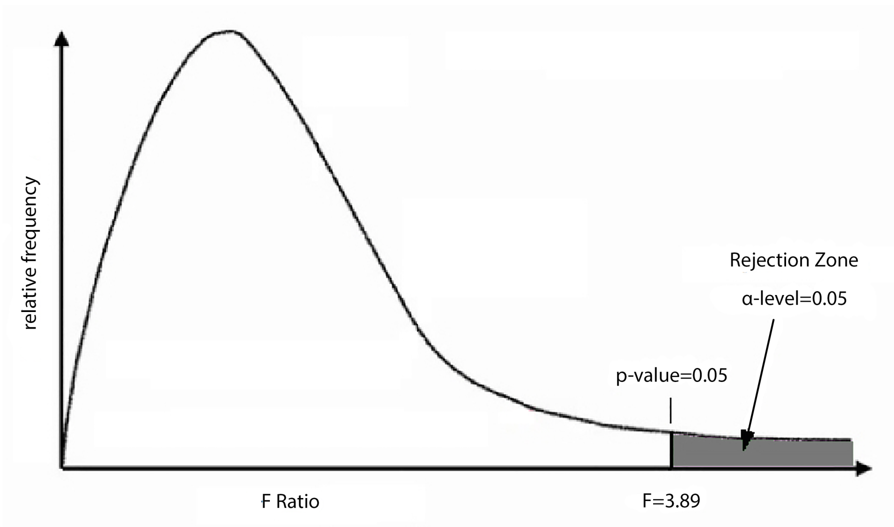

Figure 6.1: Example of F distribution with α-level = 0.05

Since the ANOVA technique is based on mean values and their relative variances, the sample groups must show normal distribution in their data, with similar variances. Due to this underlying requirement, the ANOVA belongs to the parametric tests. Before the ANOVA could be applied to the data, it needed to be verified if the data fulfilled the conditions of normal distribution and similar variances. If this was not the case, the ANOVA could not be used and a non-parametric alternative method had to be found instead.

6.1.2 Testing for Normal Distribution

Different methods are available for the verification if data points in the sample groups are normally distributed. A box plot is a descriptive graph that provides a visual illustration of the distribution patterns, showing the four quartiles of each group. Figure 6.2 illustrates a box plot for the three sample groups (Low, Medium and High) of the Potential Success Factor 'Simultaneous Development', which measures the degree of concurrent design and manufacturing activities. The horizontal line in each grey box represents the median, which should be similar (or close to similar) to the mean value, if the data were normally distributed. The grey rectangles below and above the mean, and the vertical lines below and above the box, represent each a quartile, which is a quarter of the sample group's data points. By looking at the shape of the boxes, it can already be detected if the data sample groups have similar variances. If groups had similar variances, the boxes should be of similar size. In addition, if the data was normally distributed, the horizontal line in the grey box should be approximately centered in the box. In the case of 'Simultaneous Development', it was clear that this is not the case. From looking at the distribution of the sample population (Figure 4.2), one would have already expected that not all sample groups showed similar distribution patterns.

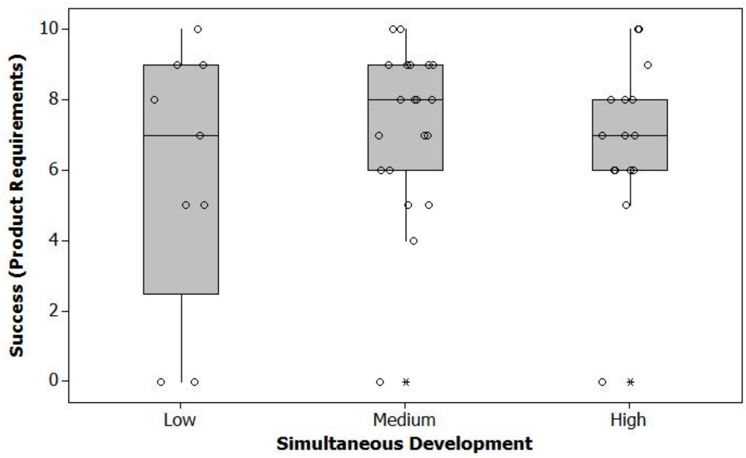

Figure 6.2: Box plot for verification if data is normally distributed

As can be concluded from Figure 6.2, the parametric ANOVA method could not be used for the first analysis step. Instead, a non-parametric method was required for determining the significance of relationships between the Potential Success Factors and Design Success. The Kruskal-Wallis method was found as an alternative to the ANOVA.

6.1.3 The Kruskal-Wallis Method as alternative for ANOVA

The Kruskal-Wallis Method is a non-parametric analog to the parametric One-Way ANOVA analysis, which can be used for two or more sample groups (Kruskal and Wallis, 1952). Instead of the means, it is based on the ranks of the data. Using ranks instead of means has advantages, which make this method very useful for research problems, especially common in the social and behavioral sciences. It is suitable for data measured on an ordinal scale and it allows for sample groups of different sizes, with a required minimum of five data points in a sample group. Most importantly, it does not assume that the population or the sample groups are normally distributed. Rather it makes no or only a very general assumption about the distribution of the data (Chan and Walmsley, 1997). This was a helpful attribute in the case of this research, as it has been shown in 6.1.2 that the collected data cannot be considered normally distributed for all sample groups.

While the ANOVA is based on the F statistic, determined from the means, the Kruskal-Wallis Method is based on the H statistic, determined from the ranks. The concept, however, is the same. If the H value exceeds a certain critical value (similar to the F ratio in the ANOVA as shown in Figure 6.1), the Null Hypothesis is to be rejected. The higher the value for H, the more likely it is that the sample groups, or at least one of them, come from different populations. The H statistic is defined as:

$$H = \frac{12}{N(N+1)} \sum_{i=1}^{k} \frac{R_i^2}{n_i} - 3(N+1). \tag{6.10}$$

A different formulation of 6.10 is

$$H = \frac{\sum_{i=1}^{k} n_i(\bar{R}_i - \bar{R})^2}{\frac{N(N+1)}{12}} \tag{6.11}$$

where

k = the number of sample groups

n_i = the number of data points in the ith sample group

$N = \sum n_i$ the number of observations in all samples combined

$\bar{R}_i$ = the mean of the sum of the ranks in the ith sample group

$\bar{R}$ = the mean of the sum of the ranks of N.

This Formulation (6.11) illustrates the analogy of the Kruskal-Wallis Method to the One-Way ANOVA. Just as in the F ratio (6.9), the expression in the numerator is the sum of squares between the sample groups. The only difference is that the One-Way ANOVA uses the means while the Kruskal-Wallis Method uses the ranks of the data. The denominator is expressed by the mean of the N ranks, which is $\frac{N(N+1)}{12}$.
The distribution of H is a close approximation of the Chi-Square distribution for $df = k-1$, which is especially true for sample sizes of at least five in each group (Kruskal and Wallis, 1952). Figure 6.3 shows a Chi-Square (χ^2) distribution for a sample data with two degrees of freedom ($df = 2$). Similar to the F ratio, the higher the value of H (χ^2), the more likely it falls within the chosen α-level and the Null Hypothesis has to be rejected.

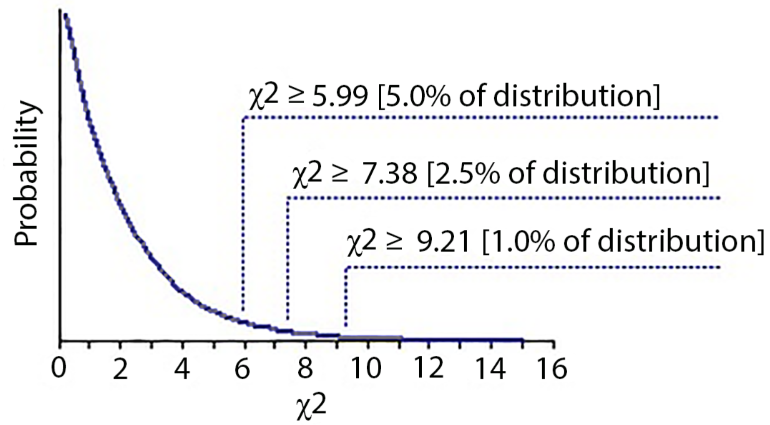

Figure 6.3: Chi-Square distribution for $df = 2$

6.1.4 Results of the First Analysis Step

The results of the analysis for relationships between the Potential Success Factors and Design Success are shown in Table 6.1 for the Potential Success Factors measured in three groups. Table 6.2 shows the results for the Potential Success Factors measured in two groups.

Potential Success Factors measured in three groups

The second, third and fourth column in Table 6.1 show the means of the success measurement for the three categories - Low, Medium and High. The two factors identified as constant were excluded from the analysis. Although the probabilities were determined with the H statistic from the ranks, the mean values are shown here, as they help to illustrate the trends better. As can be seen in Table 5.19, there is obvious variation in the sample sizes of the different groups. It was important that the analysis method provided robustness against varying group sizes, which is what made the Kruskal-Wallis Method

suitable for the kind of data collected in this study. The fifth column shows the p-value for each Potential Success Factor.
Assuming a α-level = 0.1, there are five factors which show a significant result and allow for rejection of the Null-Hypothesis. These factors are:

- **Conceptual Design performed**
- **Priority of Project**
- **Experience / Skills of Project Lead**
- **Ratio of new Technology**
- **Technical Complexity of Project**

The limit of equal or smaller of 0.1 was chosen because of the gap to the next higher p-value of 0.36. The data showed quite a leap between the five factors having a p-value equal or smaller of 0.1 and the other factors. This pattern was seen as justification for chosing this limit. Although not as stringent, it still means that out of ten different samples drawn from the same population, nine can be expected to show a similar result.

Whenever the Kruskall-Wallis Test indicates significance, it means that at least one out of the three groups is significantly different than and not from the same population as the other groups. It does not tell which of the groups is significantly different. In a worst case scenario, the Medium group would be significantly different, but the Low and High group would be on a similar level. Such a scenario wouldn't allow for the conclusion of either a positive or negative relationship between the Potential Success Factor and the success of the design project. What is of interest is a significantly increasing or decreasing trend over the three groups, respectively.
The box plot of the Success Factor 'Conceptual Design performed' is shown in Figure 6.4. As only data for two groups existed (Low and Medium) for this factor, the significance is unambiguous. The data shows that there is an inverse relationship between conceptual design and Design Success. It is shown in section 6.3 that this unexpected result can be rationalized with help of the second analysis step. Figure 6.5 shows the box plot of the determined Success Factor 'Priority of Project', measured against the Design Success. The increasing trend of the three groups is obvious. As the projects get higher priorities by engineering management, the output becomes better. It can be noticed that the Low group shows a high variance, which is due to the projects ranked with zero success (projects terminated before completion). Since the analysis method is rank based, this gap in the data distribution does not matter. After all, it could have been decided to rate terminated projects with a three instead of a zero. Due to the conversion to ranks, the resulting p-value would still be the same, but the variance in the graph would be lower,

Table 6.1: Significance of Potential Success Factors measured in three groups

Potential Success Factors	Low [$\bar{y}_i$]	Medium [$\bar{y}_i$]	High [$\bar{y}_i$]	p-value
1 Use of Design Methodology?		constant		-
2 Conceptual Design performed?	7.4	5.9	-	**0.1**
3 Decision Tools utilized?	7.1	6.8	6.1	0.65
4 Resources Provided / Project Stability?		constant		-
5 Priority of Project?	4.9	6.7	8	**0.01**
6 Team Size?	8.1	6.7	6.1	0.36
7 Team Members Experience / Skills?	7.2	6.3	7.8	0.51
9 Experience / Skills of Project Lead?	5	6.1	7.5	**0.04**
11 Level of Process Compliance?	6.8	6.5	7.4	0.63
12 Simultaneous Development?	5.9	7.2	6.9	0.72
15 Ratio of new Technology?	7.6	7.5	5.6	**0.09**
16 Technical Complexity of Project?	7.5	7.9	5.5	**0.02**

more similar to the Medium and High group.

The graphical illustration of the found Success Factor 'Experience / Skills of Project Lead' against the success, is shown in Figure 6.6. The Low group consists of only one data point and can be neglected. The reason for only one data point is specific to the product of this study. Gas turbines are technically sophisticated, high cost products, which are being built and sold in low volumes. Design errors can lead to most serious safety issues in power plants and enormeous economic damage to the company or the customer. These circumstances promote the 'habit' of putting generally experienced engineers into project lead positions. The Medium and High groups consisted of similar amounts of data points. The graph shows clearly the higher success rates of projects which have highly experienced and skilled project leads.

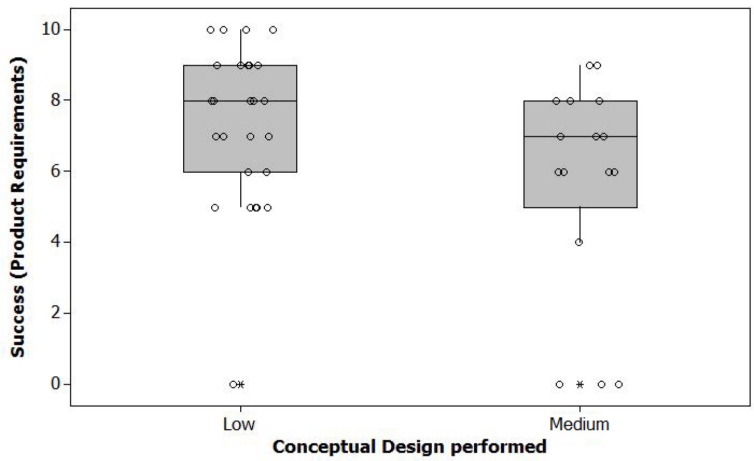

Figure 6.4: Impact of conceptual design on Design Success

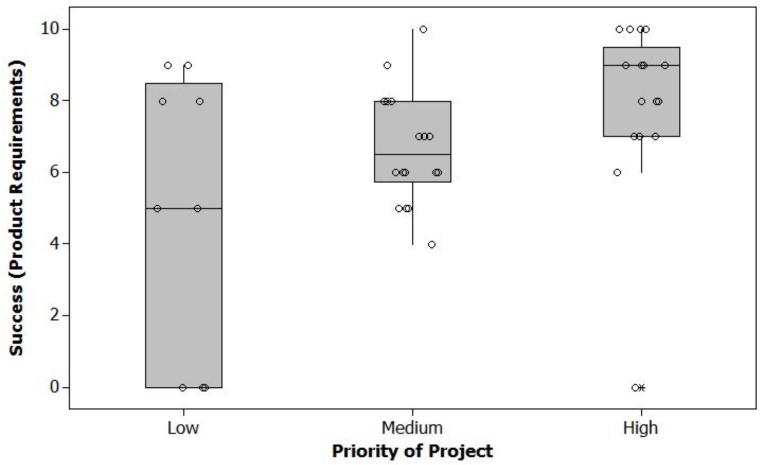

Figure 6.5: Impact of priority for engineering management on Design Success

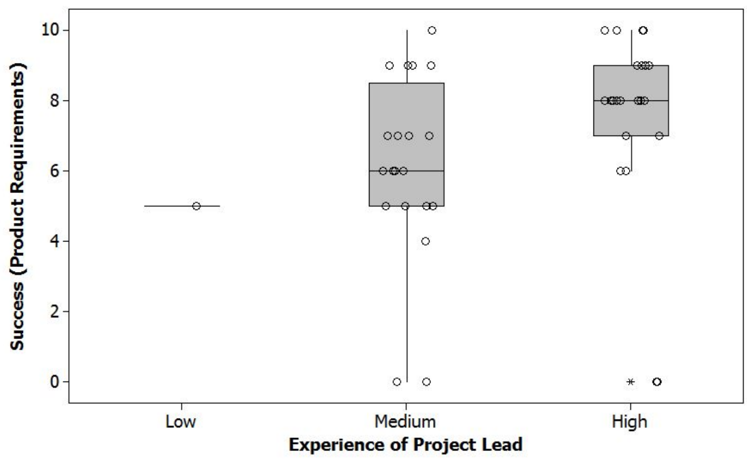

Figure 6.6: Impact of project lead's experience and skills on Design Success

Figure 6.7 shows the box plot for the Success Factor 'Ratio of new Technology', which basically measured the degree of innovation. The box plot of the fifth Success Factor in the three group category - the technical complexity of the project - is shown in Figure 6.8. It can be seen that for both these Success Factors, the Low and Medium categories were on about the same level. The High category was ranked significantly lower. Although the two graphs don't show a steadily decreasing relationship over the three groups, this factor was regarded as significant, as the High group was significantly lower (two success scale points in the mean) than the other two groups. The Low and Medium groups were treated as one group being evaluated against the High group. With these two Success Factors having similar patterns, it was expected that a dependency existed between them. The second analysis step would provide the verification for this assumption.

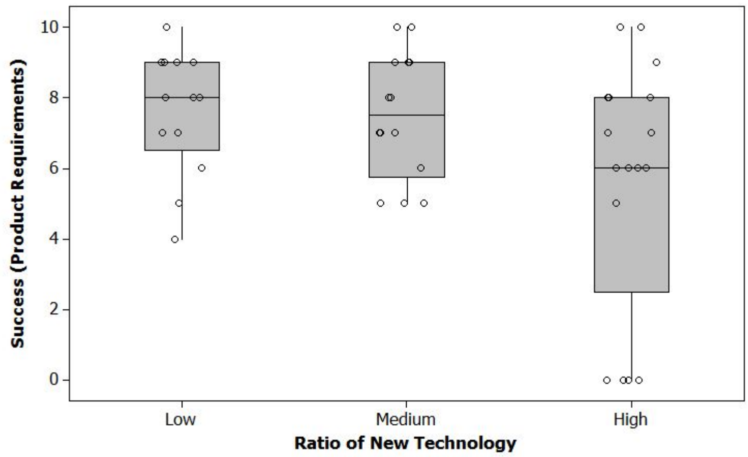

Figure 6.7: Impact of new technology on Design Success

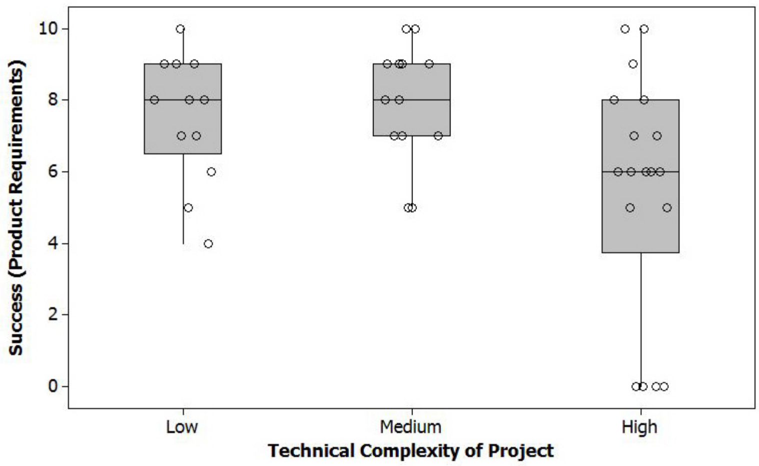

Figure 6.8: Impact of project's complexity on Design Success

Potential Success Factors measured in two groups

The second and the third columns of Table 6.2 illustrate the Low versus the High group. For the Potential Success Factors answered with Yes or No, No is referred to in the Low column, Yes is referred to in the High column. The p-value is shown in the fourth column.

Table 6.2: Significance of Potential Success Factors measured in two groups

Potential Success Factors	Low / No [$\bar{y}_i$]	High / Yes [$\bar{y}_i$]	p-value
8 Cultural Influence in Team (No Team Members from one culture, Yes Team Members from more than one culture)?	7.7	6.1	**0.08**
10a Project Lead Personality - Communication?	6.6	7.2	0.48
10b Project Lead Personality - Decision Making?	6.5	7.5	0.53
10c Project Lead Personality - Risk Awareness?	6.7	7	0.6
13 Product/Customer Requirements clearly defined and stable during Development?	6.8	6.8	0.95
14 Awareness of Lessons Learned and State of the Art Technology Knowledge?	2.4	7.6	**0.01**
17 Co-Location of Team Members (No TMs in different locations, Yes TMs in same location)?	5.3	7.1	**0.03**
18 Empowerment of Project Lead: Project and Budget Responsibility in one Hand?	6.9	6.8	0.52

Three Success Factors - with p-values equal to or smaller than 0.1 - were identified for the Potential Success Factors measured in two groups, which are:

- **Cultural influence in Team**

- **Awareness of Lessons Learned and State of the Art Technology Knowledge**

- **Co-Location of Team Members**

The box plot of the Success Factor 'Cultural Influence in Team' is shwon in Figure 6.9. The analysis of this factor compares the performance of teams with members from one culture against the performance of teams with members from different cultures. The result suggested an inverse relationship, meaning that teams with members from the same culture performed better. Again, the second analysis step was needed to verify and correctly interpret this finding. Figure 6.10 shows the box plot of the determined Success Factor 'Awareness of Lessons Learned and State of the Art Technology Knowledge'. Figure 6.11 shows the box plot of the third determined Success Factor 'Co-Location of Team Members'. It can be seen in Table 5.20 that the sample groups for the awareness of lessons learned and the co-location factor had quite varying sample sizes. For these, the robustness of the analysis method was tested by drawing 7 data points randomly from the 37 data points in the High/Yes group. Comparing the reduced High/Yes sample group to the Low/No group showed a similar significance. This test was repeated three times with similar results, which proved that the Kruskal Wallis Method was indeed robust against varying sample sizes.
As with the Success Factors found from the Potential Success Factors measured in three groups, the question about the causality and dependency of other Success Factors remained. Knowing these helped to provide answers on how design teams can improve their performance, especially in an international environment. Analyzing dependencies between Success Factors, required a different statistical method for hypothesis testing, as the data of these factors was of nominal nature. As discussed in section 6.2, the Chi-Square Test was found to be suitable for this second analysis step.

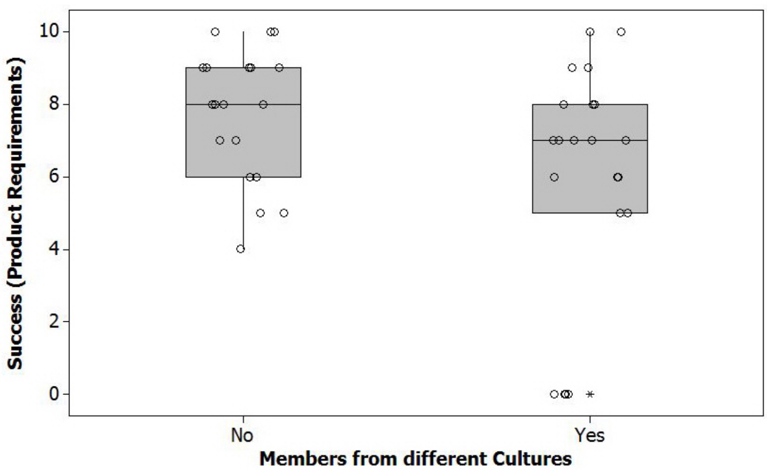

Figure 6.9: Cultural influence on Design Success

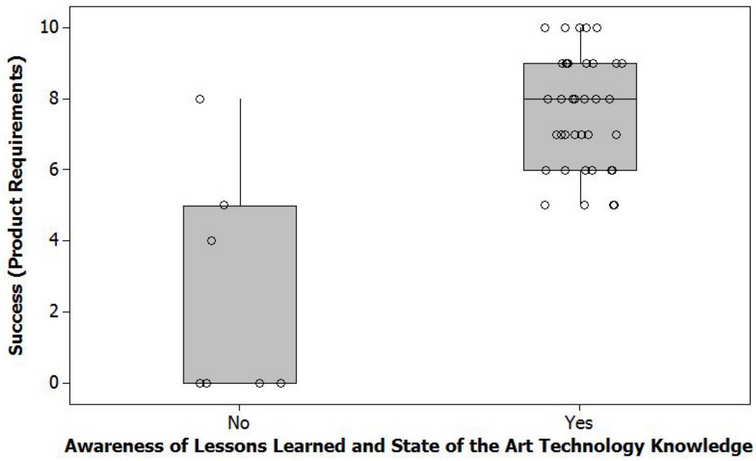

Figure 6.10: Impact of lessons learned and technology knowledge on Design Success

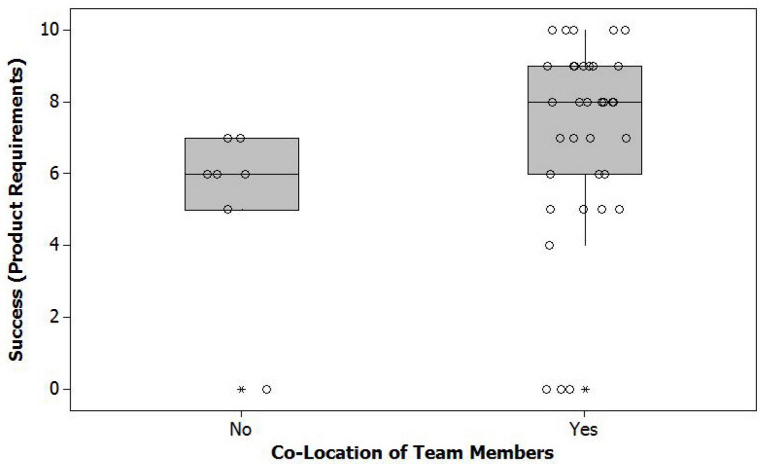

Figure 6.11: Impact of co-location on Design Success

Success Factors after first analysis step

In total, eight Success Factors with a significant relationship to successful product design were determined in the first analysis step. Figure 6.12 shows the relationships graphically. The plus and minus signs indicate the nature of the correlation, which can be verified from the medians in the box plots or the means in Table 6.1 and Table 6.2. For the factors indicated with pluses, an increase in such lead to an increase in Design Success. For the other four, indicated by minus signs, the correlations worked in the opposite direction.

After knowing the eight Success Factors, some questions remained when it came to defining measures for engineering management for better prediction of Design Success. For instance, which Success Factors can be considered independently and which have to be viewed in the context of others? Are there Success Factors which cause others to change, but are not caused by other Success Factors to change? This nature of dependency is referred to as the direction of causality. If in the end, out of the eight Success Factors found in analysis step one, the ones were identified, which not only impacted the outcome of a design project, but also influenced other Success Factors to change, they had to be considered the Dominant Success Factors. Only the results of the first analysis step and the results of the second analysis step combined, provided the necessary information to make this distinction.

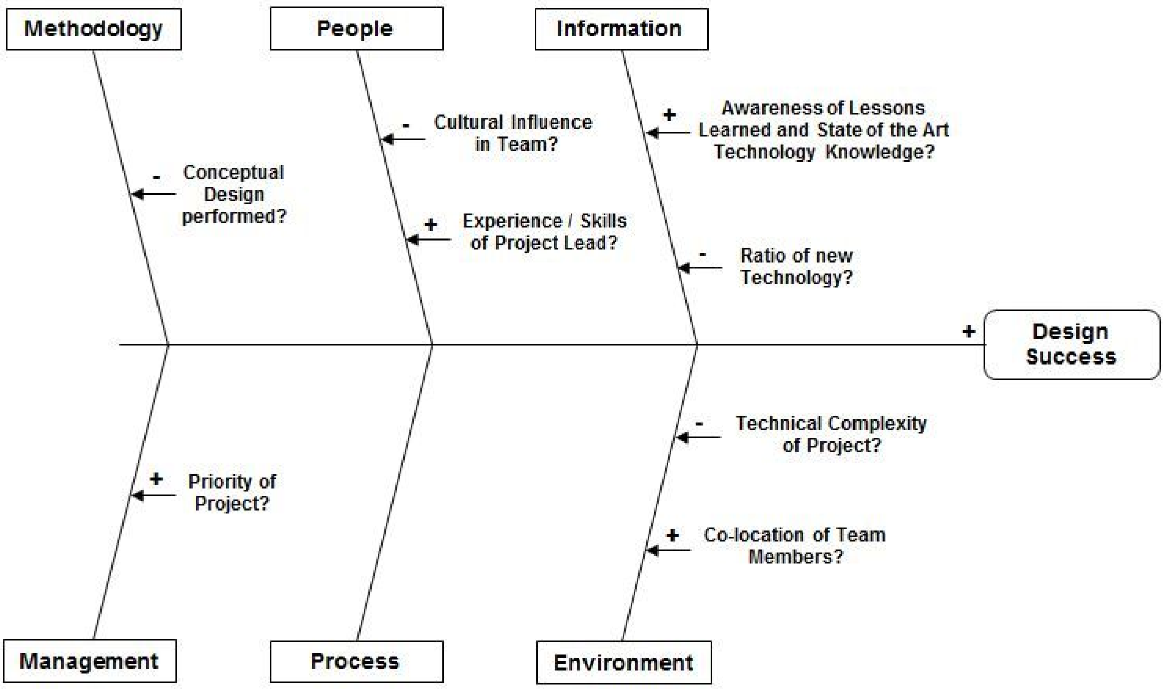

Figure 6.12: The eight Success Factor determined in the first analysis step

6.2 Second Analysis Step: Search for Dependencies

The first analysis step revealed the eight Success Factors (Figure 6.12), which showed a significant impact on Design Success. The findings suggest that these influencing factors should get special attention during the set-up and execution of development projects. However, the results of analysis step one did not give any indication of whether these Success Factors were dependent on each other. Knowing dependencies, if any existed, could provide more information and allow conclusions to be drawn about causal relationships. For instance, a dependency check on the Success Factors 'Priority of Project' and 'Experience / Skills of Project Lead' could lead to two scenarios, which would allow for different conclusions. In the first scenario, the dependency check wouldn't show any significance. The conclusion would be that management could have increased the chance

for success, by selecting more highly experienced and skilled project leads for their highest priority projects. The second scenario could be, that a dependency existed between the two Success Factors. This would be an indication for a causal relationship between the factors. The question would then be, in which direction the causality pointed. In the case of this example, it would be obvious that the priority was the causal root, as management determines the priority of projects and also selects the project leads. The elaboration of causalities and their possible explanations are part of the result interpretation in section 6.3. The Potential Success Factors that did not show significance in analysis step one were not considered for further analysis. It was excluded that any of these were dependent on any of the eight Success Factors, as otherwise a relationship to Design Success would have been seen in the first analysis step.
The input for the second analysis step were the eight Success Factors, which were quantified in either three ordinal or two categorial groups. Alternatively, these data types can be considered as categorial, with three or two groups respectively. A suitable method for determining dependencies between factors measured in categories is the Chi-Square Test (Pyzdek and Keller, 2009). This test is one of the most basic and versatile statistical tests. The concept of the test is to compare expected counts against observed counts. The Chi-Square (χ^2) Test, also known as Pearson's Chi-Square Test, is defined as:

$$\chi^2 = \sum_{i=1}^{n} \frac{(O_i - E_i)^2}{E_i} \tag{6.12}$$

where

n = number of compared groups

O_i = observed count for each compared group

E_i = expected count for each compared group

Similar to the H statistic, the p-value can be determined by comparing the calculated value to the χ^2-distribution with the respective degrees of freedom $df = n - 1$.
The comparison matrix in Figure 6.13 shows the p-values for the dependencies between the eight Success Factors found from the Chi-Square Test in analysis step two. Significant dependencies are indicated by the bold font. As in the first analysis step, a p-value equal to or smaller than 0.1 was used as significance limit. A guideline for reliable results of the Chi-Square Test is that "No more than 20% of the expected counts are less than 5 and all individual expected counts are 1 or greater" (Yates et al., 1999, p.734). The p-values marked with an asterix do not comply with this guideline, which is why caution was required in interpreting these. Looking at the distributions of the observed counts for

	Conceptual Design performed	Priority of Project	Experience / Skills of Project Lead	Ratio of new Technology	Technical Complexity of Project	Cultural Influence in Team	Awareness of LL / State of the Art Technology	Co-Location of Team Members
Conceptual Design performed		0.25	0.72*	0.12	0.19	0.14	**0.05***	**0.05***
Priority of Project			0.2*	0.36	0.19*	0.6	0.19*	0.15*
Experience / Skills of Project Lead				0.43*	0.38*	0.6*	0.75*	0.75*
Ratio of new/ unknown Technology					**0.01**	**0.04**	0.27*	**0.05***
Technical Complexity of Project						**0.02**	0.34*	**0.07***
Cultural Influence in Team							0.4*	**0.09***
Awareness of Lessons Learned/ State of the Art Technology								0.89*
Co-Location of Team Members								

*reliability of Chi-Square Test not guaranteed

Figure 6.13: P-values for dependencies between Success Factors

each pair helped to verify if a significant dependency really existed. Figure 6.14 shows an example of a table of observed counts for the Chi-Square Test between the Success Factors 'Conceptual Design performed' and 'Co-location of Team Members'. It can be seen that the project teams, which utilized a low level of conceptual design, were almost all co-located. This ratio changed however, for the projects with a medium level of conceptual design. Significantly less of these project teams were co-located compared to the total of the category. Knowing these patterns provided the information to determine the direction of causalities for all Success Factors that showed dependencies. In this example, it can be concluded that the direction of causality went from co-location to conceptual design, meaning that a less in co-location lead to a more in conceptual design. This would make sense. After all, co-location was the factor established before the design work was started. Obviously, it would mean that co-location caused the effect of a different behaviour in terms of the use of conceptual design. Before that final conclusion could be drawn, the question had to be answered if co-location by itself was a real cause, or if it was caused by another Success Factor to change. It did not seem logical that the co-location was the root cause factor that would influence the use of conceptual design. The step by step interpretation of the dependencies, described in the following, established this full picture, which eventually lead to the Dominant Success Factors. The tables of observed counts for each pair of Success Factors are shown in Appendix B.

		Co-location of Team Members	
		No	Yes
Conceptual Design performed	Low	2	25
	Medium	5	12

Figure 6.14: Example of observed counts for Chi-Square Test

6.3 Interpretation of Results

With the Success Factors and their dependencies known, it was possible to map the causalities. A dependency map was created step by step, interpreting each Success Factor and its direct dependencies, and connecting them subsequently.

Conceptual Design performed

The first Success Factor showed a significant dependency to 'Awareness of Lessons Learned and State of the Art Technology Knowledge' and 'Co-location of Team Members'. These three factors were mapped, as shown in Figure 6.15. The nature of the dependencies were verified from the tables of the observed counts and are indicated by the plus and minus signs in the dependency map. It can be seen that an increase in the awareness of lessons learned and an increase in co-location had the inverse effect of lowering the level of conceptual design applied. The direction of causality is indicated by the direction of the arrow head. As mentioned above, it was not known at this moment if co-location was the root cause for a different level of conceptual design. It had to be assumed at that point, that co-location itself was caused to change by another, more dominant factor, which is why no arrow heads are drawn yet. The relation between conceptual design and

the awareness of lessons learned was inverse in nature as well. It was concluded that the latter is the cause which lead to a change in level of conceptual design. A reasonable explanation is, that the projects where technology knowledge was high, were more of routine tasks and the teams apparently felt less need for the use of methods.
After the first step of mapping, it became obvious that 'Conceptual Design performed' was not a Dominant Success Factor, because it was caused by other Success Factors to change, indicated by an arrow pointing towards it or being connected to another Success Factor with a line without an arrow head.

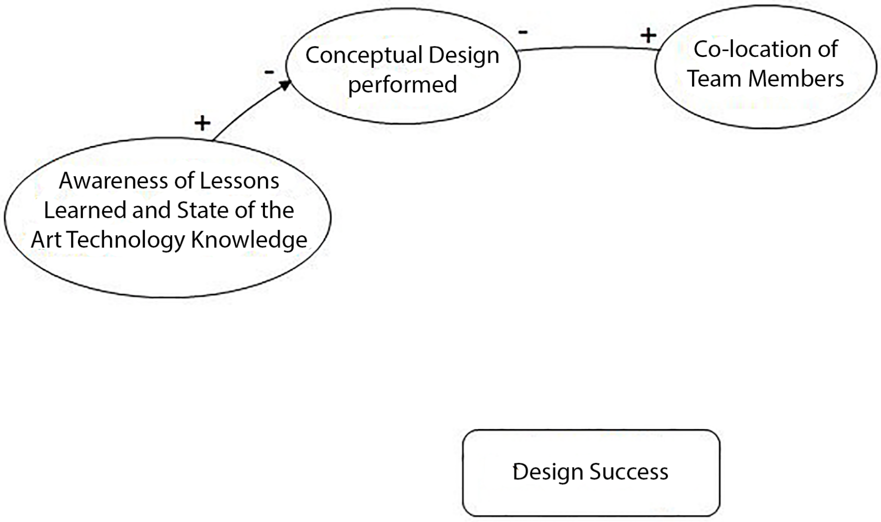

Figure 6.15: Dependency map, first step

Priority of Project

This Success Factor did not show any significant dependency to any other Success Factor. It had to be considered independent, which was a surprising finding. One would have assumed that the priority which management gives to projects, would be related to their complexity and the amount of new technology. However, it was not found to be the case, which can be seen as an indication that too many development projects were in the engineering pipeline. The apparent effect was that engineering management was not able to give the highly complex and innovative projects the priority, which they likely needed for better success. In most of the observed cases, highly complex and innovative projects were completed successfully, whenever the management priority was high. As this Success Factor had no dependencies to other Success Factors, it was not caused by any of these to change. This means that it directly influenced Design Success as determined in analysis step one and can be considered as Dominant Success Factor. The relationship to Design Success was mapped as shown in Figure 6.16.

Experience / Skills of Project Lead

Similar to the management priority of the project, this Success Factor did not show any significant dependency on other Success Factors. Again, one would have expected that a significant dependency existed with highly complex and innovative projects. But apparently not all of these projects had a highly experienced and skilled project lead.
As with 'Priority of Project', for most projects which were lead by a highly experienced and skilled project lead, even high complexity and innovative content did not prevent them from being successful. Looking at the data matrix in Appendix A, it can be seen that there were projects with a high ratio of new technology and a high complexity that were completed with high success. What these had in common was that the management priority and experience of the project lead were high. At most, one of the two Success Factors was at a medium level. Lower success resulted, whenever none of the two Success Factors was high, or when one of the two Success Factors was low. The projects on the lower end of the success scale apparently suffered from this mismatch. It likely means that the engineering department exceeded its capacity limit, which would have been the point where it could give all its highly complex and innovative projects a high management priority and a highly experienced project lead. At least one of the two factors had to be high, the other medium. At the point where this condition cannot be met anymore, due to a lack of experienced and skilled project leads or focus on priority, management should be aware that the chance for success is greatly reduced. Since no other dependencies existed, 'Experience / Skills of Project Lead' was mapped to Design Success (Figure 6.16) and considered a Dominant Success Factor.

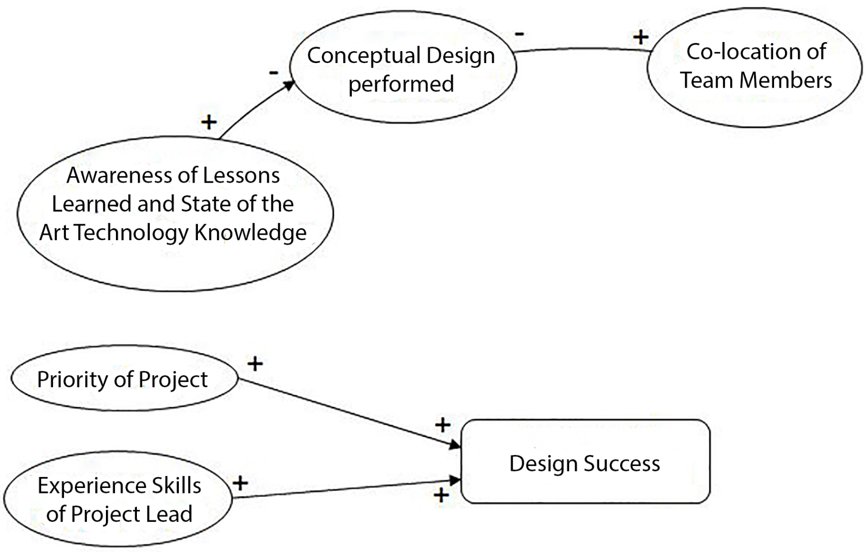

Figure 6.16: Dependency map, second step

Ratio of new Technology and Technical Complexity of Project

A very strong dependency existed between these two Success Factors. As can be seen in the data matrix in Appendix A, the two Success Factors had identical categories in almost all of the projects, which means that complex development projects had a high level of innovation as well. It suggested to combine the two Success Factors into one, as dependencies to other Success Factors were expected to be similar. The p-values in Figure 6.13 confirm that both Success Factors had similar dependencies and shared the same significant dependencies, which were to 'Cultural Influence in Team' and 'Co-location of Team Members'. The dependency between the combined Success Factor and the cultural influence changed in similar direction. Projects with lower innovation and complexity had lower cultural influence. This can be explained by the circumstance that as projects get more complex, more resources are required, which results in project teams distributed more globally. Technical complexity and innovation was the dominant factor which caused a more in cultural influence. Since more complex projects had a lower chance for success, the factor of cultural influence related to lower success rates as well. Equally, this causal relationship existed between the complexity and the co-location factor. Lesser complexity lead to more co-location. Converesly, more complexity lead to project teams which were less co-located and distributed over the the different global engineering locations.

Figure 6.17 shows the Success Factors added in this third mapping step together with their dependent factors. Since the combined Success Factor - measuring the technical complexity and the level of innovation - did only cause other Success Factors to change, but was not caused by other factors to change, it was mapped directly to Design Success

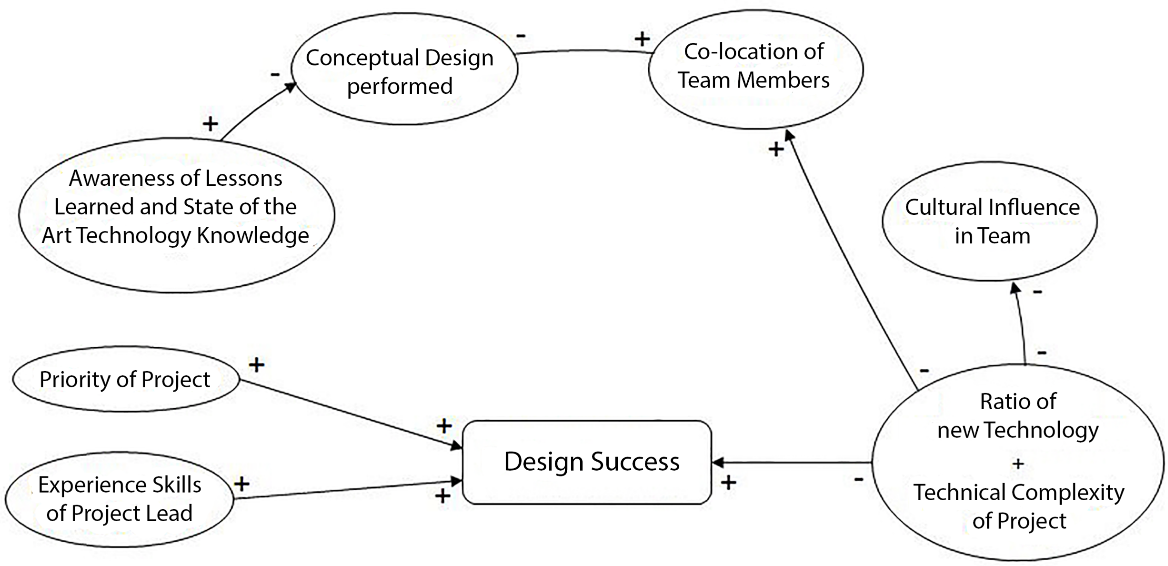

Figure 6.17: Dependency map, third step

and was identified as a Dominant Success Factor.

Cultural Influence in Team

Interpreting the dependency to the combined factor of innovation and complexity revealed, that the negative impact of cultural influence on Design Success was a symptom, that was triggered by higher complexity. This could be proven by looking at projects of similar complexity, where it was seen that cultural influence had no influence on the project outcome. The similar but inverse dependency of the co-location to the complexity factor, explains why cultural influence and co-location showed a singificant inverse dependency as well. However, none of the two caused the other to change, as both were caused to change by the combined and dominat factor of complexity and innovation. Since no causal relationship existed, no arrow heads are shown between cultural influence and co-location in Figure 6.18.

Awareness of Lessons Learned and State of the Art Technology Knowledge

Only one dependency to conceptual design existed. Since no other dependency existed and the awareness of lessons learned was determined to cause a change in the amount of conceptual design applied, it meant that it had to be considered a Dominant Success Factor. Figure 6.18 shows the added dependency to Design Success.

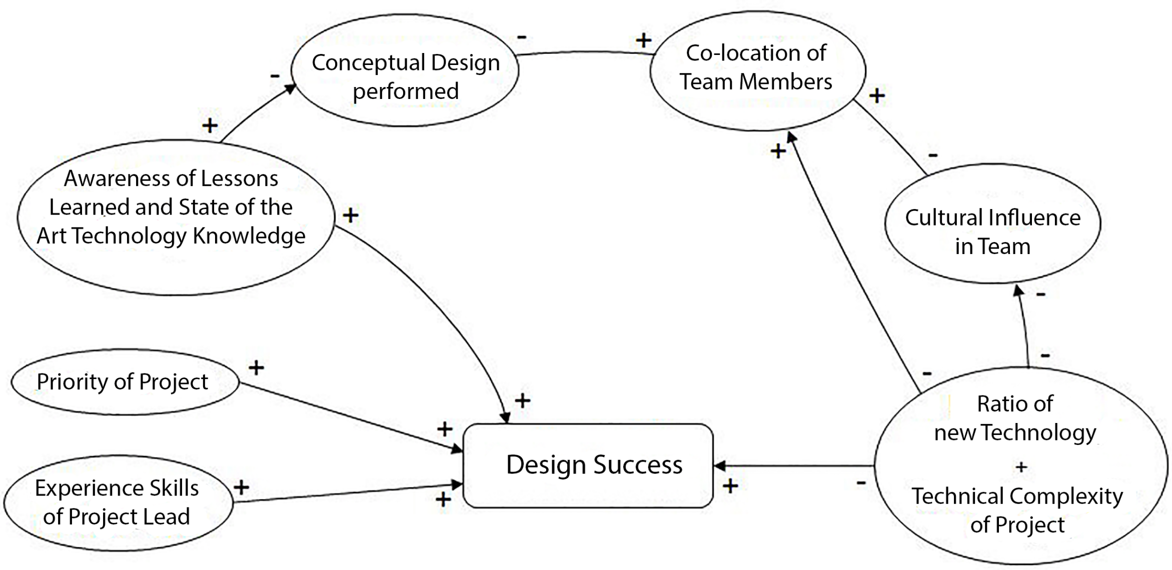

Figure 6.18: Dependency map, fourth step

Figure 6.18 still contains an inconsistency with respect to the Success Factor 'Conceptual Design performed'. The factor did not show a significant dependency to the

dominant innovation and technical complexity factor. However, this dependency must exist, as the co-location factor, which changed similar to conceptual design, was caused to change by this dominant factor. Looking at the Chi-Square Matrix in Figure 6.13, it can be seen that the dependency between conceptual design and innovation (ratio of new technology) had a significance of $p = 0.12$, which is just slightly above the limit of 0.1. Similarly, the dependency between conceptual design and the cultural influence was with $p = 0.14$ not too much above the singficance limit either. This dependency must exist as well, although without any causal relationship. Although the defined statistical treshold was exceeded, it was decided to consider these two dependencies significant as well, which then lead to a conclusive dependency map. The tables of the observed counts confirm that a trend for these dependencies existed in the data. The higher p-values have to be explained with variation in the data.
Figure 6.19 shows the completed depenceny map, with the two dependencies above the significance limit being indicated by the dashed lines.

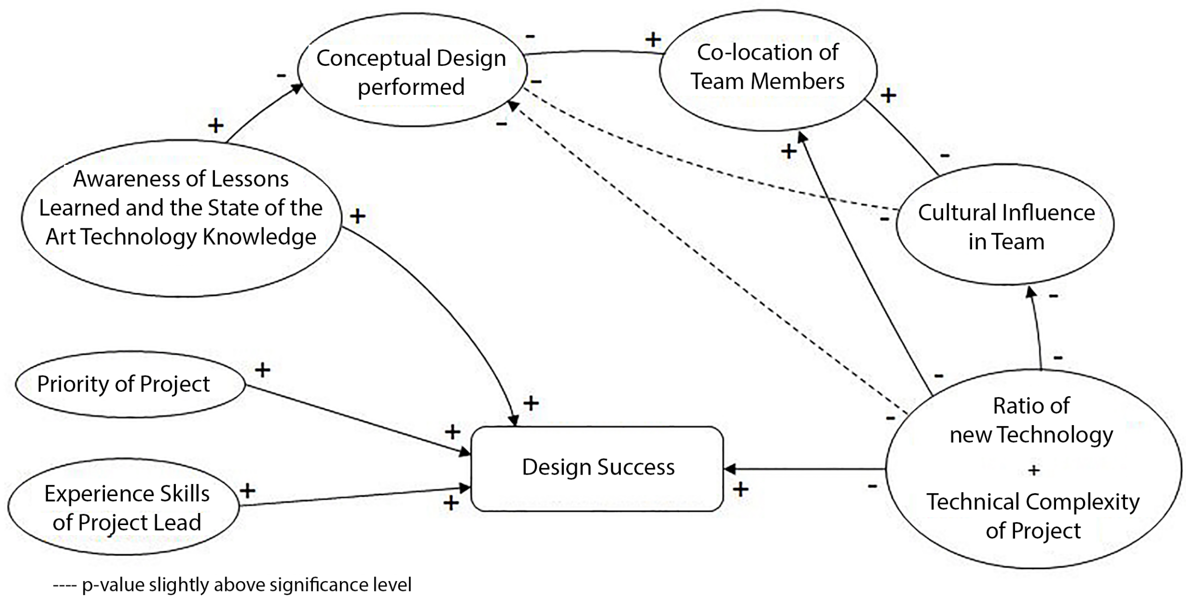

Figure 6.19: Completed dependency map

6.4 Results for Secondary Success Dimension

As explained in section 4.1, the secondary success dimension 'Timeline met' had to be analyzed indirectly by evaluating it against the primary success dimension 'Product Requirement Fullfilment'. Using the same analysis method (Kruskal-Wallis Method) as in the first analysis step of the primary success dimension, the secondary success dimension served as independent variable. The four 'zero projects' were not included in this analysis, as they had no completion date to be measured, due to their termination. The box plot in Figure 6.20 graphically illustrates that there is a relationship between projects which delivered a better fulfillment of product requirements and their completion in time. With a p-value = 0.03 (shown in Table 6.3), it can clearly be stated that this relation is significant. From that it has to be concluded that Success Factors which have a positive impact on Design Success in terms of product requirements, similarly cause a better chance for completion of projects in time.

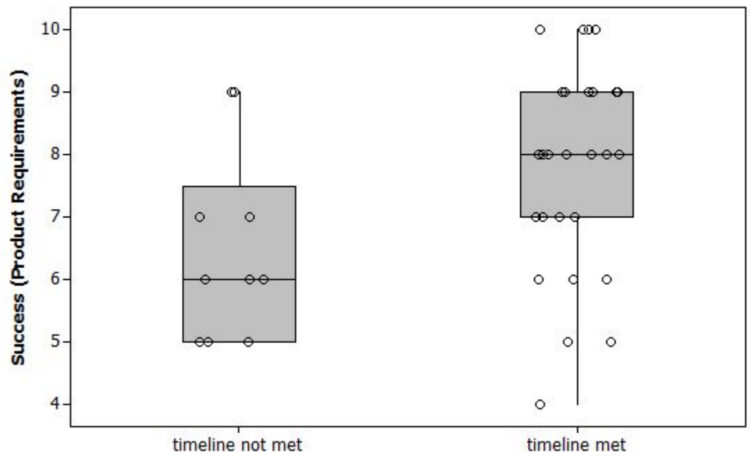

Figure 6.20: Relation between 'Product Requirement Fullfilment' and 'Timeline Met'

The Potential Success Factor 'Simultaneous Development' was not found to be a significant Success Factor to product requirement fulfillment. However, the data showed a positive relationship to the secondary success dimension, which proved that Simultaneous Engineering helps to shorten development cycles.

Table 6.3: Significance of secondary success dimension

Secondary success dimension	No $[\bar{y}_i](n)$	Yes $[\bar{y}_i](n)$	p-value
Timeline Met?	6.5 (10)	7.8 (30)	0.03

6.5 Correlation of Findings to Literature

The four Dominant Success Factors (factors with an arrow pointing to Design Success in Figure 6.19) identified in this chapter have been investigated by other researchers and can be found referenced in the Engineering Design literature as follows:

Priority of Project: The positive impact of management giving priority to development efforts is frequently cited, as Schmimoeller (2010) found in his meta-analysis about success factors in product development. Many authors refer to this factor and some aspects of it, like providing the necessary resources and attention over other projects, but also defining goals and sharing a vision that emphasizes the priority and importance of development projects (Ehrlenspiel, 2009; Gausemeier et al., 2009; Morgan and Liker, 2006; Pillkahn, 2007; Schimmoeller, 2010). Fricke and Shenbar (2000) found, that, while the prioritization is not of great relevance in a single project environment, it plays "a major role in the success of multiproject management" (Fricke and Shenbar, 2000, p.258).

Experience / Skills of Project Lead: Level of experience and the related skills of project leads that evolve from it, have been recognized in the literature to contribute greatly to development success (Ehrlenspiel, 2009; Lindemann, 2009; Pahl et al., 2007). Ehrlenspiel (2009) refers to the Heuristic Competency as an important trait of successful design engineers and project leads. This multi-dimensional trait is described as the ability to solve problems that extend the available base of knowledge at a certain time (Ehrlenspiel, 2009). The results of this research confirm, that having the experience from having been in similar situations before, contributes to this trait. Other researchers indicate another aspect of a project lead's experience, which is the political capital one obtains over time in an organization. Chollet et al. (2012) concluded, that experienced project leads, who have led successful development projects before, can make more powerful use of their internal network in order to get things done.

Technical Complexity and Ratio of new Technology: The negative impact of complexity and innovation on project outcomes has been discussed in the literature. Ehrlenspiel (2009) points out the challenges and risks of having to coordinate tasks of a larger scope with more interfaces. In addition to the increased coordination effort, authors refer also to the uncertainty related to higher complexity and innovation. The uncertainty oftentimes results in an application of inappropriate measures for managing the projects, resulting in lower success (Chalupnik et al., 2009; de Weck et al., 2007).

Awareness of Lessons Learned and State of the Art Technology Knowledge: Ullman describes this awareness as leading to a "knowledge of fact" (Ullman, 2003, p.52) over a knowledge of possibilities during the design process. This includes learning internally from past mistakes (Krause et al., 2006), but also from external partners or competitors. Knudsen (2007) found the importance of learning from partners and competitors on a broader range, extending the area of a companies own core technology. Lindemann (2009) put additional emphazise on the importance of creating an environment, where this knowledge is shared and known within the organization. Research efforts addressing the significance of knowledge sharing, can be found in the fields of Knowledge Management (Goh, 2002) and Organizational Behaviour (Argotea and Ingramb, 2000).

The research approach described in this dissertation is based on a hypothesis test of Potential Success Factors, which were found in the Engineering Design literature. That means that all factors - whether they showed significance in the applied empirical study or not - show a correlation to the literature about successful product development. However, as concluded from this chapter and described in more detail in the next chapter (Applicability), the four Dominant Success Factor have a primary impact. Only if these factors are existent in the right balance at first, can the other factors contribute as well.

7 Applicability

Figure 7.1 illustrates the results of analyzing the 18 Potential Success Factors as causes for Design Success. The two step analysis approach of the collected data revealed that out of the 18 Potential Success Factors, eight showed a significant relationship to Design Success. Out of these eight Success Factors, five were detected to be Dominant Success Factors. Complexity and the amount of new technology were combined into one factor 'Technical Complexity and Innovation', due to similarity in ratings for each project, so that four Dominant Success Factors remained. The three Success Factors that were caused to change are considered Supplementary Success Factors. Their detected relationship to Design Success was only an indirect effect of the dependencies to the Dominant

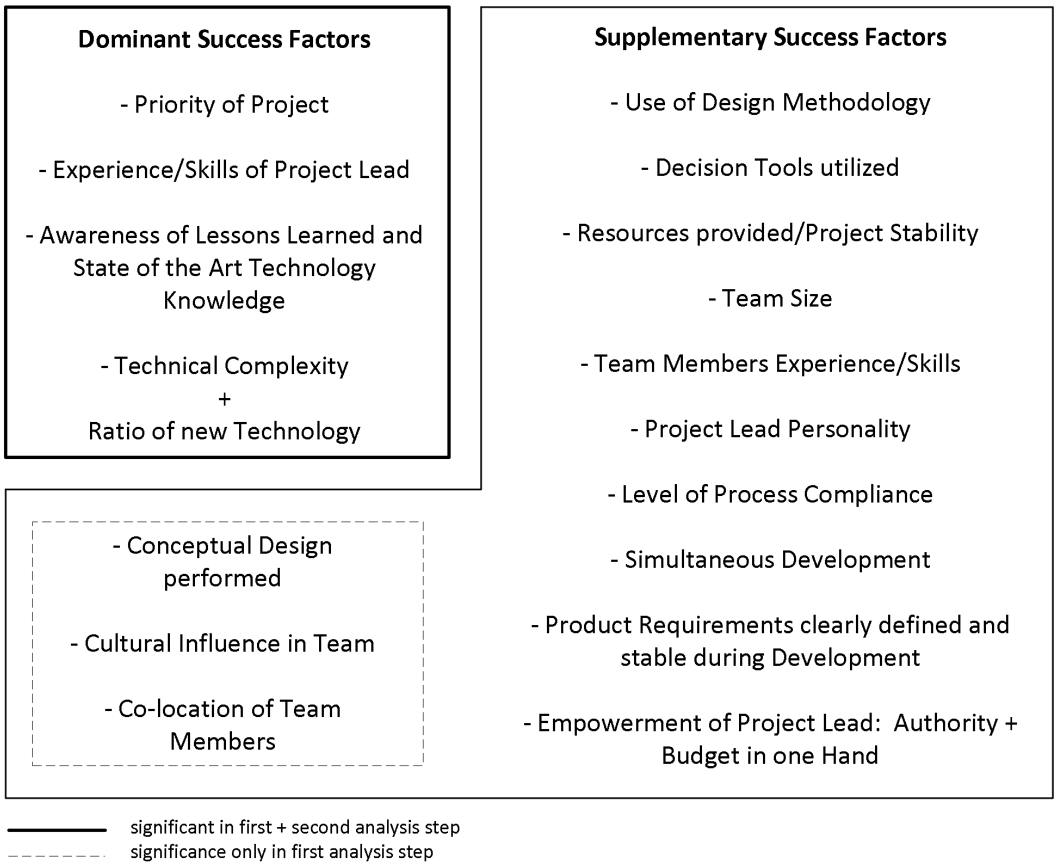

Figure 7.1: Result of analysis of all 18 Potential Success Factors

Success Factors, hence their impact is much weaker. Still it has to be recognized that they can help to improve Design Success in a supplemental manner. The same is valid for the ten Potential Success Factors, which did not show a significant correlation to the success. These are considered Supplementary Success Factors as well.

In this chapter the applicability of the research results to engineering companies is discussed. It is proposed how engineering management should focus on the Dominant Success Factors. The role of the Supplementary Success Factors in the design process is discussed as well. The last two sections illustrate the limitations of this study and recommendations for further research.

7.1 Dominant Success Factors

The four Dominant Success Factors, which were determined in section 6.3, are characterized by two criteria:

1. Show a significant relationship to Design Success.
2. Are not caused by any other Success Factor to change.

Whenever these criteria were fulfilled, it had to be concluded that a Potential Success Factor was a direct cause of successful product design. The four Dominant Success Factors are shown in Figure 7.2. This square of Dominant Success Factors represents a condensed overview of the factors recommended to engineering management to focus most. The factor 'Awareness of Lessons Learned and State of the Art Technology Knowl-

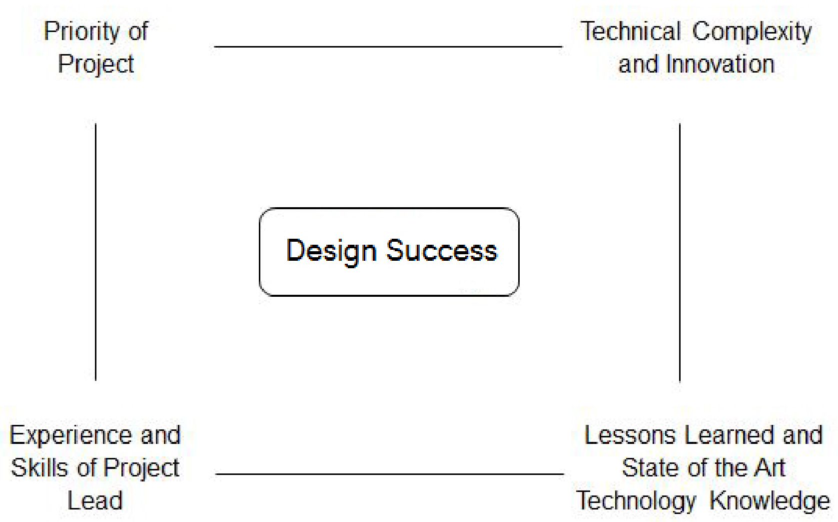

Figure 7.2: Square of all four Dominant Success Factors

edge' should always be fulfilled. Measures should be in place, allowing the company to utilize the available knowledge in the best possible way. It also means that a good system for knowledge transfer from external resources - conferences, competitor data and the latest academic research - should be established.
The other three factors however, have to be viewed in context. They allow to be adjusted and do not necessarily have to be on the highest level for each specific project. Rather they form a triangle (Figure 7.3) which needs to be in balance in order to achieve high success. Knowing this, can help the organization to decide how much of a 'leap' it possibly can take with respect to technical complexity and level of innovation.

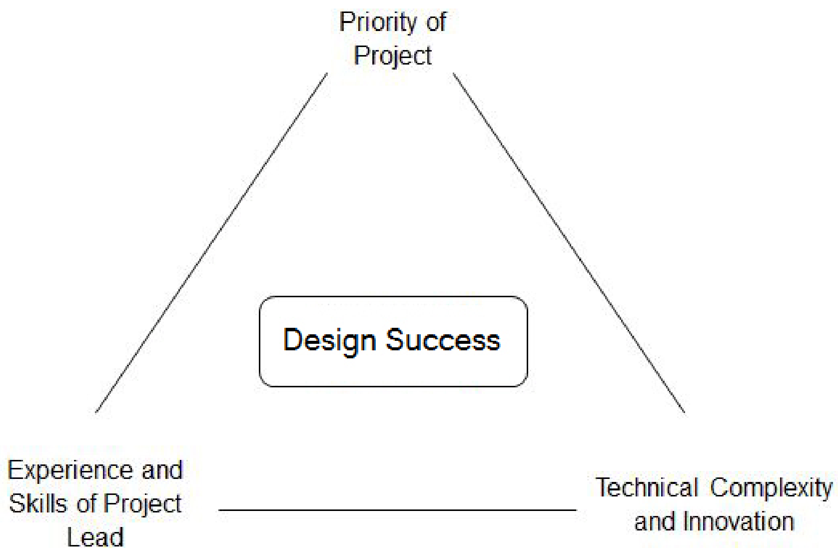

Figure 7.3: Triangle of Dominant Success Factors which need to be balanced

The balance of the triangle gives engineering management some flexibility in how priorities and resources are to be distributed. But it also provides an indication about the maximum capacity of the engineering department and the risk level for projects. Table 7.1 shows the possible combinations between the priority and project lead experience for a high level of complexity and innovation. The combinations of the first three cases are desired. It requires at least one of the two Dominant Success Factors to be high and the other to be medium. The data showed that it did not matter which one was medium and which one was high. However, as soon as both the priority and the experience of the project lead, were only medium, the chance for successful product design declined singificantly. Similarly, this was the case when one of the two factors was low, independent of what the other was.
Engineering management is advised to evaluate the balance of the triangle of Dominant Success Factors (Figure 7.3), whenever a new development project is intiated. The following two questions need to be asked for any project with an expected high complexity

and innovation level:

1. How much priority and attention can management give the project?
2. What's the experience and skill level of the available project lead(s)?

The case where the requirements as they are shown in Table 7.1 cannot be met, would be an indication that the maximum capacity level of the engineering department is reached. In order to bring the triangle back into balance in such a scenario, engineering management has the following options:

- Adjust complexity: The complexity and innovation level of the project might allow for adjustment. It is not always a question of the end goal, which needs to be met by the solution, but the way taken to achieve the goal. An example in gas turbine technology is the control of emission levels. Achieving low emission levels in the combustion process itself requires highly complex and innovative technologies. An alternative solution with lower complexity could be the treatment of emissions external to the gas turbine, simply by adding a catalyzer downstream of the turbine exhaust duct. This could be a solution to meet more stringent emission levels by using an established, less complex technology. Medium to low complexity projects were less sensitive to the other two Dominant Success Factors of the triangle and yielded significantly higher success rates, as can be seen in Table 6.1.

- Re-prioritize: Management can evalaute the balance on all the other development projects ongoing in parallel. There might be projects with medium or low complexity, where the priority and attention level can be reduced, so that management can shift the focus to a new, highly complex project.

- Change project lead: Similar to the re-prioritization, all other, ongoing projects can be evaluted for their balance. It might be possible that a lower complexity project, which is lead by a highly experienced engineer, is handed to a less experienced project lead.

If none of these alternative options are possible, engineering management should be warned that the maximum of projects is reached, where successful outcome can still be expected. It marks the point where the organization should consider reducing the amount of projects. This could either mean not starting any new development projects, until some of the ones in the pipeline are completed, or stopping ongoing projects in order to be able to start new ones.

Table 7.1: Cases for balancing the triangle of Dominant Success Factors

Priority of Project	Experience / Skills of Project Lead	Technical Complexity and Innovation	Design Success
High	High	High	$\nearrow$
Medium	High	High	$\nearrow$
High	Medium	High	$\nearrow$
Medium	Medium	High	$\searrow$
High	Low	High	$\searrow$
Low	High	High	$\searrow$

7.2 Supplementary Success Factors

All Potential Success Factors which were not identified as Dominant Success Factors are considered Supplentary Success Factors. Altough the Dominant Success Factors have a much stronger impact on success, it still has to be expected that these factors have an additional effect to some extent. In total 13 Supplementary Success Factors remained. Ten of them were detected in the first analysis step as they did not show a significant relationship to Design Success. Three were detected in the second analysis step, where it was revealed that these were caused to change by the Dominant Success Factors.

7.2.1 Supplementary Success Factors detected in the first analysis step

The role of these factors in the design process can be interpreted as:

- **Use of Design Methodology:** Almost all projects investigated showed a low utilization of design methodologies, which is why the factor had to be considered constant. The absence of formal methodologies could support the finding of Jensen and Andreason, that the best suitable methods are "outcomes of local interactions and sense-making processes in the companies" (Jensen and Andreasen, 2010, p.28), rather than general, pre-defined schemes. This would suggest that methodologies were used as part of the daily business in the company, but in a more subtle, less detectable way. Nevertheless, the results suggest that - similar to conceptual design - a more in use of design methodology could have helped to increase Design Success, provided that the Dominant Success Factors were in place and in the right balance.

- **Decision Tools utilized:** The outcome of the 44 development projects was minimally influenced by the extent to which decision tools were used during the product development process. In general, a rather low utilization of design methodologies and related tools was found in the projects investigated. Again, it suggests that the overall success rate for all projects could have been elevated, had more systematic design been applied, in addition to having the Dominant Success Factors in the focus.

- **Resources Provided / Project Stability:** Almost all projects showed that this factor was not an issue, which is an indication that the company had sufficient resources available. The bottle-neck was apparently not the overall amount of resources, but the amount of experienced and skilled project leads.

- **Team Size:** No significant influence on Design Success derived from the size of a project team. Even projects with high complexity showed varying team sizes. Some of these projects with smaller team sizes were still completed successfully. All these had in common that the Dominant Success Factors were sufficiently in place. The conlusion to draw from this pattern is, that team size is not as important. A highly complex project can still be tackled successfully, as long as it gets the right priority and an experienced project lead.

- **Team Member Experience / Skills:** Similar to the team size, no significant pattern beetween success and the experience of the teams was found. It suggests that when an experienced project lead is in place and/or the project has sufficient priority, successful teams are assembled, regardless of their experience.

- **Project Lead Personality: Communication, Decision Making, Risk Awareness:** None of the three dimensions of this Potential Success Factor showed significance. This finding appeared unreasonable at first, as the experience and skill of the project lead shows a strong correlation to Design Success. However, it does support the importance of the Heuristic Competency. The Heuristic Competency is a multi-dimensional, personality independent trait, resulting in the ability to solve problems which extend the available base of knowledge at the time (Ehrlenspiel, 2009). The findings suggest that the experience and skills of the project lead in the technical field, rather than personality traits, is the significant aspect of this competency.

- **Simultaneous Development:** In terms of product requirement fulfillment, no difference was found between the projects where manufacturing was involved very early in the process, and the ones where it happened later. However, it was found that the projects where a high degree of simultaneous development was applied, had a higher chance to be completed in time. Apparently, the utilization of Simultaneous Engineering does support shorter development cycles.

- **Level of Process Compliance:** All projects went through the minimum required process step (Detail Design Review after design completion). Some projects went through additional, not mandatory steps. No difference was seen between the projects which went through all PDP process steps and the ones which only went through the required minimum. This suggests that process steps should be kept to a minimum. It does not suggest that a process is completely irrelevant, as a minimum was always there. A minimum amount of process is always required, especially in global organizations, to ensure proper flow and documentation of information. However, as with most other Supplementary Success Factors, with enough management priority and an experienced project lead, a low level of this factor can be overcome.

- **Product / Customer Requirements clearly defined and stable during Development:** No indication of a different outcome was found between the projects that had clearly defined customer and product requirements in their documentation and the ones which did not. Again, this suggests that other factors, such as the project lead's experience and priority given by management, are able to overcome a lack of this factor.

- **Empowerment of Project Lead: Project and Budget Responsibility in one Hand:** Very low significance, with a similar explanation as for the former Potential Success Factor.

7.2.2 Supplementary Success Factors detected in the second analysis step

The role of these factors in the design process can be interpreted as:

- **Conceptual Design performed:** More conceptual design was performed on the projects with higher complexity and innovation, which is a sign that the project teams were aware that methods can be used to overcome more complex problems.

The negative relationship to Design Success resulted from the circumstance that more complex projects had a lower success rate. It cannot be concluded that the use of conceptual design lead to less success. Rather the opposite has to be assumed, since at most, only a medium level of conceptual design was applied, even on the highly complex and innovative projects. Using a high amount of conceptual design could have increased the chance for success on these. However, it has to be recognized, that this effect can only occur if the Dominant Success Factors are in place with the right balance. Only if the project teams are aware of lessons learned and the latest technology trends, and the triangle of priority, project lead experience and complexity is in balance, can conceptual design help additionally to improve Design Success.

- **Cultural Influence in Team:** The effect of projects with higher complexity was that the amount of global involvement increased, due to the need to utilize more resources. This caused an increase in cultural influence in teams, which is why this factor showed an indirect relationship to Design Success as well. The results suggest that if the Dominant Success Factors exist, cultural differences can be overcome.

- **Co-location of Team Members:** Similar to the cultural influence, this factor was a symptom resulting from higher complexity and can be overcome when the Dominant Success Factors are sufficiently existent.

As described for most of the factors above, showing statistical insignificance or only an indirect relationship to Design Success must not be interpreted that these factors do not contribute to successful product development. It is certainly to be believed that techniques like design methodologies or the clear definition of product requirements help to improve development projects. However, the results of this study show that there are more dominant factors which need to be fulfilled first. Project teams need to be aware of the latest technology trends and the lessons which have been learned in the own company. For highly complex projects, experienced and skilled project leads are essential. In addition, projects need to be given sufficient priority by management. Once these factors are established, the Supplementary Success Factors can help design teams in achieving their goals better. But they are only able to do so, if the Dominant Success Factors are established with the right balance in the first place.
The Pareto Chart in Figure 7.4 shows in a qualitative manner the weight of the Dominant Success Factors and the additional impact the Supplmentary Success Factors can have, as it was found in this study.

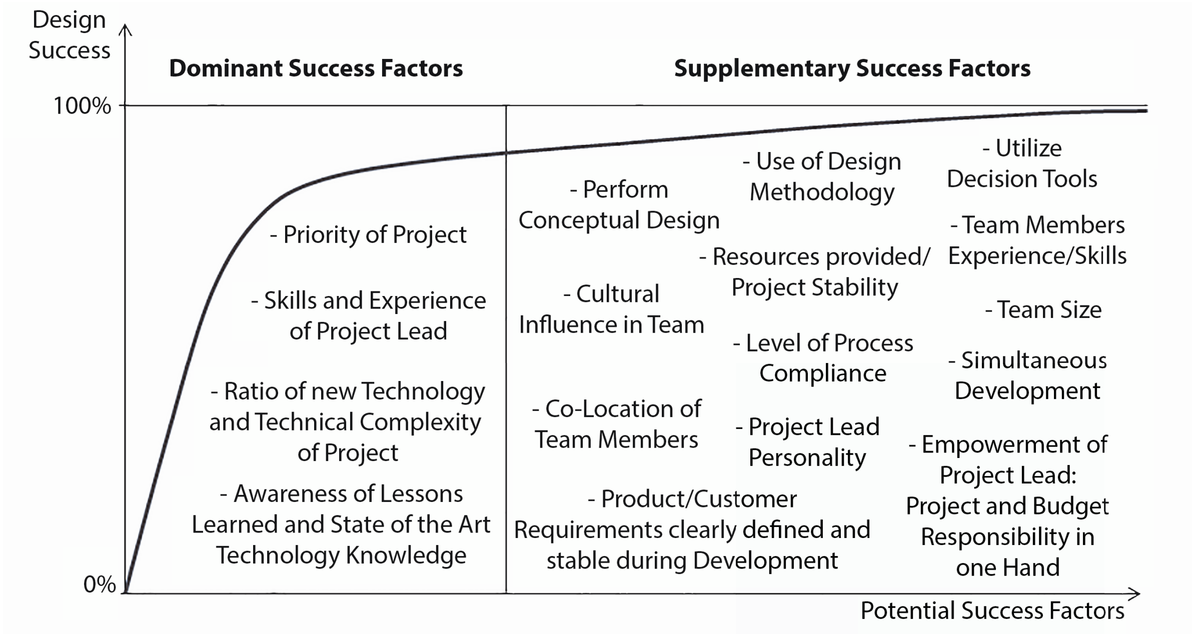

Figure 7.4: Role of Dominant and Supplementary Success Factors

7.3 Limitations of this Study

It was the aim of this study to comply with the characteristics as they were elaborated in the Literature Review Chapter and defined in Table 2.3. This Comprehensive Approach was seen as to providing results of high reliability and practicality, which can directly be used by engineering management in the industry. The complexity of the task and the limited time frame of this research left some of these 'ideal' characteristics unfulfilled. These unfulfilled characterisitics from Table 2.3, which mark the limitations of this study, are:

- Unit(s) of analysis: A holistic view on the product development process was intended, in order to ensure all factors, potentially influencing the outcome of design projects, were considered. While the developed framework (Figure 3.5) supported the determination of all influencing factors, it was also required that all factors showed sufficient variance in success over the 44 projects. Only with this variance was it possible to apply the statistical methods, which helped to detect significances of relationships. Two of the 18 Potential Success Factors did not show this variance and had to be considered constant. These factors were the use of design methodology, as well as the factor measuring provided resources and project stability. As four other Dominant Success Factors existed, it was known that these two could not be the only Dominant Success Factors. The low use of design methodologies suggests that a more in such could have yielded better results, but this remains a hypothesis. The other constant Potential Success Factor - provided resoureces and project stability - showed a high existence on almost all the investigated projects.

It suggests that a lower average success resulted, had this factor been lower. But again the lack of variance in the data did not allow for a quantitative verification.

- Number of cases: The 44 projects of the study provided a sample size which allowed for the use of inferential statistics for most of the cases. However, the fact that two of the Potential Success Factors turned out to be constant and some of the dependency tests did not comply with the guidelines for reliable Chi-Square Test results (indicated by the asterix in Figure 6.13), is an indication that more projects would have been required to obtain complete comprehensiveness.

- Object: The projects of the study were all performed in the same global organization. Although the Dominant Success Factors are general in their nature and are hence believed to apply to all product development projects executed in similar organizational environments, it needs to be pointed out that influences specific to the company or the product could not be filtered out.

- Coding and analysis method(s): While it was the goal in this research to rely solely on statistical significances, it was not possible to achieve in the second analysis step. The multifold of possible combinations for the dependency tests showed that 44 projects were not sufficient to provide results with the desired confidence and reliability. On two dependencies, personal judgements from studying the trends in the distribution of the counts could not be avoided.

The described limitations of this study in combination with the determined results, lead to recommendations for further research in Engineering Design Research.

7.4 Recommendation for Further Research

The four Dominant Success Factors identified in this study require more focus in upcoming research activities in Engineering Design Research. As explained in section 5.1, an iterative approach was chosen in this research in order to be able to reduce the amount of data to a manageable size. As a result, some of the eventual 18 Potential Success Factors, represented groups of closely related factors. An example are elements of conceptual design, such as breaking the problem into sub-functions or the use of creativity techniques, which were grouped under the Potential Success Factor 'Conceptual Design performed'. This approach allowed - considering the limited time frame of the research - to achieve the detection of the most dominant influences, by maintaining a holistic view and without compromising on comprehensiveness. For the Dominant Success Factors found, it means that more refined iterations can help to understand these factors and their impact in more detail.

Priority of Project

The role and importance of management can be found mentioned in the product development literature. Authors refer to the support in terms of providing resources, defining goals and sharing a vision (Ehrlenspiel, 2009; Gausemeier et al., 2009; Morgan and Liker, 2006; Pillkahn, 2007; Schimmoeller, 2010). However, there is still a lack in understanding, especially how engineering management can contribute to successful product development, beyond the task of allocating resources. Further research is recommended to identify specific solutions which can help engineering management to set its priorities and focus correctly. It is referred to the management sciences, like NPD and Innovation Management, where many publications with focus on the role of management and their relation to Design Success can be found (Bonner et al., 2002; Schimmoeller, 2010; Thamhain, 2003; Zirger and Maidique, 1990).

Experience / Skills of Project Lead

Project leads of engineering development projects play an essential role in the outcome of development projects. The results of this research suggest that personality traits that are related to the role of a project lead do not matter. It does not make a difference if a person is a strong or subtle communicator, quick or slow decision maker, or shows a passive rather than an active sense of risk awareness. What does matter are the skills these persons posses in the technical field and the experience they have gained from leading similar projects formerly. The exact causes why experienced project leads are more successful need to be understood, which is why more specific research is recommended. It might be what Ehrlenspiel refers to as Heuristic Competency (Ehrlenspiel, 2009), but could also be other factors, such as the fact that due to their seniority in the company, experienced project leads can make better use of social capital (Chollet et al., 2012).

Technical Complexity and Ratio of new Technology

Although the complexity of a project and the level of innovation is oftentimes given by external factors, like competitors products, some flexibility exists. Alternative solutions which have been proven for a longer time might be available. A company needs to be aware of how much of a leap it can take in terms of complexity and innovation. Evaluating the balance with the other Dominant Success Factors, especially the project lead's experience and management priority, is a helpful indication as shown in section 7.1. More research is recommended in order to provide companies with intergrated approaches on how to tie the technological planning - e.g. by technology road mapping - to the human side.

Awareness of Lessons Learned and State of the Art Technology Knowledge

Good knowledge transfer and transparency is important for companies to prevent avoidable and costly mistakes. Companies need methods helping them to ensure knowledge from the past and present is known and accessible, for both knowledge from internal and external sources. Technology can contribute partially to the solution for this challenging task, e.g. through smart databases for storing information. However, the human side needs to be considered as well in that collaborative and transparent environments are created. Specific research in this area has been performed in the fields of Knowledge Management (Goh, 2002) and Organizational Behaviour (Argotea and Ingramb, 2000), which Engineering Design Research can build upon.

In the field of Engineering Design Research, it is recommended to follow a more rigorous methodology, aspiring towards comprehensiveness and the use of hard criteria. Therefore, the Comprehensive Approach developed in this research can serve as a framework. As shown in Section 3.1, this framework complements DRM (Design Research Methodology). To verify the robustness of the approach, studies with larger populations across different companies or industries are desireable. More data would lead to more reliable results, and also help to verify the results of this study. The extended study object (different companies and different industries) would overcome the limitation of this study, with projects from only one company. This would allow for even more generalized results. It would mean an extensive effort and require active collaboration with industry partners, but provide extremely valuable information to the Engineering Design Research community.

It has to be mentioned again, that the Supplementary Success Factors are not insignificant and can help to increase Design Success. Further investigation of these is desired as well. However, researchers have to be aware - especially when researcheing them in an indepedent manner - that there are factors that are more dominant over these, when they act in a holistic context. Researchers can neutralize this dependency by considering sample projects for a study that share the same, constant rating for the Dominant Success Factors.

8 Conclusion

This dissertation comprises an empirical investigation on what distinguishes succesful from less successful product development projects in engineering design. Studying the state of the art literature and results of past research in the field of Engineering Design Research revealed the need for further work. The specific needs were formulated in three research questions at the beginning of this dissertation. The answers to these questions mark the contribution to the academic research, as well as to the beneficiaries of the results, which are engineering and technology firms.

Research Question I: How do the characteristics of an Empirical Engineering Design Research study need to be set to obtain comprehensiveness?

The goal of the study was to achieve comprehensiveness, which demanded a holistic view of the product development process, with all its factors potentially influencing the outcome. In addition, it was aimed for a high level of reliability in the results. From these boundary conditions, a set of required characteristics was derived (summarized in Table 2.3). A theoretical framework was developed in order to cast these characteristics into the research process. This developed research process (Figure 3.5) is referred to as the Comprehensive Approach. It was shown that it is compatible to overall design research frameworks like Design Research Methodology.
A systematic elaboration and grouping of all Potential Success Factors showed to be essential in order to reduce the amount of data to a manageable size, without sacrificing comprehensiveness. The clear definition of domain and dimensions of Design Success showed to be of equal importance. The need for quantification of mostly qualitative data into quantitative data required a scheme of reasonable descriptions on rating scales to reduce bias in the data. An additional measure to reduce bias was the strict separation of data collection between cause and effect. While data on the cause side (Potential Success Factors) was collected from documentation and interviews of engineering managers or project participants, data on the cause side (Design Success) was gathered from the company's internal customers of the products, outside of the engineering department. Applying advanced statistical techniques to analyze the collected data, lead to results which are expected to be of high reliability and minimal bias. The concept of regarding the

product development process as a strict matter of cause and effect served the purpose of identifying causal relationships. Adding a second analysis step for analyzing dependencies made it possible to draw a conclusive map of relationships and dependencies. Only after this step, was it possible to identify the Dominant Success Factors.

Research Question II: Which of all the influencing factors can be proven to have a significant and dominant influence on Design Success?

The analysis and interpretation of results revealed that the originally identified 18 Potential Success Factors ended up in two groups of Success Factors.
Supplementary Success Factors are the Potential Success Factors which either did not show any significant relationship to the Design Success in the first analysis step, or showed to be caused to change by other Success Factors in the second analysis step. It cannot be concluded that these factors do not contribute to successful product development, however, it can be concluded that these factors can only contribute if other more dominant factors are existent and in the right balance.
Dominant Success Factors are the factors which directly influence Design Success and cause other Success Factors to change, but are not caused by other Success Factors to change. The following four factors were identified to be dominant:

- Priority of Project
- Experience and Skills of Project Lead
- Technical Complexity and Ratio of new Technology
- Awareness of Lessons Learned and State of the Art Technology Knowledge

These are the factors which should provide the best gauges for engineering management to increase the chance for success in development projects. Only if these factors are sufficiently established in the first place, can other factors, which did not show the same level of significance, help to further increase the successful outcome of development projects.

Question III: What can engineering management do to increase the chance of Design Success?

The findings of this study suggest that engineering management can elevate success in product development, by focusing on the four Dominant Success Factors first and most. While the awareness of lessons learned and technology knowledge should always be a focus, the other three dominant factors do not necessarily have to be maximized, but in the right balance. Projects of high complexity and innovation demand for a high level of management priority and project lead experience. At least one of the two factors needs to be at a high level, the other at a medium level. As soon as none of these two factors is high, or any of them is low, a significant decrease in success has to be expected. For projects of lower complexity, these factors were found to be of less importance. The triangle and its balance between the three Dominant Success Factors management priority, project lead experience and complexity, is primarily of use in the pre-planning and early stages of development projects. It can support management in the best utilization of the engineering departments resources. It can also serve as an indicator for reaching the maximum capacity of development projects, which can be executed in parallel, but still completed successfully.

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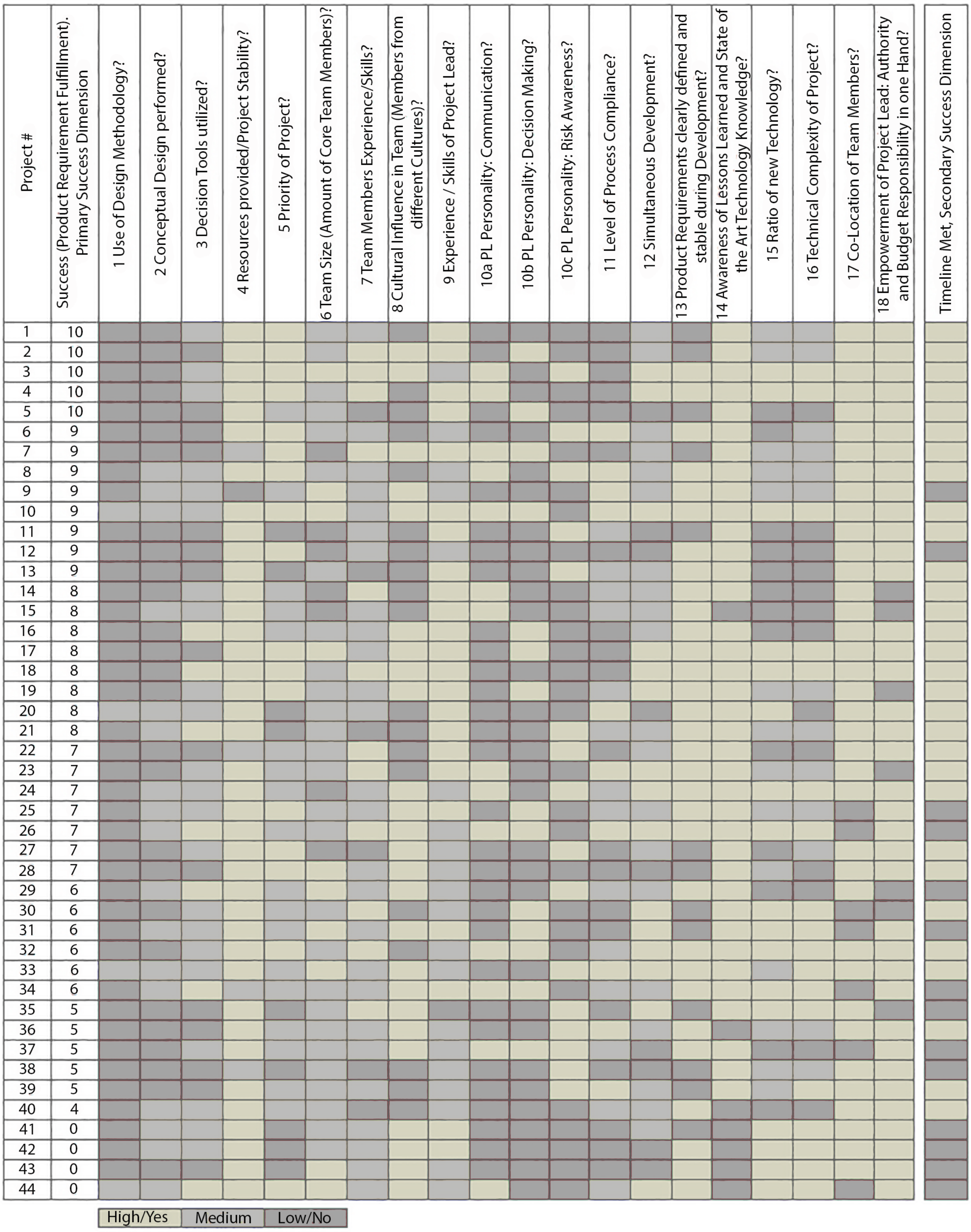
Appendix

Appendix A: Data matrix



Appendix B: Tables of observed counts for Chi-Square Test

		Priority of Project		
		Low	Medium	High
Conceptual Design performed	Low	5	9	13
	Medium	4	9	4

		Experience/Skills of Project Lead		
		Low	Medium	High
Conceptual Design performed	Low	1	12	14
	Medium	0	8	9

		Ratio of new Technology	
		Low + Medium	High
Conceptual Design performed	Low	19	8
	Medium	8	9

		Technical Complexity of Project	
		Low + Medium	High
Conceptual Design performed	Low	18	9
	Medium	8	9

		Cultural Influence in Team	
		No	Yes
Conceptual Design performed	Low	14	13
	Medium	5	12

		Awareness of LL/State of the Art Technology Knowledge	
		No	Yes
Conceptual Design performed	Low	2	25
	Medium	5	12

		Co-Location of Team Members	
		No	Yes
Conceptual Design performed	Low	2	25
	Medium	5	12

		Experience/Skills of Project Lead		
		Low	Medium	High
Priority of Project	Low	1	2	6
	Medium	0	10	8
	High	0	8	9

		Ratio of new Technology	
		Low + Medium	High
Priority of Project	Low	4	5
	Medium	13	5
	High	10	7

		Technical Complexity of Project	
		Low + Medium	High
Priority of Project	Low	5	4
	Medium	11	7
	High	10	7

		Cultural Influence in Team	
		No	Yes
Priority of Project	Low	5	4
	Medium	8	10
	High	6	11

		Awareness of LL/State of the Art Technology Knowledge	
		No	Yes
Priority of Project	Low	3	6
	Medium	3	15
	High	1	16

		Co-Location of Team Members	
		No	Yes
Priority of Project	Low	0	9
	Medium	5	13
	High	2	15

		Ratio of new Technology	
		Low + Medium	High
Experience/ Skills of Project Lead	Low	0	1
	Medium	13	7
	High	14	9

		Technical Complexity of Project	
		Low + Medium	High
Experience/ Skills of Project Lead	Low	0	1
	Medium	11	9
	High	15	8

		Cultural Influence in Team	
		No	Yes
Experience/ Skills of Project Lead	Low	0	1
	Medium	8	12
	High	11	12

		Awareness of LL/State of the Art Technology Knowledge	
		No	Yes
Experience/ Skills of Project Lead	Low	0	1
	Medium	4	16
	High	3	20

		Co-Location of Team Members	
		No	Yes
Experience/ Skills of Project Lead	Low	0	1
	Medium	4	16
	High	3	20

		Technical Complexity of Project	
		Low + Medium	High
Ratio of new Technology	Low + Medium	25	2
	High	1	16

		Cultural Influence in Team	
		No	Yes
Ratio of new Technology	Low + Medium	15	12
	High	4	13

		Awareness of LL/State of the Art Technology Knowledge	
		No	Yes
Ratio of new Technology	Low + Medium	3	24
	High	4	13

		Co-Location of Team Members	
		No	Yes
Ratio of new Technology	Low + Medium	2	25
	High	5	12

		Cultural Influence in Team	
		No	Yes
Technical Complexity of Project	Low + Medium	15	11
	High	4	14

		Awareness of LL/State of the Art Technology Knowledge	
		No	Yes
Technical Complexity of Project	Low + Medium	3	23
	High	4	14

		Co-Location of Team Members	
		No	Yes
Technical Complexity of Project	Low + Medium	2	24
	High	5	13

		Awareness of LL/State of the Art Technology Knowledge	
		No	Yes
Cultural Influence in Team	No	2	17
	Yes	5	20

		Co-Location of Team Members	
		No	Yes
Cultural Influence in Team	No	1	18
	Yes	6	19

		Co-Location of Team Members	
		No	Yes
Awareness of LL/State of the Art Technology Knowledge	No	1	6
	Yes	6	31