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The Lean Innovation Roadmap – A Systematic Approach to Introducing Lean in Product Development Processes and Establishing a Learning Organization –

Diploma Thesis

by

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Zusammenfassung

Die Anwendung von Lean Prinzipien im Bereich der Produktentwicklung ist Gegenstand einer steigenden Zahl von Publikationen. In der Vergangenheit konnten wichtige Elemente eines Lean Product Development (Lean PD) Systems identifiziert und beschrieben werden. Die Frage, wie sich diese Elemente in einem Unternehmen einführen lassen, hat in der Literatur bisher allerdings nur ungenügende Beachtung gefunden. Die vorliegende Diplomarbeit untersucht den Prozess der Implementierung von Lean PD und leitet Handlungsempfehlungen für eine effiziente Einführung von Lean Prinzipien im Bereich der Produktentwicklung ab.

Im Sinne eines deduktiven Ansatzes werden zu Beginn dieser Arbeit zunächst die Grundlagen des Lean Thinking dargestellt und eine Abgrenzung von Produktentwicklungssystemen vorgenommen. Aufbauend hierauf wird ein Überblick über existierende Ansätze des Lean PD gegeben und eine neuartige Definition eines Lean PD Systems, bestehend aus elf Komponenten, abgeleitet. Die elf Lean PD Komponenten werden bezüglich der zwischen ihnen bestehenden Interdependenzen untersucht. Diese Untersuchung dient als Grundlage für die Ableitung fünf maßgeblicher Hypothesen zu einer effizienten Implementierung von Lean PD.

Um die Hypothesen zur Einführung von Lean PD zu testen, wurde im Rahmen dieser Arbeit eine großangelegte Umfrage unter 113 internationalen Unternehmen durchgeführt. Die auf diesem Wege gewonnenen Daten wurden mittels umfangreicher deskriptiver und explorativer statistischer Verfahren untersucht. Die Ergebnisse der Untersuchungen zeigen, dass, in Übereinstimmung mit den theoretischen Überlegungen, Lean PD als ein System stark verwobener Einzelelemente verstanden werden muss, deren Implementierung nicht losgelöst voneinander erfolgen kann. Hinsichtlich der Reihenfolge der Implementierung besteht eine Pfadabhängigkeit, da einige der Komponenten die Implementierung anderer Komponenten messbar vereinfachen. Weiterhin wird gezeigt, dass einige der in der Literatur beschriebenen Hilfsmittel, wie z.B. die Wertstromanalyse, keinerlei nachweisbaren Beitrag zur Einführung von Lean PD leisten.

Auf Basis der aus den Hypothesentests gewonnenen Erkenntnisse und der empirischen Daten wird im Rahmen dieser Arbeit schließlich die Lean Innovation Roadmap, ein Vorschlag für das Vorgehen bei der Implementierung von Lean PD, abgeleitet. Hierfür kommt eine neuartige, zweistufige Methodik namens Adjusted Past Implementation zur Anwendung. Der resultierende Fahrplan für die Implementierung von Lean PD besteht aus vier Phasen und beschreibt die Einführung der elf Lean PD Komponenten in Form sich überlappender Implementierungsströme. Für jede Komponente sind vier detaillierte Bestandteile definiert, deren empfohlene Implementierungszeitpunkte relativ zueinander anhand der Roadmap nachvollzogen werden können. Unternehmen, welche beabsichtigen, sich auf den Weg zu einer lernenden und kontinuierlich verbessernden Organisation zu machen, liefert die Lean Innovation Roadmap wichtige Hinweise für eine möglichst effiziente Einführung von Lean Prinzipien im Bereich der Produktentwicklung.

Abstract

The application of Lean principles in the field of product development is the subject of a growing number of publications. In the past, significant efforts have been undertaken to identify and describe the practices of a Lean Product Development (Lean PD) system. The important question of how these elements of Lean PD can be implemented in a company, however, remains under-investigated. The thesis at hand examines the process of implementing Lean PD and gives recommendations for a successful introduction of Lean principles in product development.

Following a systematic approach, at the beginning of this work the basics of Lean Thinking and product development systems are reviewed. Existing approaches to Lean PD in literature are discussed. Building upon this, a novel and coherent definition of a Lean PD system, consisting of eleven distinct Lean PD components, is derived. The components of Lean PD are described in detail and investigated with regard to their interdependencies. The findings of this analysis serve as a basis to derive five major hypotheses on the efficient introduction of Lean PD.

To test the hypotheses on the implementation of Lean PD, as part of this work, a comprehensive survey among 113 product development departments of international companies was conducted. The survey data was analyzed using descriptive statistics to give an overview of the use of different Lean PD practices and measures supporting the process of implementation. Moreover, an exploratory analysis including correlation analyses, a content analysis and t-tests was conducted to better understand the nature of a Lean PD system. The results of the analyses show that, in concordance with the hypotheses, Lean PD has to be understood as a system of highly interwoven elements which cannot be implemented independently. The order of implementing the eleven Lean PD components follows a certain path dependency since several components measurably facilitate the implementation of others. Furthermore, it can be shown that some of the supporting measures described in literature, such as value stream mapping, do not have a significantly positive effect on the introduction of a Lean PD system.

Based on the insights gained from the testing of the hypotheses and the available empirical data, finally, the Lean Innovation Roadmap, a suggested path for implementing Lean PD, is derived. For this purpose, a novel, two-step methodology called Adjusted Past Implementation is used. The resulting roadmap for implementing Lean PD consists of four major phases and shows the introduction of the eleven Lean PD components in the form of eleven overlapping implementation streams. For each of the components, four detailed characteristics are defined. The time of implementing these 44 characteristics is depicted on the roadmap, giving an idea of when to introduce the elements of Lean PD relative to each other. For companies intending to implement a Lean PD system, the Lean Innovation Roadmap can serve as a valuable guideline on their way to a learning and continuously improving organization.

Declaration

I hereby declare that I am the sole author of this thesis and assure that no other resources than those indicated have been used in the accomplishment of this work. Any literal or analogous citation of published or unpublished material is marked as such.

Ich versichere durch meine Unterschrift, dass ich die Arbeit selbständig und ohne Benutzung anderer als der angegebenen Hilfsmittel angefertigt habe. Alle Stellen, die wörtlich oder sinngemäß aus veröffentlichten oder unveröffentlichten Schriften entnommen sind, habe ich als solche kenntlich gemacht.

Braunschweig, 26 June 2009

Jörn Hoppmann

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Contents

List of Abbreviations

API	Adjusted Past Implementation
CF	Correction Factor
DSM	Design Structure Matrix
MDT	Module Development Team
OEM	Original Equipment Manufacturer
PD	Product Development
SE	Simultaneous Engineer
TPDS	Toyota Product Development System
TPS	Toyota Production System
VSM	Value Stream Mapping

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1 Introduction

1.1 Lean Product Development as the New Frontier

Since the publication of "The Machine that Changed the World" by Womack et al. in 1990 the concept of Lean Thinking has attracted increasing attention of practitioners and scholars around the world. Numerous case studies have been published showing examples for the successful implementation of Lean principles in different areas of corporate enterprises. The convincing results have lead to a spreading of the concept beyond its origin in the automotive sector to other domains and resulted in the creation of new research fields such as Lean Construction, Lean Health Care and Lean Service.

In literature, it has long been argued that, in order to reap the full benefits of the concept, Lean Thinking has to be applied to the entire value stream rather than to distinct subsystems within a company. Despite this notion, which is reflected in the ultimate goal of the "Lean Enterprise", up to this point the application of Lean principles has largely been limited to the domain of production [Morga 06] p.3. While there is abundant experience with introducing Lean on the manufacturing shop floor, concepts on how to employ Lean in up- or downstream processes and supporting functions are relatively new and remain to be investigated in detail [Fiore 04] p.29.

Arguably, an area with a particularly high potential for the application of Lean principles is the field of product development. Product development by definition plays an important part in defining customer value. It determines the physical appearance of the product, defines the materials to be used and, thus, largely constrains the set of production processes which can be employed to manufacture the product. Consequently, the impact on cost, quality and manufacturing lead-times is usually much bigger in the phase of product development than it is during production [Morga 06] p.4, [Kenne 03] p.13. As Fiore points out, already during the concept phase of product development where only 5 percent of the total development costs have been invested, about 50 percent of the product cost is committed [Fiore 04] pp.5f.

The importance of considering product development when striving towards the Lean Enterprise is further augmented by current market trends. Today's companies operate in a highly dynamic environment. Over the past years, the speed of innovation has been continuously increasing. The time span between subsequent product relaunches has shortened drastically [Adick 08] p.475. To keep their market share, companies are forced to bring products to market at an ever-increasing speed while at the same time the number of product variants is rising. In many markets, such as the automotive industry, this has led to a microsegmentation of markets. Companies offer a higher variety of products with a lower sales volume per product variant [Morga 06] p.7.

For traditional product development these market trends pose a major challenge in three major dimensions: time, cost and quality. First and foremost, persisting in the competitive environment requires companies to drastically reduce their development cycles and minimize time-to-market. In automotive product development, since the 1980s the average time to develop a car from styling to freeze has gone down by about a third to 24 months in 2006 [Morga 06] p.7. Second, lower sales volumes per product with a simultaneous increase in product complexity have resulted in an increased cost pressure. If one seeks to avoid an increase in the development cost per unit produced, total development costs for a product with a smaller sales volume have to be much lower than for a product with a larger sales volume [Morga 06] p.8, [Adick 08] p.475. Third and last, shortening product life-cycles come with a decreased tolerance for quality issues. High rates of early failures after market introduction, causing lengthy efforts of rework, are even less acceptable for a product with a short life-span than they are for long-lived ones [Morga 06] p.8.

Lean Product Development (Lean PD) as a domain addresses these major challenges and intends to investigate how product development systems ought to be designed in order to achieve a streamlined and cost-efficient product innovation process. To this end, several authors have studied instantiations of product development systems, such as the Toyota Product Development System (TPDS), in detail. They showed that, akin to the findings of "The Machine that Changed the World", performance of companies in product development differs significantly. So, according to a report by the National Center for Manufacturing Sciences, Toyota develops cars in half the time and with four times less personnel than its US American competitors. [Balle 05] p.18

The detailed explanation of these differences in performance is still the subject of ongoing research. However, lately in literature a number of interdependent Lean PD components have been described which are characteristic of particularly successful product development systems. Like the best practices of Lean production these Lean Product Development components are mainly based on the observation of practices at Toyota. Comprehensive benchmarks performed by the Aberdeen Group or the Laboratory for Machine Tools of the RWTH Aachen and case studies conducted by various authors indicate that the use of these practices is closely linked to a better performance in product development. [Schuh 07-2] p.4, [Brown 07] p.4

1.2 Shortcomings of Existing Approaches to the Introduction of Lean Product Development

While significant endeavors have been undertaken to identify and describe the practices of a Lean Product Development system, the important question of how to introduce Lean PD in a company remains under-investigated. So far, only few authors, namely Kennedy, Fiore, Schuh, Ward as well as Morgan and Liker, have published first suggestions for possible Lean Product Development roadmaps. In what follows, these existing approaches shall be presented and briefly discussed with regard to their obvious shortcomings.

As one of the first to deal with the implementation process of Lean Product Development, Kennedy in his publication "Product Development for the Lean Enterprise" presents a case study of a company which decides to adapt parts of the Toyota Product Development System. Telling the story of the company as a novel, Kennedy puts strong emphasis on describing social inhibitors that oppose the introduction and proposes ways of how to successfully manage the change initiative. His description of the TPDS, however, remains rather superficial and is reduced to four major components. Regarding the introduction of the concept of "set-based concurrent engineering" Kennedy contradicts himself stating that "the rest of the lean elements must be in place in order to support this concept" [Kenne 03] p.124 and "the set-based approach is the natural starting point to begin focusing on the other three principles" [Kenne 03] p.236.

A proposal for a Lean Product Development roadmap which is not explicitly based on the TPDS is presented by Fiore. In his book "Accelerated Product Development – Combining Lean and Six Sigma for Peak Performance" Fiore outlines a number of Lean methodologies he considers important to improve a company's performance in product development. Providing detailed descriptions of the single steps and checklists for maturity assessment, Fiore's roadmap achieves a much higher level of detail than Kennedy's. However, like Kennedy, Fiore presents his roadmap without arguing why the steps he proposes should be undertaken in the order he suggests. Although he points out that "experience has demonstrated that the benefits resulting from the implementation of the various product development activities are maximized when they follow a specific order" [Fiore 04] p.75, he does not present empirical data to back his ideas.

Another approach towards a model for the implementation of Lean Product Development is taken by Schuh et al. According to their maturity model, the introduction of Lean principles in product development can be distinguished into five separate stages. At stage one product development does not include any Lean principles, whereas at stage five a Lean culture with continuous improvement processes has fully evolved [Schuh 07-2] p.29. The authors claim to have defined characteristics for every stage that allow to assess the current maturity level of a company and derive further steps to be taken on the path towards Lean PD. Unfortunately, Schuh et al. do neither detail the nature of these characteristics nor do they provide any information on why their maturity model has been structured this way. The titles of the maturity phases and their short descriptions, as published by Schuh et al., are highly generic and not suited to serve as a guideline for the implementation of Lean Product Development.

Ward, whose thinking on Lean Product Development has strongly influenced Kennedy's approach, suggests an action plan consisting of ten interacting steps. Similar to the roadmap proposed by Kennedy, Ward focuses on the organization of the change process and limits his suggestions to the same four components of Lean PD that Kennedy describes [Ward 07] pp.205ff. Encompassing only four pages of his 200-pages publication "Lean Product and Process Development", Ward gives nothing more than general advice on how to transition to the new concept. The reasons for the steps and cadence chosen by Ward remain unclear.

A fifth framework for the introduction process of Lean PD has been published by Morgan and Liker in their book "The Toyota Product Development System". Morgan and Liker's study of the TPDS is based on over 1,000 hours of interviews held with 40 Toyota and supplier representatives at 12 different sites in the United States and Japan and can be considered one of the most comprehensive descriptions of Lean practices in the field of product development. Surprisingly, after explaining the TPDS on more than three hundred pages, Morgan and Liker dedicate only 19 pages to the Lean transformation process. Although they emphasize that there "is no one roadmap for all companies" and that models using discrete phases in a linear order do not reflect reality, they provide a framework with five separate phases, each of which contains five to six activities [Morga 06] pp.347ff. Compared to the roadmaps discussed above, Morgan and Liker's approach provides more details on the order in which single parts of the Lean PD system should be implemented. However, just like the other roadmaps, Morgan and Liker's approach seems to be based more on intuitive feel rather than broad empirical data. They do not provide a solid reasoning why the sequence of steps chosen is considered to be superior to alternative solutions.

In summary, existing approaches to the introduction of Lean Product Development in literature tend to be vague, are not based on specific empirical data and rarely take into account the high amount of interdependencies between the different principles which have to be implemented. So far, guidelines for the implementation process are mainly treated as additional information to a previous detailed description of the Lean PD elements. A critical discussion on the alternative paths that can be taken does not exist.

While, in the light of the nascent discipline of Lean PD, the lack of well-grounded roadmaps is understandable, it offers interesting opportunities for research. As already Womack et al. point out in their groundbreaking publication "Lean Thinking" "even once you begin to see the importance of the five Lean principles, it's often hard to imagine how to install them in your own organization without a clear example of successful practice to follow, a template for action" [Womac 03] p.101. For a company that decides to implement its own Lean PD system, choosing the wrong path of implementation may lead to a waste of financial and human resources. Furthermore, experience with introducing Lean principles has shown that taking measures in a wrong order can not only have unintended negative effects on a company's performance but decisively threaten the stability of the operations. Thus, a coherent, experience-based roadmap for the implementation process can strongly contribute to a successful adaptation of Lean practices to the field of product development.

1.3 Goal of Research

Regarding the rising importance of Lean Product Development and an apparent lack of discussion in literature, the thesis at hand aims to examine how Lean principles can be successfully implemented in product development systems. Specifically, it shall be investigated which steps a company planning to introduce Lean PD has to take in which order to achieve the ultimate goal of developing and evolving a learning and continuously improving PD organization. Towards this end, a theoretical framework shall be developed which allows to systematically analyze the elements of a Lean PD system regarding their interdependencies. Based on this, hypotheses on the most efficient order of introducing Lean PD shall be derived. Using empirical data, it shall be shown what order of introducing the single parts of a Lean PD system is likely to require the least amount of resources and bears the largest potential for a successful implementation. Furthermore, it shall be investigated how the use of a particular infrastructure or supporting tools can contribute to the implementation process.

As the final outcome of this research, a roadmap shall to be developed which can be used by both companies which have not yet started their journey towards Lean Product Development as well as companies that have already taken the first steps. With the systematic development of a well-grounded "Lean Innovation Roadmap" this thesis intends to make an important contribution to the growing body of knowledge on Lean PD, serving both practitioners and scholars in this field.

1.4 Thesis Organization

The remainder of the thesis is structured as shown in Figure 1.1. At first, as a basis for subsequent sections, Chapters 2 and 3 discuss the basics of Lean Thinking and product development.

Building upon this theoretical background, in Chapters 4 and 5 the research framework is introduced. Chapter 4 reviews existing approaches towards Lean Product Development systems and provides a definition of a Lean PD system, consisting of eleven Lean PD components. In Chapter 5, the eleven Lean PD components are investigated with regard to their interdependencies. This serves to derive of a number of hypotheses regarding the introduction of Lean PD.

To test the hypotheses, this research uses a survey among a large number of international companies. The goal and structure of this survey as well as the sampling is described in Chapter 6. Chapter 7 provides the methodology and findings of a descriptive analysis of the survey data. The methodology and results of an in-depth exploratory analysis of the survey data are detailed in Chapter 8.

Chapter 9 consolidates the findings of the Chapters 7 and 8 and discusses the implications of the survey results for the implementation process of Lean PD. In this chapter, the hypotheses derived in Chapter 5 are tested.

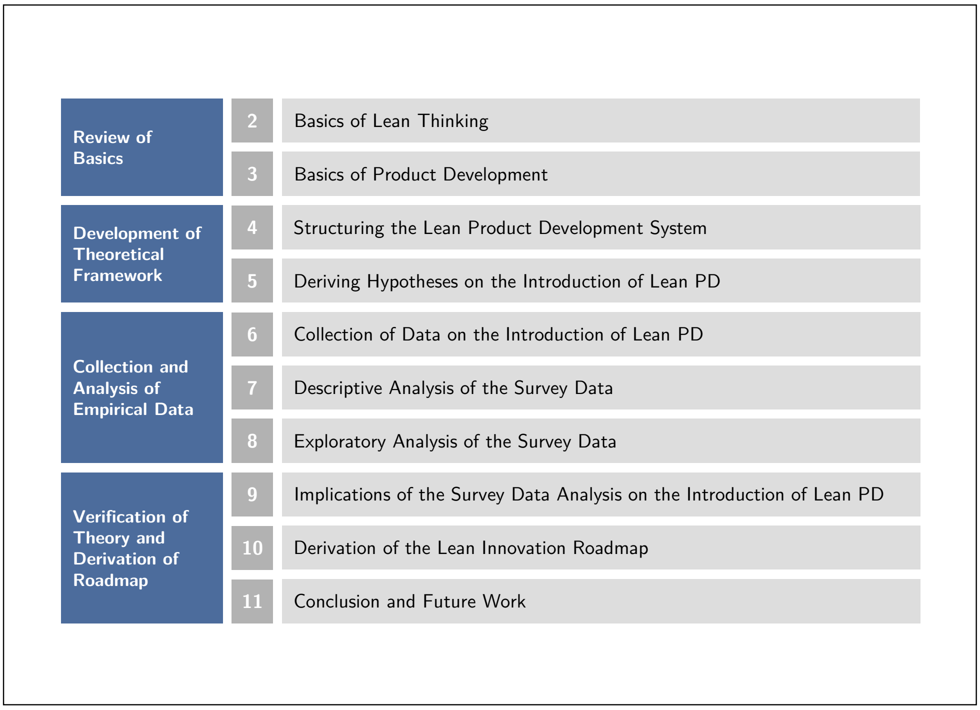


Figure 1.1: Structure of the thesis

Based on the findings of Chapter 9, Chapter 10 describes the derivation of the Lean Innovation Roadmap. After defining requirements the roadmap has to fulfill, two alternative approaches for deriving the roadmap are presented. The roadmap as well as its differences to existing roadmaps are discussed in detail.

This thesis concludes with a summary of the findings and contributions in Chapter 11. Possible research questions which might be addressed by future investigations are pointed out.

2 Basics of Lean Thinking

In what follows, as a basis for all subsequent chapters, the concept of Lean Thinking shall be described. In this context, first the origin and historical development of the concept is outlined. Hereafter, the goals and principles of Lean Thinking, which are also fundamental to the philosophy of Lean Product Development, are presented.

2.1 Lean Thinking in its Historical Context

The term "Lean" as a new paradigm of structuring and conducting business operations was coined 1990 by Womack et al. in "The Machine that Changed the World". In their comprehensive 5-million dollar 5-year study of the automotive industry, Womack et al. investigated differences in performance between leading western and Japanese automobile manufacturers. They compared defect rates, plant productivities, manufacturing lead-times, use of resources in engineering and development times and found that the Japanese manufacturers clearly outperformed their western competitors in all measures. For example, American and European manufacturers required on average 25.1 and 36.2 hours to produce a car respectively. Japanese car companies, in contrast, needed a time of only 16.8 hours while at the same time achieving a lower defect rate [Womac 90] p.92.

Although production was only one of the areas investigated in the "Machine that Changed the World", the large differences in manufacturing performance pointed out in the study attracted the largest interest. In their effort to explain the productivity gap, Womack et al. particularly investigated the Toyota Production System (TPS). They found that its underlying principles differed significantly from traditional ways of mass manufacturing employed by the western car manufacturers. Since, as the authors found, Toyota was able to do "more and more with less and less" Womack et al. baptized the concept "Lean Production" [Womac 03] p.9, [Womac 90] p.49.

Despite their close connection, the roots of the Toyota Production System go back much further than the term "Lean Production". The fundamentals of the TPS were laid in the 1950s when in the Post-World War II era Toyota was forced to manufacture a wide range of different models for small-volume markets [Ohno 93] p.27, [Womac 90] pp.49f. Taichi Ohno, who after 1947 was employed as a production manager in various plants at Toyota, conducted experiments with different arrangements of machines and generated workplaces where one worker was assigned to several machines [Ohno 93] p.38. Based on these experiments and the experience he had gathered when visiting plants mainly in the US, he developed a production system which was characterized by a particularly high flexibility. The principles and methods developed at Toyota were refined over the years and extended to include its suppliers [Ohno 93] p.59. Although the main ideas had been translated and published by Shigeo Shingo as the "Study of the Toyota Production System" in 1980, the new taxonomy developed by Toyota remained largely unknown in the western world until the beginning of the 90's of the 20th century [Woma 03] p.23.

Today, Lean principles have spread well beyond their origin in automotive manufacturing in two major dimensions. Firstly, Lean principles have been adapted by a variety of different sectors [Spear 99] pp.96ff, [Drew 05] pp.19, 21. Concepts like Lean Construction or Lean Healthcare which apply Lean in domains other than automotive are – although still in a nascent stage – gaining increasing attention. Secondly, in the last years there has been a growing awareness that the application of Lean to the area of manufacturing is by no means sufficient. Following the notion of the "Lean Enterprise", Lean principles are increasingly implemented from a lifecycle perspective, in corporate support functions as well as in leadership processes [Womac 94] p.93, [Murma 02] p.142.

To better understand the nature of Lean, in the following section, the general goal of Lean Thinking as well as the five Lean Principles shall be outlined.

2.2 Goal of Lean Thinking

Due to its ambiguous meaning, in the past the term Lean has led to some confusion. Lean Thinking has been interpreted as "doing the same work with fewer employees" or "creating flatter hierarchies". While any of these notions might in fact be observed as a side-effect of implementing Lean in a corporate environment, neither of these understandings fully covers the fundamental intention of Lean Thinking.

The central vision of Lean Thinking is an uninterrupted, continuously flowing value stream which delivers the desired customer value with the least waste of resources in the shortest time possible. The way to achieve this goal lies in identifying and eliminating all non-value adding activities, the so-called muda, and consistently aligning all required corporate activities to the customer. The result and a particular characteristic of any Lean system is a drastic reduction of the time required to deliver the value to the customer. This, in turn, goes along with a strongly increased responsiveness of a Lean Enterprise in all stages of the product life-cycle. [Womac 03] p.16, [Fiore 04] p.11, [Biche 04] pp.8ff

One might expect that the tremendously increased speed with which Lean systems operate comes at the cost of lower quality or higher monetary expenses. However, as reality shows, the opposite holds true. As a consequence of the strong focus on customer value as well as the comprehensive elimination of non-value adding activities an introduction of Lean can simultaneously reduce lead-times, save cost and improve quality. This rare combination of benefits is what makes Lean Thinking as a concept particularly attractive.

2.3 Lean Principles

In an effort to detail the goal of Lean Thinking and describe the transition path towards a Lean Enterprise, in the past different authors have presented principles they had identified to be characteristics of Lean systems. The most popular definition of Lean principles was published by Womack and Jones in the first edition of their book "Lean Thinking" [Womac 96]. According to their approach, Lean Thinking encompasses five major principles. These Lean Principles which at the same time represent a high-level guideline for implementing Lean, are displayed in Figure 2.1 and shall be outlined in the subsequent sections.

Although the principles are presented in separate sections, it should be noted that by no means they can be regarded as isolated, independent steps. In fact, the Lean principles are highly interconnected and have to be implemented in a body when striving towards the Lean Enterprise. This idea, which also has important implications for the following chapters, ought to be kept in mind when reading the following descriptions.

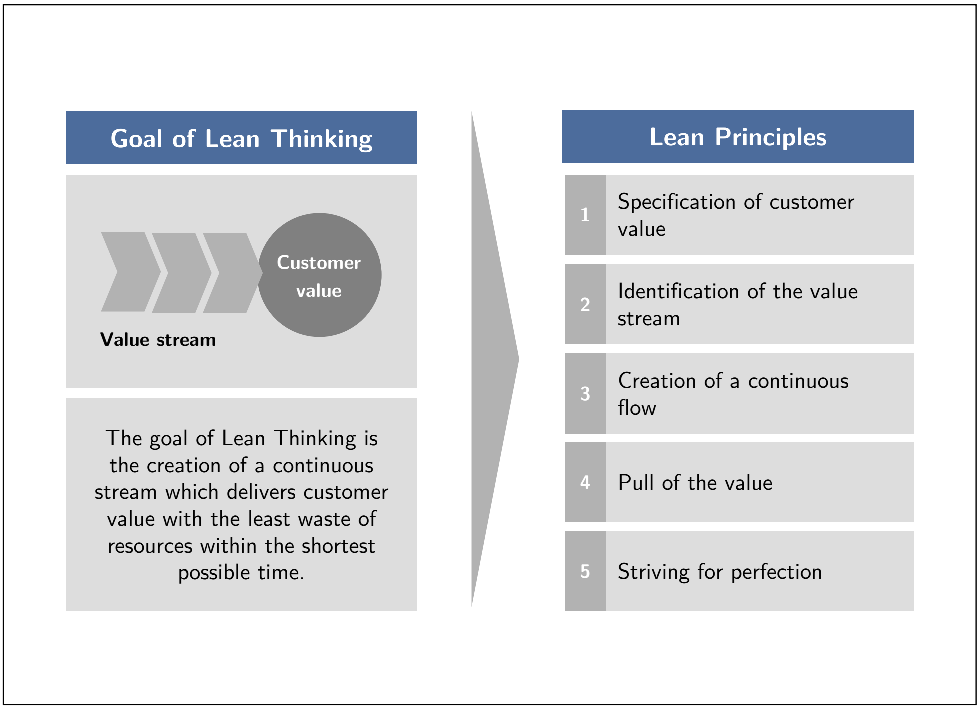


Figure 2.1: Goal and principles of Lean Thinking

2.3.1 Specification of Customer Value

The first Lean principle – and the basis for all following principles – is to specify the value as defined by the customer of the particular enterprise. As Womack and Jones strikingly point out, "providing the wrong good or service in the right way is muda" [Womac 03] p.19. Therefore, a company has to thoroughly analyze the needs of its customers and clarify which value the organization plans to deliver.

For a company confronted with a heterogeneous set of customers, specifying value is not a straight-forward task. While one customer might value a low price of a product, other customers might favor a high quality, a good performance, fast delivery or extraordinary service. Therefore, the appropriate value proposition of a company will strongly depend on the market segment it targets and strategic considerations on how it wants to position itself. Customer value for a company pursuing a penetration strategy will naturally differ from customer value as perceived by a producer of premium goods.

2.3.2 Identification of the Value Stream

Once a company has specified which value it plans to deliver to the customer, the next step of Lean Thinking is to identify all specific value-added and non-value added activities associated with the creation of the product or service. The sequence of these actions required to bring the product to market is called value stream. Since for a customer, value can consist of the creation of a physical product as well as the delivery of information, a company will typically have value streams for both of these objects. An example for the former is the physical transformation process which transforms the raw material into the final product. An example for the latter is the order management process flow which handles the information that goes along with each customer order [Fiore 04] p.23, [Womac 03] p.19. To achieve a holistic picture of its value streams and potentials for future improvements, a company should uncover all of the existing value streams beyond its own boundaries to include the entire value chain [Biche 04] p.10.

A tool frequently used for describing and analyzing the value stream is value stream mapping (VSM) [Rothe 99]. The detailed examination of a company's value streams using this tool allows to categorize activities according to their contribution to customer value. Next to those that unambiguously create value, usually a large proportion of activities can be found that are non-value adding. These non-value added activities, in turn, can be differentiated into those that do not create value but cannot be directly avoided with current technologies and production assets (Muda Type 1) and those that are directly avoidable (Muda Type 2). Waste of the latter category can be eliminated immediately. The elimination of Muda Type 1, in contrast, is more complicated and addressed by the following three Lean principles: the creation of a continuous flow, pull of value by the customer and striving for perfection [Womac 03] p.20, [Murma 02] p.99.

2.3.3 Creation of a Continuous Flow

After customer value has been specified, the value stream has been identified and obviously wasteful activities have been eliminated, the next step in Lean Thinking is to make the remaining, value-creating steps flow. The concept of flow is central to the philosophy of Lean and some authors go as far as to refer to it as a superordinate vision [Biche 04] p.8.

Traditionally, organizations are often structured in a strongly functional manner. Grouping similar functions at the same location is believed to allow for the highest amount of efficiency and the steepest learning curves through specialization. From a value stream perspective, however, this way of structuring organizations may bear large disadvantages. Whenever functional divisions are geographically separated, physical goods travel long distances between subsequent value-adding activities. Hence, for economic reasons, functionally structured organizations are often forced to work with batches. The use of batches, however, significantly prolongs the lead-time of a product because in a batch-oriented organization, rather than being processed, the product spends most of its time in an intermediate storage facility. At the same time, storing usually has negative effects on the quality of the product. Large inventories of goods go along with increased probability of damages, decreased orderliness and reduced possibilities for quality checks. [Womac 03] pp.21f

It is for these reasons that Lean Thinking proposes a flow-oriented instead of a strictly function-oriented way of structuring an organization. In manufacturing, flow is achieved through the physical alignment of formerly separated functional tasks, the reduction of batch sizes and a harmonization of activities using takt times and workload leveling. In domains not primarily dealing with physical goods, such as product development, the flow of value cannot be observed as easily. As will be discussed in Chapters 3 and 4, here, the implementation of a continuously flowing value stream is a more challenging task.

2.3.4 Pull of Value by the Customer

The usually drastic reductions in lead-times which can be achieved when applying the principle of continuous flow are an important prerequisite for the next Lean principle: the pull of value by the customer. Strictly speaking, the concept of pull means that all processes along the value stream are triggered by the customer. A product is only created if there is a concrete demand by the customer. [Fiore 04] pp.17f

Since in the Lean Philosophy the definition of the customer includes not only the external customer but also subsequent value adding activities as internal customers, the concept of pull can be separated into two levels. On the macro level, between the company and the external customer, the concept of pull is identical to build-to-order. Products are not manufactured to stock but produced to fulfill an instant customer request [Biche 04] p.11. On the micro level, pull means that none of the upstream stations in the value chain produces a good before it is actually required in the subsequent downstream station. This concept has become widely known as just-in-time (JIT).

The advantage of pull compared to traditional push systems lies in its inherent responsiveness. In traditional push systems, production of service or goods is managed by a central planning system which forecasts customer demand, generates a production program and determines the quantities to be produced by the single working stations in the value chain. Due to uncertainties in forecasting and unintended disruptions in the production process, however, this approach requires the use of time buffers which lead to over-production, inventories and waiting time. To avoid these shortcomings, pull systems largely forego on centralized planning and use methods like kanban to signalize demand through direct communication between subsequent working stations [Liker 04] pp.106f. The introduction of the pull principle usually leads to a significant reduction of inventories. By eliminating the safety buffers, however, at the same time the whole system becomes more vulnerable for perturbances. Process bottlenecks and quality problems which were previously covered by high safety stocks become obvious. This offers the opportunity to identify and eliminate the actual root causes of problems [Biche 04] p.18.

2.3.5 Striving for Perfection

The last and most challenging – because never-ending – Lean principle is striving for perfection. The goal of this principle is to create a perfect value-adding process through an ideal implementation of the previously mentioned principles and the delivery of flawless products to the customer. Towards this end, striving for perfection includes a systematic avoidance of errors in the value-adding processes as well as a continuous improvement of all processes.

The need for a systematic avoidance of errors is a direct result of the observation that the cost for correcting an error is significantly higher in late phases than with early detection. Therefore, it is imperative that in a Lean Enterprise flawed parts be not passed on to the next working station. The margin of error has to be reduced to the minimum. Instead of reworking the finished product, errors, when made, have to be corrected immediately [Liker 04] p.129, [Liker 06] pp.71ff. A critical enabler for a systematic avoidance of errors is a high amount of transparency. Employees have to be able to assess the result of their work with regard to clearly defined quality attributes. Error rates have to be published and tracked over time so that employees are sensitized to their personal impact on product quality [Liker 04] p.130, [Biche 04] p.61.

Although important, in the long run for a Lean Enterprise, simply avoiding errors is not sufficient. To remain competitive, Lean Thinking requires a continuous improvement of all processes, the so called kaizen [Biche 04] p.148. Kaizen strongly contrasts with traditional top-down improvement efforts traditionally initiated by management. The core idea of the concept is to use the expertise, detailed knowledge and creativity of every single employee and incentivize them to make suggestions on how to improve their own working environment. Improvements are usually done in small steps with short planning periods and low investment. This, in turn, largely reduces the risk of missing the goal of the improvement efforts and allows for an easy correction of unfavorable changes [Dickm 07] p.19.

The principle of striving for perfection, as described above, is the last of the five Lean principles. After in this chapter the basics of Lean have been outlined, the following chapter deals with the basics of product development.

3 Basics of Product Development

Before being able to apply the concept of Lean Thinking to the field of product development, it is necessary to first give a clear definition of a product development system. For this purpose, Section 3.1 discusses the system boundaries of the product development system in the context of the larger corporate enterprise system. The subsequent Sections 3.2 and 3.3 investigate the particularities of "value" and "value stream" for the domain of product development in greater detail.

3.1 Boundaries of the Product Development System

As pointed out in Section 2.3.2, a corporate enterprise will usually have several value streams which can be distinguished according to the object they deliver to the customer. While, for example, the main objective of a value stream in production is to create physical value, there is a large number of processes within a company focusing on the generation and exchange of information. Four major value streams of a company which develops and manufactures products to deliver them to the customer are depicted in Figure 3.1.

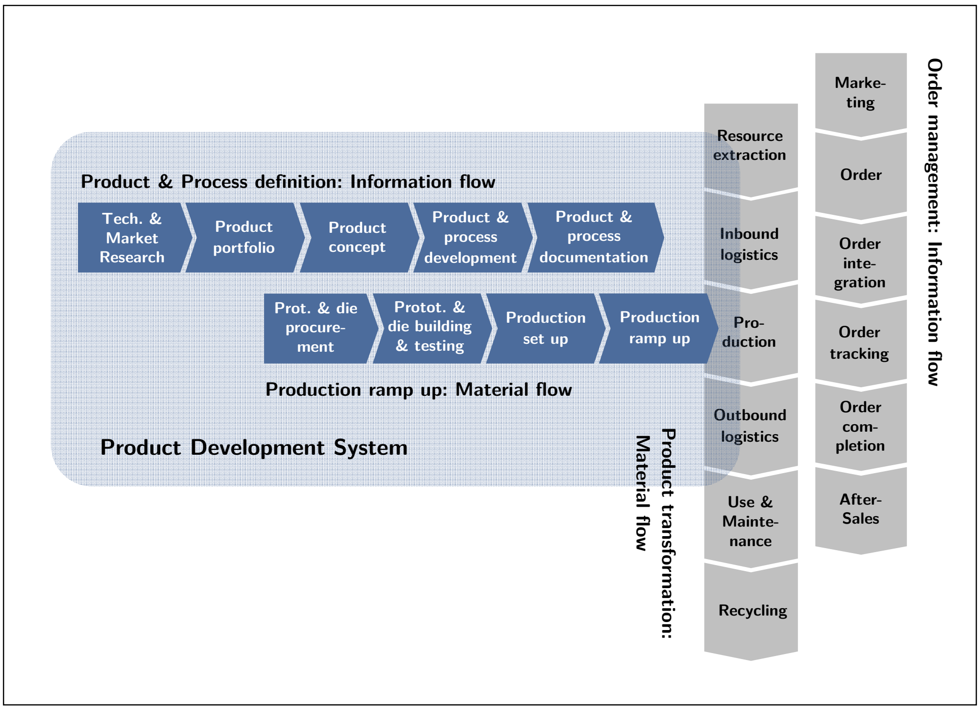


Figure 3.1: System boundaries of the product development system

Running in vertical direction, Figure 3.1 shows two streams of activities a company has to execute as part of its business of selling products to customers. First, with the help of marketing, an order is generated which in turn triggers the production of the good to be delivered. The consequent product transformation flow, encompassing the process of physical transformation from resource extraction to recycling, runs in parallel to the order management to ensure that the right products are delivered to the right customer at the right time.

In the short-term, a company which possesses value streams for order management and product transformation is able to successfully satisfy customer demands for products and related information. For a company acting in a competitive environment, the ability to deliver a certain set of products to the customer, however, is not sufficient. Technological advancement requires to constantly update both the product design as well as the processes and equipment used to produce them. For this purpose, a company has the two value streams of product and process definition and production ramp up, shown as horizontal flows in Figure 3.1. These value streams run at a pace that differs from that of the vertical value streams. The product and process definition flow defines the information on the product to be delivered to the customer and, hence, ends in the product transformation value stream. Along with this information flow of product and process definition goes a material flow which includes testing, prototyping and production ramp up in order to achieve a seamless innovation of products and processes in the vertical product transformation value stream.

In this work, the sum of activities in the two horizontal value streams will be defined as the product development system. According to this definition, product development includes all processes necessary to generate and document the information required to successfully produce the physical product in the product transformation stream and ensure a smooth ramp up of production for the newly defined product [Wheel 92] p.7, [Ulric 95] p.9, [Walto 99] pp.12ff. The next Section 3.2 will shed more light on the detailed goals of product development and discuss the resulting definition of value and waste in this field.

3.2 Value and Waste in Product Development

As mentioned before, product development and production differ significantly regarding their intended outcome. Production converts physical resources into a tangible product which is then sold to the customer. In contrast to this, rather than directly producing a good to be sold, product development creates documented knowledge on the product and the production processes required to produce the product. The customer of product development is not only the end user. In fact, product development has to consider the expectations and needs of a large number of stakeholders along the product transformation process, ranging from the suppliers of resources and parts, operations divisions, maintenance personnel and product users to recycling. [Ward 07] pp.9, 18, 27, [Haque 04] p.10, [Oppen 04] p.355

It is due to this large number of different customers that value in product development is harder to define than in production. In production value consists in manufacturing a particular product at the right time with high quality and short lead times at a low cost. Since the desired product dimensions, material and production processes are predefined, the desired and actual outcome of the production process can be compared. Value in production therefore is usually directly measurable.

In product development, value is a compromise of meeting complex and conflicting stakeholder expectations [Oehme 05] pp.12f. Manufacturing has to be able to easily produce the product. The user demands high functionality and usability of the product. Recycling and service are interested in a product which is easy to disassemble and reuse. These different dimensions of value product development generates are displayed in Figure 3.2, which shows the product development system as a generic input/output model. As inputs, the product development process requires financial investment, engineers and time. As an output, product development generates information which allows manufacturability, functionality and usability as well as serviceability and recycling of the product. These outputs, representing the value a product development system, should be maximized if one aims to improve the performance of the system. At the same time, an increase in inputs which does not lead to an improved output represents waste which ought to be minimized. [McMan 02] p.3, [Chase 00] pp.6ff

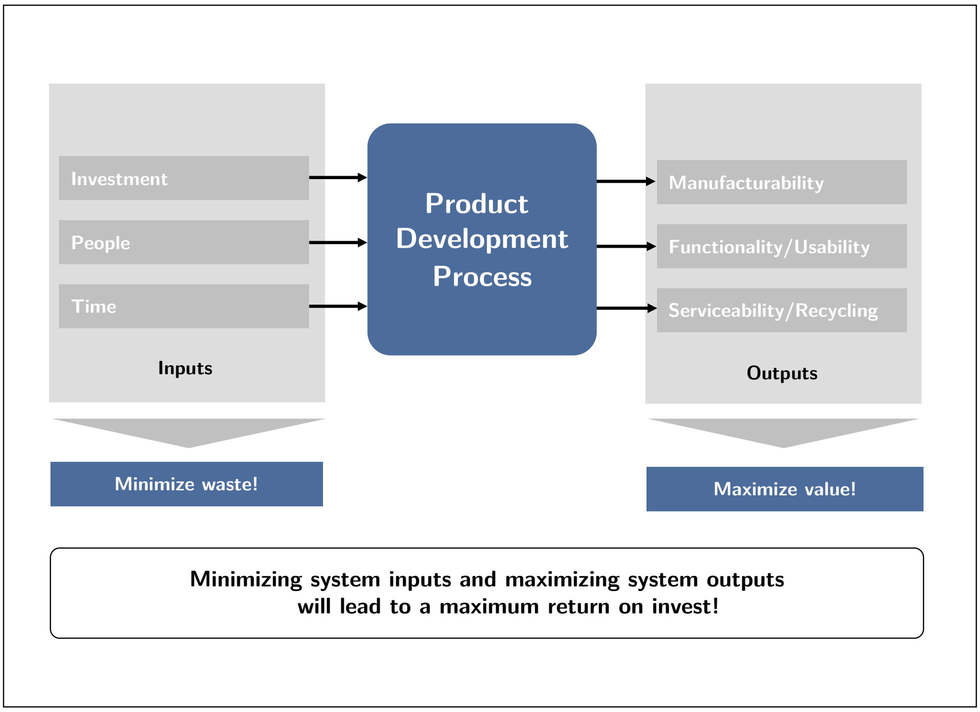


Figure 3.2: Waste and value in product development

The exact nature and sources of potential wastes in product development have been the subject of a considerable number of publications. A detailed description of the different concepts that have been developed is beyond the scope of this work. Some authors have used the concept of seven wastes, which describes causes of non-value-added activities in production, and adapted it to product development [Milla 01], [McMan 02], [Fiore 04] p.32. Others, through detailed observation of product development systems, derived new categorizations of wastes particularly suited for product development activities [Morga 02], [Ward 07], [Graeb 07] p.45, [Kato 05] p.39, [Masci 07] p.18, [Pesso 08] pp.15f. An overview of existing approaches to waste in product development, their similarities and differences is given by Bauch [Bauch 04] p.107.

It should be noted that, while both eliminating waste rather than on increasing value can yield a better performance of a system, the concept of Lean Production has strongly focused on the first strategy. This phenomenon can likely be traced back to the fact that value creation in production is bounded by the product and process specifications it receives from product development. Since production operates on predefined goals, its opportunity of value creation is inherently limited. Compared to this, even though not free of constraints, the phase of product development offers much more flexibility for value creation. As a consequence, applying Lean to product development will differ from Lean Production in the way that it requires a much more balanced approach of simultaneously minimizing waste and maximizing value. In fact, even more than combating waste, applying Lean principles to product development can play an important role in fostering innovation and long-term organizational learning. [Oppen 04] p.353, [Brown 00] pp.168f

3.3 Value Stream in Product Development

In the previous section it was pointed out that product development and production differ significantly with regard to the goals they pursue. Production intends to *create value* through the transformation of a physical entities according to previously defined specifications. In contrast to this, the task of product development essentially is to *define the value* to be created in production. From a theoretical point of view, production can therefore be described as an execution system, product development as a planning system. This observation is of particular importance as it has major implications for the objects dealt with in the value streams, the amount of repetition allowed and the time required for the objects to flow through the stream.

In production, the value stream is represented by the flow of information and material through subsequent working stations which continuously add value to the product. Since the dominant flow in production is the flow of the physical product, the value-adding process can actually be observed in reality. In product development, the dominant stream is not the flow of material but the flow of information [McMan 02] p.1, [Haque 04] p.15. Just like in production, the information flows through subsequent working stations and is transformed to add value. However, information as an object is much more elusive than a physical part and its flow much harder to observe [Fiore 04] p.30, [Garza 05] p.48. Information can be transmitted in various ways using oral or written communication and effortlessly travels long distances, not requiring geographical proximity of subsequent working stations.

While production operates with clearly defined goals and tries to minimize variation in outcome as much as possible, in product development variability can and should not be fully eliminated [Schuh 07-1] p.1. It is the purpose of product development as the planning system to generate information that has not been generated in exactly the same way before. Only through the deviation from existing definitions of products, a product development system can serve as the source for innovation [Kenne 03] p.135. Typically, in product development every unit flowing through a particular working station is unique and the information generated different from the one generated before. As a result, since the outcome cannot be fully predicted in advance, product development activities are subject to considerable uncertainty [McMan 05] p.17. They often assume an iterative or cyclic nature [Oppen 04] p.368, [Reine 05] p.40, [Morga 02]. In this sense, product development, despite opposing trends, remains a creative task that is hard to automate and strongly relies on human labor. This constitutes a stark contrast to mass and serial production, where the same value-adding process is repeated for a large number of units, is often highly automated and product flow is largely linear. In consequence, time product development tasks usually require a much longer time to complete than production activities. Time in production is measured in seconds, minutes and hours, product development cycles take weeks, months and years [Schuh 07-1] p.1. Figure 3.3 summarizes the differences between the value streams in production and product development.

	Production	Product Development
Goal	Goal is value creation, i.e. value to be created has been specified in advance and has to be created with the least variation possible	Goal is value definition, i.e. value to be created in manufacturing is planned and the outcome is not exactly known in advance
Object	Product flows through working stations where product is transformed (value)	Information flows through working stations where new information (value) is added
Time frame	Product transformation typically takes only short time (seconds, minutes, hours)	Information transformation takes longer time (hours, days, months, years)
Repetition	High amount of repetition (same value adding process is repeated for a large number of units of the same product)	Ideally no repetition (same information generation process is used for only one unit; only fragments of information from previous products can be reused)

Figure 3.3: Value stream in production and product development

With the discussion of Lean Thinking in Chapter 2 and the detailed investigation of the concepts of value, waste and value stream in the context of product development in this chapter, the foundation for investigating the concept of Lean Product Development is laid. In the subsequent Chapter 4, the existing approaches towards the application of Lean principles in product development will be discussed. Furthermore, a definition of a Lean PD system, consisting of eleven Lean PD components, will be presented.

4 Structuring the Lean Product Development System

The previous Chapters 2 and 3 covered the basics of Lean Thinking and outlined the general characteristics of product development systems. This chapter will build upon these basics, bring the information of the two separate trains of thoughts together and introduce the concept of Lean Product Development. First, based on a comprehensive literature review, Section 4.1 will present existing approaches to the question of how Lean principles can be applied to product development. This review in turn serves as the basis to discuss the structure of a Lean PD system in greater detail. Towards this end, Section 4.2 proposes a comprehensive framework of 11 Lean Product Development components which were found to represent important parts of a Lean PD system.

4.1 Existing Approaches to Lean Product Development

The discussion of value, waste and the value stream in product development in Chapter 3 made clear that product development and production differ considerably in a number of different aspects. In literature, this notion has led to the conclusion that, although the five Lean principles described in Section 2.3 are generally valid and can thus be applied to the domain of product development, creating a Lean Product Development system requires a different methodological approach than Lean Production [Schuh 07-1] p.1. Components and structures that have been found to support an efficient and effective product development process show only few similarities between production and product development [Haque 04] p.8. Therefore, most of the authors, rather than simply adopting tools from the manufacturing shopfloor, have taken the approach of investigating and identifying best practices in the field of product development that leverage the benefits of the five Lean principles. In the following, a selection of the most prominent approaches that have been suggested by various authors shall be briefly presented. The detailed description of the single components of Lean PD is not part of this section but the following Section 4.2.

The basis for the theory of Lean Product Development, although not yet termed this way, was laid through a series of detailed studies of product development systems by Clark, Chew, Fujimoto and Sheriff even before "The Machine that Changed the World" was published. In their study "Product Development in the World Auto Industry", published in 1987, Clark et al. compare the product development performance of 22 projects of international automotive manufacturers and find that Japanese companies outperform North American and European competitors particularly with regard to engineering hours and lead time. European and American development projects on average require about 3.5 million engineering hours and take about 62 months. Projects of Japanese car manufacturers – despite including a higher number of unique parts – are completed on average with 1.155 million engineering hours within 42.6 months [Clark 87] p.741. Based on a number of statistical tests, Clark et al. attribute this difference in productivity to the strong involvement of suppliers in the design process and the role of a "heavy-weight project manager" with extensive authority who leads the multifunctional teams through the problem-solving cycles. In addition, Clark et al. find that Japanese product development projects make use of overlapping development stages to a larger extent than projects of European or American car manufacturers [Clark 87] p.766. The hypothesis that this overlap could contribute to the significantly shorter lead times was subsequently confirmed by follow-up analyses conducted by Fujimoto, Clark and Sheriff [Clark 89], [Fujim 89], [Cusum 90] p.18.

In "The Machine that Changed the World", Womack et al. take on the detailed findings of Clark, Chew, Fujimoto and Sheriff and elaborate on the potential explanations for the tremendous difference in product development performance between Japanese and western automobile manufacturers. While the major impact of their book has been in the area of manufacturing, more than 30 pages of "The Machine that Changed the World" are dedicated to the idea of Lean Design and Lean Product Development [Womac 91] pp.104ff. Under the title of "techniques for lean design" Womack et al. identify four major design methods that differentiate a mass from a lean producer: a powerful project leader with a strong authority, teamwork, early and controlled communication and simultaneous development [Womac 91] pp.112ff.

In the following years, the idea of overlapping phases and simultaneous development was the one that attracted the most interest of researchers and practitioners. In their effort to find methods to shorten lead times, a number of authors studied cross-functional integration, team structures as well as communication and coordination techniques [Liker 96] p.165. The new findings resulted in expansions of the four characteristics of Womack. As an example, Karlsson and Ahlstrom, studying the product development system of a manufacturer of mechanical and electrical office equipment, developed their own interpretation of Lean Product Development. According to their definition, Lean PD comprises six techniques, which are supplier involvement, simultaneous engineering, cross-functional teams, integration of activities, a heavy-weight team structure and strategic management of projects [Karls 96] p.285.

The strong focus on simultaneous development as the reason for the superior performance of Japanese car manufacturers in product development was in part questioned by the findings of Ward et al. who pointed out that the best in class, Toyota, neither collocated its teams nor intensively communicated with its suppliers [Ward 95] p.43, [Liker 96] p.167. Building on experiments with design automation conducted by Ward and Seering and intensive studies of practices at Toyota, Ward et al. developed what they called set-based concurrent engineering. In essence, they found that paradoxically, in the case of Toyota, delaying decisions and following a large number of alternatives for the same product module can contribute to better and faster product development [Ward 95] p.44, [Liker 96] p.168.

The theory of set-based concurrent engineering, particularly attractive due to its counter-intuitive nature, was a strong impulse for the revision and expansion of existing Lean Product Development concepts. In a manuscript from 2001, published posthumously in 2007, Ward describes a Lean Product Development system consisting of five major principles: "value focus", "entrepreneur system designer", "set-based concurrent engineering", "cadence, flow and pull" and a "team of responsible experts" [Ward 07] pp.59ff. Kennedy, referring to work with Ward during a study at the National Center for Manufacturing Sciences, names set-based concurrent engineering as one of the four critical elements of Lean PD next to "system designer entrepreneurial leadership", "responsibility-based planning and control" and an "expert engineering workforce" [Kenne 03] pp.120, 212.

To further explore the particularities of Toyota's approach, Morgan conducted a two-and-a-half year in-depth study of Toyota's product development system. Through more than 1,000 hours of interviews held with Toyota and supplier representatives at different sites in the US and Japan, Morgan tried to answer the fundamental question what underlying characteristics made Toyota's approach to product development so successful. Together with Liker, who had been strongly involved in the investigation of set-based engineering, Morgan published his findings in "The Toyota Product Development System". In the book, the authors identify 13 Lean Product Development principles they group into the three broad categories process, people and technology. [Morga 06] pp.4f, 18

The comprehensive and detailed description of Toyota practices given by Morgan and Liker has induced researchers to test whether the principles described as the reasons for Toyota's success could be found to foster better product development performance in other companies as well. Towards this end, in two independent studies Brown and Schuh et al. surveyed 400 and 143 manufacturing firms respectively and linked the use of particular Lean PD practices to performance indicators [Brown 07] p.16, [Schuh 07-2] p.4. Both find that the use of particular practices is correlated with the success of product development projects as measured by the adherence to schedule, product and product development costs, product quality, revenues and market share. Interestingly, these practices show strong overlap with the principles of Lean Product Development defined by Morgan and Liker. Schuh et al., based on their findings, describe 10 key principles which are motivation, value system, design sets, product architecture, product line optimization, value stream definition, capacity planning, synchronization, perfection and derivation [Schuh 08] p.1133. Brown lists 13 components he identifies to have the largest impact on improving performance [Brown 07] p.10.

In sum, a multitude of different approaches to Lean PD have been described in literature. So far, none of these approaches has found wide-spread and general acceptance. Since a consistent definition of Lean PD, however, is of great importance for this thesis, the following section will present a framework comprising 11 components which summarizes and integrates the different approaches outlined in this section. After describing the general structure of the framework and briefly comparing it to the definitions of Lean Product Development given in this section, the single components will be described in greater detail.

4.2 Components of Lean Product Development

The main focus of this thesis is to discuss the question of how Lean principles can be introduced in the domain of product development. Before one is able to deal with *how* Lean Product Development can be implemented, however, it is of superordinate importance to first have a clear idea of *what* should be implemented. The previous chapter showed that different authors have identified particular sets of success factors of PD systems which show apparent overlaps. However, as could be seen, the focus and number of components varies from author to author.

To eliminate this heterogeneity and have a well-founded basis for discussion, in a first step towards a Lean PD roadmap the multitude of different definitions of Lean PD described in literature were integrated into a single, comprehensive and consistent framework. For this purpose, the approaches described in the previous section were scanned for characteristics of a Lean PD system. The extracted characteristics were then analyzed regarding their content and subsumed under clearly differentiable categories. In sum, eleven Lean PD components could be identified this way (see Figure 4.1). In their concurrence, these eleven components result in the application of the five general Lean principles of Section 2.3 in product development and build the Lean PD system as defined in this thesis.

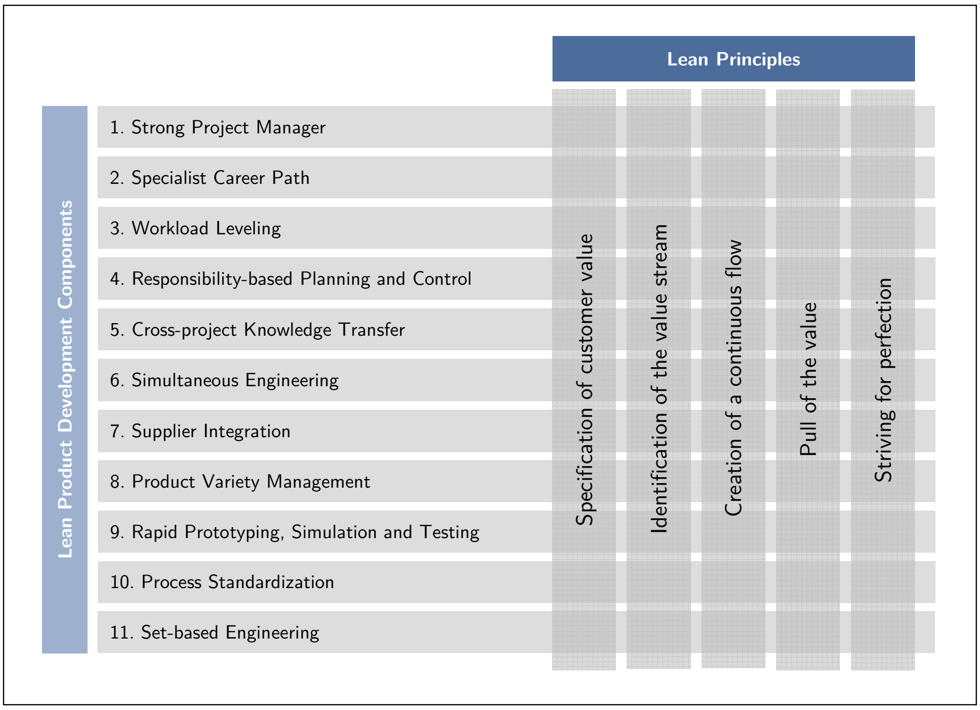


Figure 4.1: The eleven components of Lean Product Development

To give a better idea of their origin and their use by different authors, Table 4.1 details how the 11 Lean PD components of Figure 4.1 relate to the approaches described in Section 4.1.

Table 4.1: Different approaches to Lean PD

Lean PD Component	Clark et al. 1987	Womack et al. 1991	Karlsson and Ahlstrom 1996	Ward 2001	Kennedy 2003	Morgan and Liker 2006	Brown 2007	Schuh 2008
Strong Project Manager	X	X	X	X	X	X		X
Specialist Career Path				X	X	X		
Workload Leveling			X			X	X	X
Responsibility-based Planning and Control				X	X	X	X	X
Cross-project Knowledge Transfer						X	X	
Simultaneous Engineering	X	X	X			X	X	
Supplier Integration	X		X			X		
Product Variety Management						X		X
Rapid Prototyping, Simulation and Testing						X	X	
Process Standardization						X	X	X
Set-based Engineering				X	X	X	X	X

Table 4.1 shows that in the literature covered in Section 4.1, most authors, when describing key principles of Lean PD, focus on a rather small number of components. The only approach which comprises all eleven Lean PD components building the framework of this thesis is the one by Morgan and Liker. Their framework was found to be very comprehensive. However, since Morgan and Liker describe 13 general Lean PD principles, it was considered necessary to restructure their broad and sometimes not mutually exclusive categories into more operationalizable components.

Furthermore, it should be noted that the number of components in the table listed for a particular author differs from the one described in Section 4.1. This is due to the fact that related concepts described by authors as separate success factors were sometimes summarized to build one Lean PD component in the framework. As an example, the success factors of simultaneous engineering and cross-functional teams, listed as different parts by Karlsson and Ahlstrom, were, since related, subsumed under the common heading of "simultaneous engineering".

In what follows, the eleven Lean PD components shall be described in greater detail. Although, for reasons of presentation, the components are presented in separate sections, this should not imply that the components are not connected. In fact, in Chapter 5 it will be hypothesized that the Lean PD components are highly interdependent, reinforce each other and thus build a complex system. This notion ought to be kept in mind when reading the following sections.

4.2.1 Strong Project Manager

The concept of the Strong Project Manager is one of the oldest and most publicized aspects of a Lean PD system. Also known as the "Heavyweight Project Manager" or the "Chief Engineer", the concept was first used in the Japanese defense industry and subsequently adopted by Toyota in the 1950s. Its basic idea is to introduce the role of an experienced project manager who leads the development projects from concept definition to market and is ultimately responsible for delivering value to the customer [Morga 06] pp.30, 118f.

The use of project managers in research and development is not unusual. In fact, most organizations have a person who is responsible for coordinating the different functions involved in the design of a product and ensures that time and budget goals are met. The tasks of a strong project manager, however, go beyond the sole management and integration of functions with regard to several aspects [Womac 90] p.113.

First, in many traditional product development systems the concept for a product is developed by the marketing department and then handed over to the product designers. In contrast to this, in a Lean PD system it is the strong project manager who is responsible for investigating and defining customer value. At the beginning of a project at Toyota, the Chief Engineer and his support team usually put themselves in the shoes of the customer. They immerse themselves in the use of products similar to the one they intend to develop and, drawing on customer research and competitive benchmarks, gather as much information on the product as possible [Morga 06] p.260, [Balle 05] p.19. This way, they try to understand what exactly the customer values and how the new product can meet these expectations. The customer requirements are then documented in the form of a concept paper, presented to management, evaluated, refined and eventually translated into a product definition [Morga 06] p.260, [Ward 07] p.103. This product definition serves as a basis for a comprehensive study phase which examines ways of translating the product definition into precise lower level goals for the single functional engineers. It is the role of the Chief Engineer as the "voice of the customer" to ensure that program objectives and the goals among the cross-functional team are well aligned [Haque 04] p.9. This includes not only the definition of project milestones and negotiation of deadlines with development engineers but also the derivation of clear cost and performance targets for particular components.

The adherence to the project schedule, cost and performance targets set at the beginning of the project is continuously checked by the strong project manager during the actual design phase [Schuh 07-2] p.4. The project manager communicates directly and frequently with designers and engineers. In contrast to the role of a classical project manager, however, his role is not limited to administrative tasks, personnel decisions and project controlling. Instead, the strong project manager is strongly involved in the development of the technical details. Ideally, he is the most experienced and knowledgeable engineer on the project, makes major component choices and chooses the technology used for the product [Morga 06] p.45. While the engineers focus on the development of detailed solutions for components, the strong project manager as the lead engineer is mainly concerned with the integration of these subsystems to an overall high-performance, high-quality system [Morga 06] p.21. He ensures that the value stream across different functions is aligned and advocates the project throughout the enterprise. He "owns" the program and, due to his far-reaching leeway, can be held fully responsible for its outcome [Oppen 04] p.368, [Karls 96] p.285, [Sobek 99] pp.72f, [Kenne 03] p.101, [Ward 07] p.74.

In a seemingly paradoxical manner, despite the large responsibility that the strong project manager has, his formal authority, for example at Toyota, has been found to be very limited [Morga 06] p.130. At Toyota, the Chief Engineer is embedded into a matrix organization as shown in Figure 4.2. The Chief Engineers, leading the vehicle programs, draw on resources from different, highly specialized functional domains. Apart from a small team of staff, however, the engineers on the program do not directly report to the Chief Engineer. In fact, it is the functional managers who supervise the engineers, assign them to projects, evaluate their performance and decide on promotions [Morga 06] p.132. This way of task distribution among the functional manager and the Chief Engineer relieves the latter from administrative work and promotes clear responsibilities. At the same time, however, it leads to a situation where the Chief Engineer depends on the functions to supply the necessary resources for the project. This lack of formal authority of the Chief Engineer has to be compensated by a surplus of informal authority. In the case of Toyota, Chief engineers are highly experienced and recognized for both their extraordinary technical as well as interpersonal skills. They often have worked in their particular technical domain for decades, have strong leadership qualities and, due to their abilities, are often more admired than Toyota's directors or vice presidents [Morga 06] p.119, [Kenne 03] p.134, [Ward 07] p.94, [Balle 05] p.20, [Oppen 04] p.368.

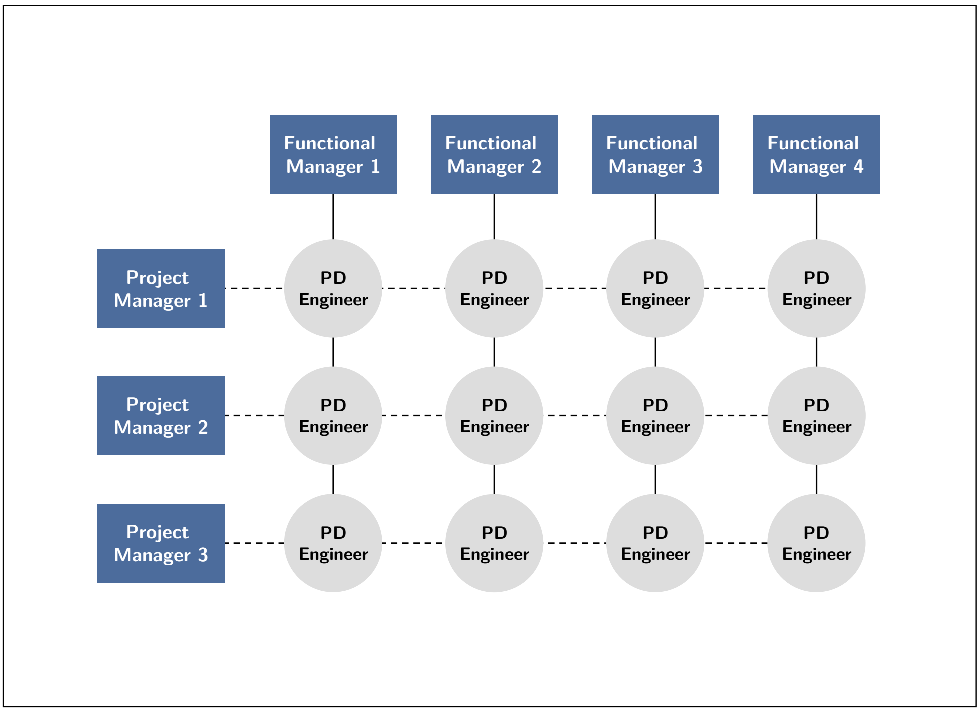


Figure 4.2: Product development matrix organization

4.2.2 Specialist Career Path

As discussed in the previous section, the role of the strong project manager ensures customer orientation throughout the entire duration of a project. This coordination function is of major importance for the success of a product development project. Nevertheless, in literature it has been noted that a pure product line organization, i.e. a strong focus on the project dimension of the matrix, goes along with a number of disadvantages. Considering the complexity of problems which have to be solved in the course of a PD project, it is indispensable to make use of technical specialists with dedicated expertise in a particular field. To develop this expertise and foster the exchange of knowledge among specialists of the same domain, engineers are traditionally assigned to functional divisions. As Womack and Jones point out, the functions serve as schools which continuously gather knowledge and best practices and teach it to their members. This ensures that engineers have a standard skillset which enables them to fulfill their particular tasks on the project teams in the best way possible. [Ward 07] p.71, [Haque 04] p.9, [Womac 94] pp.99f

In traditional organizations, engineers often do not spend a long period of time in the same functional division. Career paths are built in a way that with promotions technical focus gets increasingly substituted by general management and administrative tasks. It has been observed that this practice seems to be less used by companies following Lean principles. Engineers in Lean companies tend to stay within their technical position for a much longer period of time than engineers in traditional companies [Ward 07] p.197. Furthermore, to give engineers the possibility to gather more experience in their particular functional domain, many lean companies have introduced designated specialist career paths that promote the development of technical expertise in a field [Schuh 07-2] p.4.

One of the companies making strong use of a specialist career path is Toyota. It usually requires a Toyota engineer a minimum of 10 to 12 years before he or she becomes eligible for promotion to a first-level management position [Morga 06] p.172. New hires, after being selected in a rigorous admission process, first have to spend about half a year assembling and selling cars. This procedure is supposed to increase their understanding of value as perceived by the end customer and production [Ward 07] p.194, [Morga 06] p.22. Following this period, engineers spend another three to four years with intensive training before being considered a serious team contributor. In body engineering it requires five or six more years until the engineer reaches the level of a first-rate engineer [Morga 06] p.112. Throughout all this development period, cross-functional rotation is unlikely to occur [Balle 05] p.21.

Toyota, in order to promote technical expertise and a standardized skill set among its engineers, invests heavily in their development. From the beginning, following the traditional Toyota philosophy of Genchi Genbutsu, engineers are given hands-on problems which aims to make them familiar with the Toyota way of product development [Morga 06] p.174. During this intensive training on the job, which includes a four- to nine-month freshman project, they are closely supervised by a designated mentor [Ward 07] p.196. Until they have achieved a certain level of skill, the mentor double-checks every draft developed and action taken by the engineer [Ward 07] p.194. Furthermore, performance and potential areas for improvement are discussed in feedback interviews which are held on a regular basis for six to eight years [Sobek 98] pp.36ff. The performance of engineers is regularly evaluated with regard to the demonstrated level of technical competence as well as the adherence to Toyota processes and standards [Morga 06] p.164. Using Hansei events, engineers are encouraged to reflect about their weaknesses which ought to be addressed in their further development. Assignments for engineers are chosen such that they ensure a continued technical growth and provide the engineer with the necessary set of standard skills. Based on the level of their demonstrated skill set and their adherence to standard procedures, engineers then slowly climb up the career ladder [Morga 06] p.112, [Ward 07] p.198.

The fact that Toyota has a well-defined advancement path for engineers and uses technical expertise as the main criterion for promotion has strong implications for the company's management culture. At Toyota, management hierarchy is a skill-based hierarchy [Morga 06] p.21. Since supervisors have taken the same technical career path their subordinates are on, they are usually more knowledgeable in technical aspects than the engineers reporting to them [Morga 06] p.164. The high technical expertise of managers, in turn, is the reason why Toyota can make comprehensive use of mentoring as one of its core leadership principles. It is mainly through the extensive use of mentoring in combination with direct hands-on experience that engineers in a Lean PD system gain technical expertise [Morga 06] p.163. Managers at Toyota are seen as both excellent engineers and great teachers who have a strong interest in developing the people within their function [Sobek 99] p.72. By fostering the role of management as a mentor for subordinates, Toyota succeeds in handing tacit knowledge from one generation to another and constantly developing engineers with a strong, standardized technical skill set. Specialist career paths can therefore be considered an important element of organizational learning [Schuh 07-2] p.20.

4.2.3 Workload Leveling

The use of a Specialist Career Path discussed in the previous section contributes to a workforce with high technical expertise. The extent to which this expertise can be leveraged during the actual PD projects, however, strongly depends on the amount of resources available for a particular project and the distribution of tasks among the different project team members. The planning and allocation of resources for the single projects is the subject of the third Lean PD component Workload Leveling which shall be described in the following.

To display the general idea of Workload Leveling, Figure 4.3 compares an idealized, leveled with an unleveled workflow. In the left part of the figure, a number of processes is started at random intervals. The resulting capacity utilization, shown in the lower left part of the figure, is very uneven with high peaks. In contrast to this, leveling the workflow by determining optimal starting points for the single activities can yield a constant, even use of capacities.

Figure 4.3: General idea of Worload Leveling

The strong variation of capacity requirements, as observed with an unleveled workflow, has several undesired effects. PD organizations usually only have limited possibilities of adapting their existing capacities to a changing demand. As a result, highly cyclic PD workloads tend to induce periods of capacity over-utilization, followed by times where resources are not used to their full capacity [Morga 06] p.77. Capacity-overutilization is tightly connected with overburdening of employees, a drop in creativity and a decrease in the quality of PD activities [Adick 08] p.495, [Ward 07] p.33. Furthermore, the extent to which a company uses workload leveling and capacity planning has important effects on product development flow and lead times. This is due to the fact that from a workstream perspective, an unleveled workstream leads to the occurrence of bottlenecks. These bottlenecks in turn have large influence on the throughput of the overall system. As soon as a bottleneck emerges, the work piles up in front of it, subsequent processes are underutilized and, even though the overall system capacity might be sufficient to produce outputs at a higher rate, the actual output is restrained by the capacity of the bottleneck [Fiore 04] pp.80ff. Findings from queue theory suggest that systems operate best at a planned capacity utilization of 80 percent. With additional loading beyond this capacity utilization, queuing starts to increase in a nearly exponential manner [Morga 06] p.78. Consequently, it has been found that projects where engineers are not highly utilized progress in a relatively constant manner. In projects where workload has reached about 70 to 80 percent of system capacity, further unexpected increases in workloads significantly prolong the project beyond planned deadlines [Morga 06] p.80. According to Fiore, a lack of resource and workload management can reduce productivity and raise product development costs by more than 20 percent [Fiore 04] p.81.

To avoid the negative consequences of capacity-overutilization, in literature a number of practices have been described which yield at planning system capacities and leveling the demand of resources. In general, according to their focus they can be divided in cross-project and intra-project measures.

Cross-project measures

Different product development projects with timely overlap compete for the same financial, technical and human resources. When trying to maximize the overall product development performance of an enterprise, it is therefore not sufficient to plan and schedule projects independently. Instead, it is of major importance that before concurrent PD projects are actually executed, their resources be planned on a cross-project basis – a methodology Cusumano and Nobeoka refer to as multi-project management [Cusum 98]. Multi-project management usually starts with a detailed analysis of a company's product portfolio. Based on a company's current position in the market, market forecasts and strategic considerations, it is determined which product development initiatives should be funded in the future [Brown 07] p.11. The desired set of future products is then translated into a cycle plan. The cycle plan details which products, components, modules and platforms the company plans to develop at which point in time [Morga 06] p.84. Since the decision which and how many projects are started when strongly affects the availability of resources and consequently the project's the success, available capacity is one of the key factors for determining the starting point of a particular project.

To achieve a leveled workload and generate a smooth flow of PD projects, it is generally recommended to stagger projects and launch them in constant intervals [Adick 08] p.503. As Ward points out, PD projects within a company are likely to differ according to their resource requirements, their speed and the time they require to complete. Therefore, he suggests first classifying each project by its type, i.e. tailoring, re-integration, strategic breakthrough and research, and determining a typical cycle time for each type. He proposes to then arrange the specific project types in the cycle plan so that their cumulated demand in resources is approximately leveled [Ward 07] pp.118f. When determining the exact scheduling of projects, the availability of different functional specialists and their capabilities has to be taken into account. In this context, a particular challenge lies in avoiding inefficiencies through multitasking. To be able to effectively support the project, the number each employee is assigned to should be kept as small as possible [Ward 07] p.75, [Fiore 04] p.35, [Masci 07] pp.37ff, [Smith 97] p.206f.

The important role that cross-project workload leveling plays for a Lean PD system can be seen when taking a look at multi-project management practices at Toyota. Toyota maintains designated planning divisions for each of its three vehicle centers. In each of these planning divisions as many as 200 employees – about 10% of the overall capacity of a center – are concerned with conducting advanced concept studies, planning the product portfolio, scheduling the projects and allocating the resources [Morga 06] pp.84, 146.

Intra-project measures

A reliable planning of shared resources is not possible if the duration and resource demand of the single projects is highly unpredictable. Hence, the practices of multi-project management described in the previous paragraphs need to be supported by detailed scheduling and capacity planning on the project level. The tasks to be solved by the participating functions need to be clearly prioritized and synchronized. During the execution of the project, the degree to which tasks are completed should be checked frequently [Morga 06] p.98.

In order to establish an even flow of the activities within the project, some authors, like Ward, Oppenheimer, Haque and Adickes et al., suggest replicating the cadence of project launches of the multi-project level and establishing rhythmic cycles within the projects [Ward 07] pp.162f, [Haque 04] p.27. Similar to the idea of takt time in manufacturing, they propose to introduce periods of equal duration which are framed by integrative target events [Adick 08] p.499. The use of such a rhythmic cadence according to the authors can significantly contribute to frequent communication, a more equal distribution of workload and hence a steadier flow [Oppen 04] pp.359ff.

Despite all efforts of scheduling activities and leveling workload on both the project and the cross-project level, due to the inventive, uncertain nature of product development, it is impossible to precisely predict the timeframe and resource demands beforehand. Unforeseen events and required iterations cause deviations from schedule [Oppen 04] p.362. Thus, actual and planned capacity utilization have to be compared frequently [Adick 08] p.495. In case that in the course of the product development project a bottleneck occurs, resources have to be flexibly adapted. For a Lean PD system, the availability of flexible extra capacity is of large importance. Toyota, for example, compensates excess resource demands through a combination of flexible staffing and the use of external satellite companies to which work can be outsourced [Morga 06] p.88. In this context, Toyota strongly benefits from the fact that its workforce has a highly standardized skillset and maintains a close relationship with its suppliers. The latter aspect, which constitutes a separate Lean PD component, will be discussed in Section 4.2.7.

4.2.4 Responsibility-based Planning and Control

In the previous section it was mentioned that to level the workload, it is of major importance to rigorously schedule and track the detailed activities of the product development project. In fact, rigorous planning of the single product development workstreams is not only required to reconcile the capacity requirements of parallel projects. It also serves the purpose of coordinating and integrating the multitude of subsequent and parallel activities within the project itself. A comprehensive up-front scheduling of activities forces the participants to think about the required activities and their link to tasks of other functions. Furthermore, only if activities have been carefully planned in advance it is possible to frequently control whether the project proceeds in a way that ensures a timely launch of the product. With appropriate intermediate target dates, it is possible to identify problems and deviations from schedules very early so that corrective actions can be taken [Morga 06] p.39.

In general, as shown in Figure 4.4, two different approaches for planning and scheduling the detailed activities of a product development project can be distinguished. Using top-down planning, displayed in the left part of Figure 4.4, all activities of the project are planned by the project leader or a designated project planner. The engineers who execute the tasks are not involved in the planning process but are assigned detailed tasks with clearly defined, non-negotiable deadlines by their superiors. In contrast to this, in a responsibility-based planning approach, shown in the right part of Figure 4.4, the project leader sets only the major milestones for the project and communicates the according target dates to the engineers. Based on the targets, the engineers detail their particular workstreams, estimate their duration and report to the project leader whether the proposed schedule is feasible. Through several iterative loops, the project leader and the engineers negotiate deadlines for critical activities to ensure that goals are realistic but at the same time challenging enough to allow for a short lead-time of the overall project. At Toyota, this procedure of breaking higher-level goals down into meaningful lower-level objectives and aligning them across different stakeholders through extensive negotiations is known as Hoshin Kanri [Morga 06] p.24. Once the project leader and the engineer have agreed on milestones, it is up to the individual engineer to plan his work around these key dates. Hence, in the responsibility-based planning approach the project manager does not plan the detailed activities of the particular engineers. The engineer is free to choose the starting point of his work himself as long as he can meet the deadline [Ward 95] p.47, [Kenne 03] pp.101f.

It is obvious that, due to its iterative nature, responsibility-based planning involves more communication and therefore usually requires a longer time and more resources than top-down planning. In the literature on Lean PD, however, several authors such as Ward, Kennedy, Morgan and Liker, Brown and Schuh have argued that responsibility-based planning is superior to top-down planning because it induces several positive effects that more than compensate for the higher coordination effort during the planning phase.

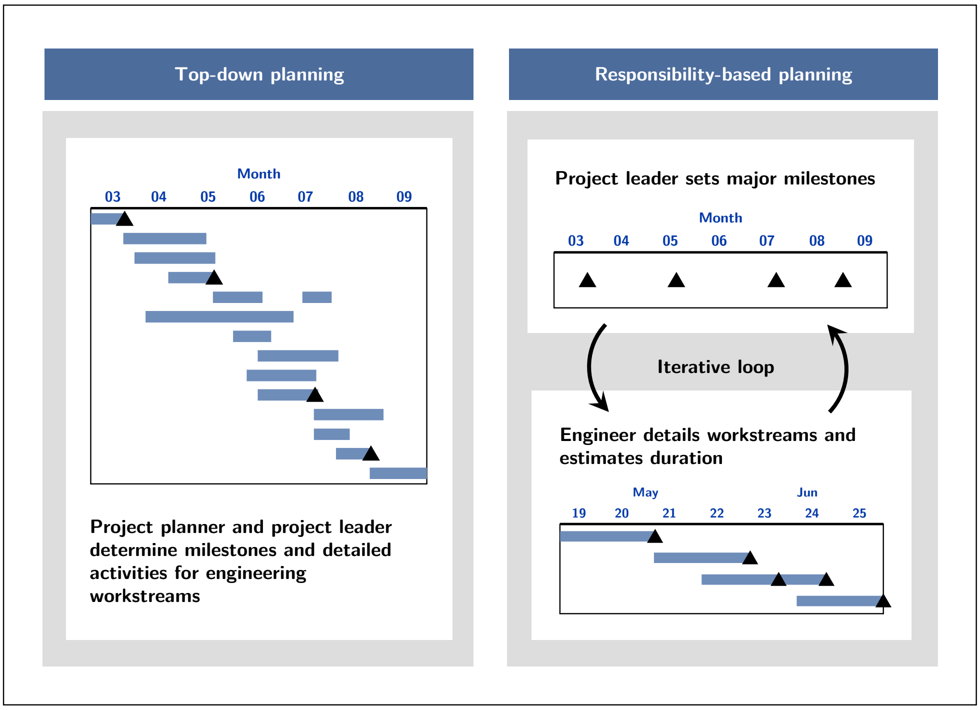


Figure 4.4: Top-down planning vs. responsibility-based planning

The first positive effect that goes along with responsibility-based planning and control is a higher accountability and motivation of the individual engineer. In a top-down planning approach, the tasks of planning and execution are assigned to at least two different persons, a characteristic Ward terms "scientific management" [Ward 07] p.10. In scientific management, there is little identification of the individual engineer with the goals of his work because they are externally imposed, often without considering the engineer's opinion. In responsibility-based planning, engineers have a much larger incentive to meet the targets because the engineers are highly involved in setting the goals and timeframes of their own work. Since, at least to some degree, the targets are self-chosen, the individual cannot turn to the excuse that the goals set were unrealistic in the first place. Responsibility-based planning creates a sense of ownership. The engineers can actually be held responsible for the results they deliver [Kenne 03] p.137.

A second advantage of responsibility-based planning is due to the fact that usually the approach of centralized, top-down planning in an uncertain environment is much more error-prone than decentralized, local planning of activities. It is reasonable to assume that the individual engineer is more knowledgeable about the details and potential constraints of his work than a project manager or a project planner. Thus, strong involvement of lower levels in the process of project planning is likely to lead to more robust schedules with less need for corrective actions in the course of the project [Ward 07] p.153.

Finally, the use of responsibility-based planning can significantly contribute to the continuous improvement of processes [Schuh 07-2] p.19. Engineers usually have the best insight into how to improve their own processes. Therefore, giving them the flexibility to plan their own work and experiment with new approaches leads to improved efficiency in product development. At the same time, due to the more local approach, responsibility-based planning increases the responsiveness to unexpected events and changing environments [Brown 07] p.10, [Kenne 03] p.137, [Smith 97] p.189.

Once the target dates have been set, to ensure that the stronger distribution of responsibilities and higher flexibility does not go to the detriment of the project's lead time, it is highly important that they are adhered to throughout the whole project. For this purpose, program status, open issues and performance to metrics are normally tracked in frequent project reviews which, equivalent to kanban cards in production, pull the work of the engineers [Ward 07] p.153. Furthermore, engineers have to be enabled to autonomously check their own performance based on appropriate feedback mechanisms. Key information on the planned and actual progress should be made transparent to every engineer. Using andon boards and visual management, every project member should be given the opportunity to check his own performance to determine if additional efforts are required to achieve a milestone on time [Ward 07] pp.180ff, [Morga 06] p.94.

4.2.5 Cross-project Knowledge Transfer

The fifth Lean PD component which has been described in literature is the component of Cross-project Knowledge Transfer. Cross-project Knowledge Transfer comprises capturing, reviewing, updating and generalizing successful methods, designs and tools as well as documenting potential areas for improvement.

In Section 3.3 it was described that the main goal and value of product development is to create information which has not been created previously. If product development seeks to generate an innovative product, the information generated for a unit has to differ from the one designed before. It is this uniqueness of products that in the past has induced development engineers to think of product development projects as independent, unrelated undertakings which make knowledge transfer appear hard and not useful.

In fact, as several studies have shown, even highly innovative products strongly depend and build upon knowledge of older products. This knowledge, if not appropriately captured, has to be continuously regenerated [Thomk 00] p.132, [Morga 06] p.207. As an example, Watkin and Clark, studying the design of front and rear auto body closures, found that problems are often repeatedly solved in consecutive projects [Watki 94]. Similarly, in a study of field problems with two novel process machines, von Hippel and Tyre discovered that of 22 problems identified after installation, 15 involved information that had existed prior to installation. In 10 of the cases, the information had simply not been transferred by the designers [Hippe 94].

A common way of avoiding the constant regeneration of previously created knowledge is the transfer of engineers between the projects. By assigning engineers to tasks which show strong similarities with activities they have been assigned to in previous projects, an organization is able to leverage the experience of the specialists and reuse some of the knowledge from older programs. But while the transfer of people plays an important part for the transfer of knowledge, this method is inherently limited. Firstly, in a well-organized project setting, an engineer is only assigned to a small number of projects which limits the scope of knowledge transfer. Secondly, if not documented, the quality of knowledge transfer by transferring people strongly depends on the extent of face-to-face communication. Newly generated knowledge is not directly available to other functional specialists or new hires working in the same domain who wish to draw upon the experience of senior engineers.

Due to the limitations of people transfer for cross-project knowledge transfer, it is generally recommended to explicitly document the best practices and lessons learned of projects. In the literature on knowledge management, a vast number of methods and tools for capturing and storing knowledge have been described, ranging from sophisticated web-based repositories to simple checklists. The detailed discussion of all the alternatives with their particular advantages and disadvantages is a separate stream of research and beyond the scope of this thesis. Here, it should only be noted that, for the viability of knowledge transfer, it is of particular importance that the barriers to enter, retrieve and update the knowledge be as low as possible. Data should be organized in a clear, logical way so that engineers can quickly review it as they face a particular design task [Brown 07] p.11. Additionally, the usefulness of a knowledge database strongly depends on how often the data it contains is updated. An organization should have clearly defined processes for capturing insights on both good and bad design practices during the projects. Engineers should be given both sufficient time and an incentive to share their experience with other members of the organization [Morga 06] p.207, [Oppen 04] p.362. The accumulated knowledge base should be regularly reviewed, reorganized and simplified to maintain its usability [Masci 07] pp.131ff.

To give an example for a successful management of cross-project knowledge transfer, in what follows the practices at Toyota shall be discussed in a little more detail. At Toyota, for every major part of a vehicle there is a part-specific checklist containing what the company has learned over the years. The checklists do not only list the steps not to be missed during the design process but contain highly detailed, often visual information regarding "good and bad design practices, performance requirements, critical design interfaces, critical to quality characteristics, manufacturing requirements as well as standards that commonize design" [Morga 06] p.102.

The checklists are maintained and updated by the engineers responsible for the development of the particular part [Sobek 99] p.71. At the beginning of every project, each function shares its most updated checklist with the other functions involved in the development of the particular product. This serves to inform each other about newly available technologies and problems solved since the last program [Sobek 99] p.74, [Morga 06] p.281. Throughout the development project, the engineers then use the checklist to guide the decision making in the design process and facilitate the review of designs [Morga 06] p.289. Generally, engineers are urged to have their design conform to the best practices defined in the checklists as much as possible. In case that an engineer decides to deviate from the checklist, he has to justify his decision, discuss it with the other functional groups and – if his solution turns out to be superior to previous designs – include it in the checklist. To ensure that with the frequent updates the checklists do not turn into case-specific product histories, engineers have to abstract and generalize their experience [Sobek 99] p.74. This is done using so-called trade-off curves which graphically describe the governing influence factors determining performance and failure modes of a part [Ward 07] p.141, [Morga 06] p.284. The use of trade-off curves allows for a fast detection of feasible design spaces and strongly facilitates the integration of the different functional domains throughout the whole project [Ward 95] p.52, [Sobek 99] p.71, [Ward 95] p.52.

To make the knowledge gathered by the specific engineers available on a broader basis, the checklists are integrated in a centralized know-how database [Morga 06] p.281. It is the functional manager's job to make sure that the database reflects the accumulated knowledge of his specialty at all times [Morga 06] p.144, [Adick 08] p.497. The functional organizations maintain, validate, and update their own portion of the database as needed [Morga 06] p.206. This is in line with the idea that in a Lean Enterprise functions serve as the organization's school. They gather and generalize knowledge and disseminate it to its members who spend their time on value-adding projects [Womac 94] pp.99f. Updates of the knowledge base are encouraged through frequent Hansei events. During theses events participants are given the opportunity to share shortcomings and lessons learned of PD programs and develop countermeasures [Morga 06] pp.206, 283.

Toyota has long kept its checklists and knowledge database in a handwritten form. Meanwhile, the information is computerized which allows for a more detailed and organized representation and integration of data. For easy import and export of design geometries the checklists are now linked to the design database. Manufacturing process sheets describe the processing of parts using quality matrices as well as pictures and videos from the factory floor. Engineers can access quality and performance data of parts. Pictures of competitor products and teardown analysis allow engineers to benchmark specific components against those of competitors [Morga 06] p.282. In this way, Toyota can make sure that all designs are based on previously generated knowledge and current best practices in industry.

4.2.6 Simultaneous Engineering

During the last 20 years, the concept of simultaneous engineering, also known as concurrent engineering or concurrent design, has attracted a lot of interest from researchers and practitioners likewise. Similar to many of the other Lean PD components described in this thesis, the core principles of simultaneous engineering were first described when studying the product development system of Japanese car manufacturers [Clark 87] p.766, [Clark 91]. The basic idea of simultaneous engineering in comparison with sequential engineering is shown in Figure 4.5.

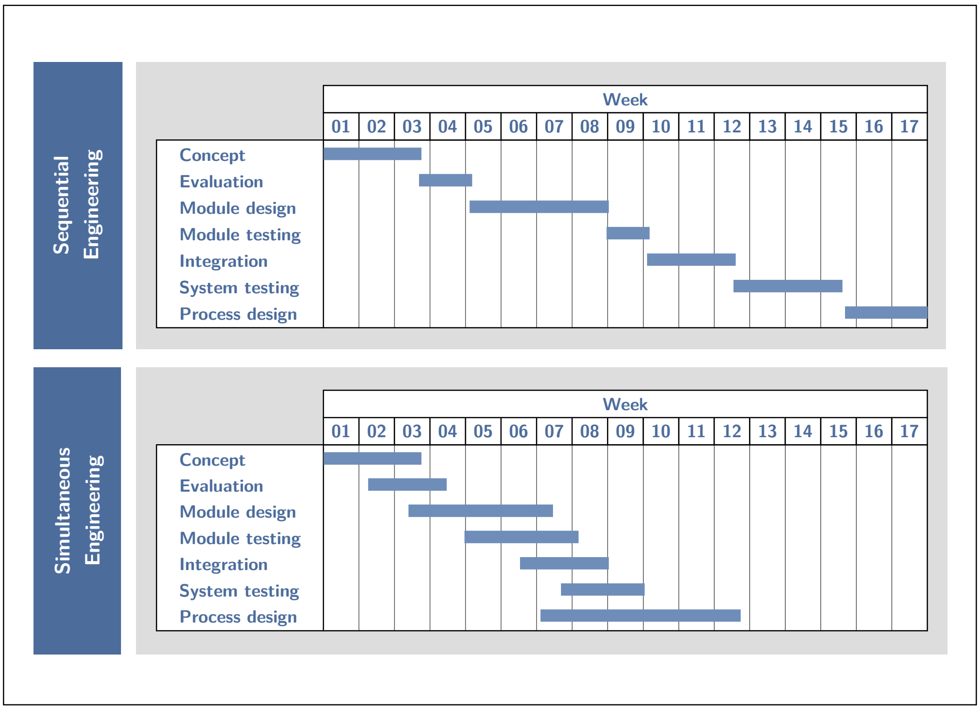


Figure 4.5: Sequential vs. simultaneous engineering

In sequential engineering, depicted in the upper half of Figure 4.5, product development is conducted in subsequent, mostly independent phases. After the product concept has been developed and evaluated, the single modules are designed, tested and integrated. Once integration is complete, the system of modules is tested and serves as the basis for the design of production facilities and processes. In contrast to this, in simultaneous engineering the single phases of product development are not conducted one after the other but in an overlapping way [Haque 04] p.4. This concurrency of activities offers the potential to significantly reduce the lead-times of the product development project. At the same time, however, it requires a much higher communication effort to compensate for the loss of clear hand-offs between functions and guarantee an efficient coordination of previously subsequent activities [Ward 95] p.45, [Karls 96] p.285, [Sobek 99] p.72.

In practice, simultaneous engineering is typically implemented in the form of cross-functional teams and meetings. Representatives from manufacturing, quality assurance, purchasing and other organizational stakeholders are integrated in the product development project at an early stage [Karls 96] p.285, [Sobek 99] p.68. From the beginning, they are highly involved in discussing the product concept and reviewing design proposals to make sure that the drafts meet the needs of all internal and external stakeholders [Haque 04] p.3. Interrelated modules and parts are designed simultaneously to avoid selecting a particular solution which conflicts with requirements in later design phases [Liker 96] p.166. Furthermore, representatives from manufacturing and assembly work with designers and product engineers to develop production processes and facilities in parallel to the product [Womac 90] pp.116f. The product developers receive information on process capabilities and trade-offs. This early consideration of abilities and constraints in manufacturing helps to avoid iterations and rework of designs at later points when decisions are already locked in [Brown 07] p.10, [Liker 96] p.166. Simultaneous engineering is therefore suited to not only impact development times but reduce product cost and increase product quality [Liker 96] p.165, [Nevin 89], [Susma 92], [Karls 96] p.284. As Schuh et al. find in their study of product development success factors, simultaneous engineering is one of the decisive characteristics that separate outperformers from underperformers [Schuh 07-2] p.4.

Toyota, to foster simultaneous engineering in its PD processes, uses two major mechanisms: Module development teams (MDT) and the obeya (big room) [Morga 06] p.159. At the beginning of each product development project, Toyota conducts a comprehensive study period, called kentou, during which the concept paper developed by the Chief Engineer is translated into specific component level goals [Morga 06] p.300. For each of the vehicle subsystems, a module development team consisting of a variety of different functional representatives is set up. These cross-functional teams go through intense negotiations on how to achieve the performance characteristics given by the Chief Engineer and resolve key challenges early in the process when there is still a large amount of flexibility [Morga 06] pp.37, 260, 300. They study field data, tear down competitor products and visit manufacturing plants to identify important influence factors on their particular module [Morga 06] p.32. In addition, every of the MDTs is assigned one or more designated simultaneous engineers (SE) who serve as a program-dedicated representatives from manufacturing [Morga 06] p.56. The SEs are experts in their particular manufacturing specialty. In their role as an intermediary, they advise the MDT regarding questions of manufacturability of designs. Moreover, they act as a contact person for the engineers in production who actually have to perform the manufacturing of the module [Morga 06] p.154. Since every SE is responsible for meeting the investment and variable cost targets for a set of parts, there is a large incentive for them to work closely with designers and product engineers to maximize manufacturability of the design proposals [Morga 06] pp.57f. Before the kentou period, the SEs gather as much data on the production processes as possible and talk to machine operators as well as other functional specialists within production. Based on this information the SEs in the course of the project then prepare a process plan for each of their parts [Morga 06] pp.58f.

To facilitate cross-functional communication throughout the project, Toyota has set up special rooms, called obeya, which serve as venues for regular meetings between the chief engineer and the leaders of the functional groups. The geographical location of the obeya changes as the PD project progresses from concept development to start of production. On the walls of the obeya the functional engineers post the latest information on the status of the project. Modern communication technology in the rooms allows for easy displaying of drafts, simulations and test results, thereby enhancing cross-functional collaboration. [Morga 06] pp.262f

The discussion of MDTs and the obeya as used at Toyota concludes the description of the sixth Lean PD component simultaneous engineering. The following Section 4.2.7 will explain the component of Supplier Integration.

4.2.7 Supplier Integration

In the past, product development and manufacturing of parts, modules and larger subsystems have been increasingly outsourced to suppliers who have specialized in particular areas. In case of an automobile, about 70 to 80 percent of all parts are purchased from outside companies. Due to this large share that supplied parts have in the end product, efforts for optimizing product development effectiveness and efficiency must always involve the interface with suppliers [Liker 95] p.152, [Fiore 04] p.151.

Traditionally, chiefly in the western world, companies work with a large number of suppliers for every part. Before approaching the suppliers, they define detailed part specifications, invite for tenders and – mainly based on price as a criterion – award the business to a supplier. As Liker points out, in the case of the automotive industry this tradition has resulted in a situation with adversarial relationships between automakers and outside suppliers. Automakers have often used their market power to extort low prices from suppliers. Suppliers, in turn, have been reluctant to share inside information with Original Equipment Manufacturers (OEM), fearing that their customers could use this knowledge against them in the bidding process. After being chosen as the supplier for a particular part, they have used inevitable changes in the product development process to raise their initially negotiated price [Liker 95] pp.152f, [Morga 06] p.193, [Ward 07] p.83. The process of price negotiation with a large number of suppliers usually requires a high amount of resources on the part of the OEM, resulting in large purchasing organizations which are responsible for the correspondence with the suppliers [Liker 95] p.178, [Morga 06] p.200, [Fiore 04] p.146.

Companies with a strong emphasis on Lean practices have been found to follow a fundamentally different approach regarding their relationship with suppliers. They usually have a much smaller supplier base they work with on a longer-term basis. Suppliers are integrated into the product development activities at an early stage and work closely with the development engineers of the OEM. [Morga 06] p.194, [MacDu 96] p.354

Toyota, according to the findings of Morgan and Liker, divides its suppliers into four different categories: Contractual, consultative, mature and partner [Morga 06] pp.183ff.

- Contractual suppliers supply very simple commodities such as nuts, bolts, brackets and spark plugs, which can be ordered via catalogue.
- Consultative suppliers produce slightly more technically complex parts like tires and frequently report their innovations to Toyota.
- Mature suppliers, compared to the first groups, have stronger engineering skills and design their product according to only general specifications given by Toyota.
- Partner suppliers are large and highly capable suppliers which develop, produce and supply complete subsystems and are technically autonomous.

Particularly the suppliers of the last two categories, mature and partner, are integrated into the product development process very early. Based on the criticality of the part and the supplier's engineering capability, a small set of suitable suppliers with a positive track record are identified already in the concept stage of the project. Using presourcing arrangements, these suppliers, typically two or three per part, are incorporated in the extended product development team [Morga 06] pp.22, 182. Usually, they are not given detailed specifications on the part they have to deliver. Instead, they are assigned the responsibility for a particular subsystem and help draw up the specifications for their module by actively participating in the design process [Liker 95] p.188, [Karls 96] p.285. Following a practice known as "black box sourcing" Toyota gives its key suppliers only general functional and interface requirements as well as cost and weight targets for the subassembly. The detailed design of the "black box" is then done by the suppliers. As long as they meet the general requirements, they are free to choose the interior according to their needs [Sobek 99] p.78, [Liker 95] p.154. At the same time, the suppliers manage and coordinate the activities of all second-tier and third-tier suppliers that supply parts for their particular subsystem [Liker 95] p.189.

In the further course of the development of the product, based on the targets given by Toyota, the suppliers make drafts, simulate and conduct tests. Toyota expects its suppliers to explore the trade-offs among different requirements, back decisions with test data and demonstrate designs by delivering fully functional prototypes early in the process [Liker 95] pp.165, 172, 188f. While in traditional product development the supplier for a particular component is picked at an early stage, at Toyota at least two suppliers compete for the same part throughout the whole product development process. Only after the second prototype stage, close to launch of the vehicle, Toyota uses the test results to decide which of the supplier better meets the performance requirements. This supplier is then awarded the business and continues to be monitored by Toyota very closely [Morga 06] pp.189, 192, [Liker 95] p.185, [Sobek 99] p.75. The supplier who loses the bid, will not be able to supply the part for the particular program. However, since Toyota follows a strategy which focuses on long-term partnerships with suppliers, the investment is not lost but can be seen as an investment in the general relationship. As Morgan and Liker point out, at the beginning of a partnership with Toyota most suppliers lose several bids and win only small contracts before they are awarded larger businesses [Morga 06] p.193. Toyota allows its suppliers to make profit on the overall relationship rather than on every individual contract [Liker 95] p.179.

In general, suppliers of Toyota are expected to continuously improve their performance and reduce costs [Liker 95] p.179. Every year, the suppliers are given ambitious cost reduction targets. However, Toyota does not only demand the cost to be reduced but works very closely with the supplier to achieve the goals set. Toyota engineers discuss with the suppliers how their product and development processes can be improved and offer their help to solve issues with designs [Ward 95] p.56, [Liker 95] p.165. Furthermore, Toyota constantly hosts several hundred guest or resident engineers. These are engineers from suppliers who are residing full-time at Toyota's product development department. They are tightly integrated into the product development activities and thereby inevitably get familiar with Toyota's design practices. The strong insight of suppliers into Toyota's product development practices in turn enables Toyota to draw on its suppliers as flexible capacity in case of occurring bottlenecks [Morga 06] pp.193f, [Liker 95] p.166.

Despite its close cooperation with suppliers and extensive outsourcing of parts and engineering, Toyota is very careful to not lose critical knowledge and prematurely award business to suppliers who cannot guarantee to deliver the expected quality. The strategic importance of parts is carefully evaluated before its development is transferred to suppliers. Development and production of critical parts are not outsourced but kept within the company to maintain control [Morga 06] p.195. In a similar way, new suppliers are integrated very carefully. Suppliers with whom Toyota has not had prior contact are first asked to give technology presentations at the preconcept stage for two to five new models. If Toyota is convinced of the technological capability of the supplier, he may be given a small amount of rather uncritical business, such as providing the spare tire for a low volume vehicle. Only after several programs and rigorous testing, a supplier is typically awarded more business so he can start collecting on the initial investment. In spite of this difficult path and large up-front investment, there is large competition to become a first-tier Toyota supplier. This shows the value of a fair and stable long-term partnership that enables learning across companies. [Morga 06] p.189, [Liker 95] p.181

4.2.8 Product Variety Management

For a product to be successful on the market, it has to clearly differentiate itself from other products available – either through a low price, a high performance, a better quality, additional service or a combination of these factors. The necessity for a company to sell products and generate revenue therefore inevitably leads to a variation of products across companies and, for companies producing more than only one product, within the company itself. Not only needs a product be better than the ones of competitors. It should also be different from other products of the company and the predecessor of the model to be sold [Ward 95] p.55.

On the one hand, differentiation, as perceived by the customer, is therefore important for the company's unique selling position. Yet, on the other hand, a large variety of products, components and parts comes at the cost of larger complexity, higher inefficiencies and decreased possibilities for using economies of scale throughout the entire product lifecycle. During product development, large variety leads to higher efforts and cost in design, testing and prototyping. If parts are purchased from external companies, a larger number of suppliers have to be managed and integrated (see previous section), more parts have to be ordered, stored and maintained in the ERP system. For self-produced parts higher variety goes along with higher set-up costs, decreases in labor productivity due to higher complexity of tasks, more difficult balancing of assembly lines and more complex quality assurance. At service stage, maintenance, identification of failure modes, supply of replacement parts and repair become more difficult and costly. Finally, dealing with a larger number of parts and materials also has a negative impact if the product ought to be recycled [MacDu 96] pp.353, 367, [Schuh 07-1] p.1, [Fiore 04] pp.91ff. As Fiore points out, only the carrying cost to maintain a part number in its system for some companies amounts to $2000 and $3000 annually [Fiore 04] p.92.

To avoid this large number of drawbacks that are connected with a high variety in products and parts, in the literature on Lean PD several authors have suggested using techniques which can be summarized under the common heading of "product variety management". Four of the most important elements of product variety management are shown in Figure 4.6.

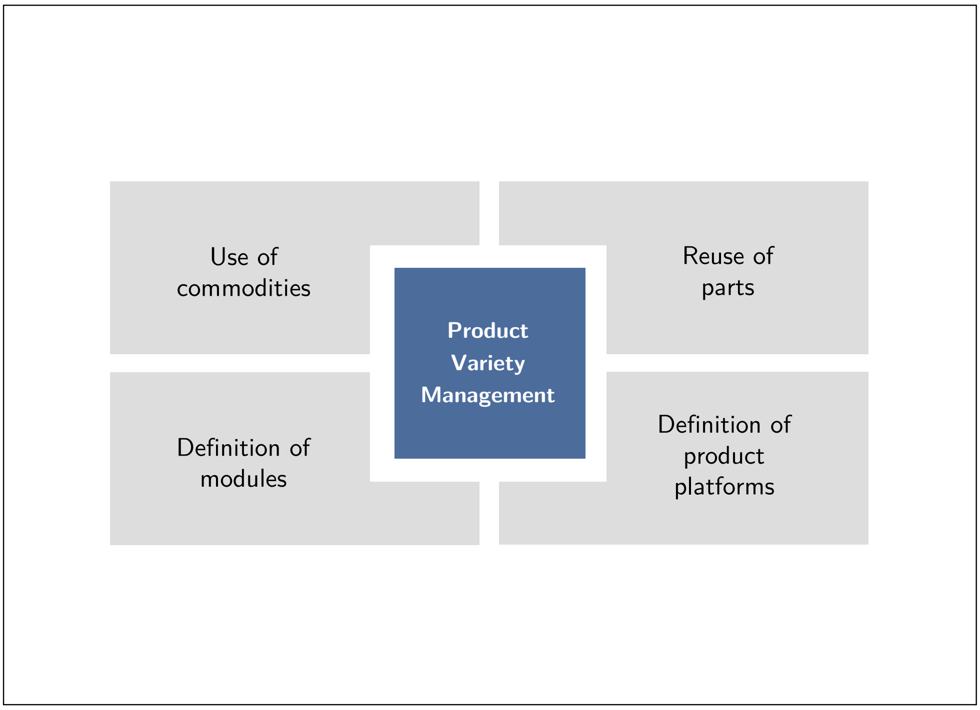


Figure 4.6: Major characteristics of product variety management

The first way of reducing part variety is the use of commodities. Whenever a part of a product is not perceived as a critical differentiating feature by the customer, can be easily ordered from a catalogue and cannot be manufactured by the company at a significant cost advantage, it is generally recommended to order the part from a supplier instead of developing and producing the part within the company. Using catalogued parts allows an organization to draw on the knowledge of suppliers who have specialized in an area and may have longer experience in developing and producing a particular component. Furthermore, if it can be easily integrated into the product design, a standard part can significantly reduce engineering effort and risk. The component can be treated as a black box and its interior parts do not have to be maintained in parts lists. [Ward 07] p.82, [Fiore 04] p.102

Besides making use of commodities in designs, a company should also try to reuse product parts among different modules, products and product families as well as subsequent versions of the same product. Every creation of a new part is connected to considerable cost, introduces process uncertainty and reduces the possibility of achieving economies of scale. Therefore, parts should only differ and be redesigned if this is justified by a perceivable value-added for the customer. Toyota, for example, has a carry-over rate, i.e. percent reuse of components from a pervious model to the successor, of about two third. Toyota is very cautious about introducing new technologies and tries to leverage their proven solutions from existing products as much as possible. [Schuh 07-2] p.24, [Fiore 04] pp.91f, [Oppen 04] p.370

It should be noted that the use of the two previously described elements of product variety management is not possible when the product cannot be broken down into distinct subsystems. Ordering single components from catalogues and reusing parts from previous products and other subsystems, is much harder if the product is highly integrated. Therefore, the literature on Lean PD generally recommends dividing the product into distinct modules and subassemblies with standardized interfaces. What's more, modules facilitate the redesign of particular parts of the product, allow parallelization of design tasks, improve maintenance issues, reduce complexity and foster learning and continuous improvement. [Fiore 04] pp.120ff, [Haque 04] p.8, [Morga 06] p.198, [Smith 97] pp.107ff

To be able to use modules across several product lines and maximize the reuse of parts, a company can furthermore make use of product platforms. Product platforms serve as a carrier for the different subassemblies. They allow to combine modules with standard geometries and interfaces in a way that leads to high flexibility and diversified products while keeping overall part variety low [Meier 07] pp. 206, 210, [Morga 06] pp.42f. Products of different product lines can be built on the same platform with a large number of shared components. Using the concept of mass customization, they can then be differentiated by adding a small number of features late in the process which are particularly obvious to the customer [Haque 04] p.8. Since product platforms constitute the basis for a larger number of products, they have to be designed very carefully to account for the interaction between the modules and potential future evolutions of the product lines [Adick 04] p.487. Toyota employs the same product platform for about seven vehicles and introduces a new platform every 15 years [Ward 07].

In summary, integrating product variety management into PD practices offers large potential for improved efficiency of a company's operations. However, to not lead to poor product differentiation and an uninspired product portfolio, it has to be used strategically. As Fiore points out, the right balance between reuse and innovative designs depends on many factors, including the company's expertise, the perception of the customer as well as the company's position in the market. [Morga 06] p.42, [Fiore 04] p.130, [MacDu 96] p.353

4.2.9 Rapid Prototyping, Simulation and Testing

As described in Section 3.3, it is the goal of product development to generate information which has not been generated before. For the development of a new product or part, a product development engineer has to solve a set of specific design problems. The solution to these problems is – at least to some extent – not known before the beginning of the product development project. As a result, from a micro perspective, every engineer goes through a cycle of tasks which can be described by the well-known plan-do-check-act (PDCA) cycle introduced by Deming. The engineer first defines the requirements for the product. Then, he executes the design task, conducts tests and simulations and, based on the outcome, decides whether the design needs to be changed or refined (see Figure 4.7). From a micro-level perspective, a product development process therefore can be regarded as a large number of iterative cycles which incrementally move the product development project forward. [Ward 07], [Morga 06] p.210

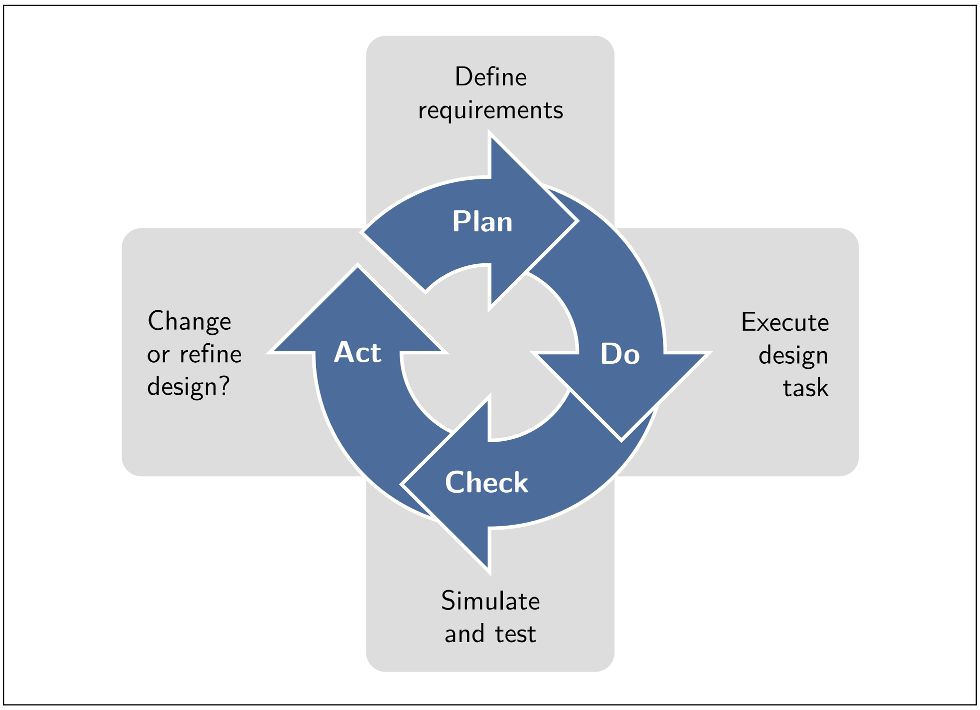


Figure 4.7: Micro-level product design cycle

The understanding of product development as a large number of micro-level iterative cycles can help answering the question of how the efficiency of product development practices can be improved. Obviously, assuming that the number of cycles does not change, the overall lead-time of product development strongly depends on the speed in which an engineer can go through a single iteration. Considering the large number of iterations that are required for one product development project, an increased speed of problem-solving will not only shorten time-to-market but have a positive effect on product quality, performance and organizational learning [Brown 07] p.11, [Smith 97] p.178. In this context, many authors in the literature on Lean PD have emphasized that methods and technologies supporting fast prototyping, simulation and testing of designs can significantly contribute to a high-performance product development system. They provide the engineers with a quick feedback on ideas, result in a faster convergence of designs and ensure integration among different modules [Thomk 00] p.133, [Oppen 04] p.370, [Ward 07] p.135, [Schuh 07-2] p.15, [Morga 06] p.351.

The traditional way of quickly evaluating designs lies in building physical models and prototypes. It has been pointed out that, to foster well-grounded decisions and avoid problems in later phases, prototypes should be build already in early stages of product development [Ward 07] p.77. Using low-cost techniques mock-ups of products can first be modeled out of foam, foam core, cardboard or wood to gain fast insights on geometric properties [Ward 07] p.135. Later, the designs should be translated into more sophisticated prototypes with as much functionality as possible. This helps to identify problems with the integration of the single modules and allows to intensively test the system for failure modes. At Toyota, the phase of prototyping is characterized by very close interaction of all participants. Prototype specialists work together with production engineers, designers and quality assurance experts to understand the physical limitations of the designs [Morga 06] p.174. Results are discussed in daily wrap-up meetings. Designers are expected to make changes to their designs within 48 hours, often on the spot [Balle 05] pp.20f, [Morga 06] p.175. While at Toyota, the first prototypes are assembled very carefully to check the interfaces of subassemblies, all subsequent prototypes are produced and assembled using Lean Manufacturing techniques [Balle 05] p.20. Through an accurate and standardized design of dies, Toyota can produce prototypes at a much faster speed than its competitors [Morga 06] p.108. As Ward reports, by the consequent application of Lean Manufacturing techniques, the Toyota supplier Delphi in one instance has been able to cut times for simulation and tests from weeks and months to 24 hours each. This allowed them to go through a significantly larger number of learning cycles than previously [Ward 07] p.22.

In the last years, traditional ways of prototyping have been more and more complemented by advanced digital technologies such as computer-aided modeling, simulation, digital assembly and 3D prototype printers. The use of these techniques can, if employed appropriately, strongly contribute to identifying and solving problems at a faster rate. Iterations can be run earlier and often at a lower cost than it is possible with elaborate, expensive physical prototypes which require long to build [Morga 06] p.60, [Thomk 00] pp.132, 137. At the same time, virtual tools such as digital assembly can help to identify many problems before the program enters prototype phase which can result in a lower number of prototypes needed [Morga 06] p.247.

The importance of prototyping, simulation and testing capabilities for the overall performance of a PD system becomes clear when considering the findings of a survey conducted by the WZL Aachen among German product development managers. Asked which parts of their product development system represented the major bottlenecks, producing waiting times, the respondents rated test stands first, prototyping on the second and simulation on the fifth rank [Schuh 07-2] p.15.

4.2.10 Process Standardization

It has already been pointed out in previous chapters that every product development project is inherently unique. Due to the creative nature of product development, the information generated in one project naturally differs from the one generated in previous projects or other product lines of the same company. Depending on whether the goal of the project is to only redesign portions of a product or develop a completely novel product concept, scope and complexity of product development projects can vary significantly.

The unique character of each product development project has been paid regard to in the literature on Lean Product Development. Nevertheless, many authors have argued that, while the detailed nature of projects may differ from case to case, the general procedure and methodology of product development is quite consistent across projects [Morga 06] p.20, [Fiore 04] p.184. Tasks required for planning and executing different product development projects are often similar. Likewise, within the single projects many activities reveal a repetitive nature [Adick 08] p.493. To increase product development performance, it is widely recommended to identify these reoccurring tasks and standardize them. Standardization provides a clear guideline for action and helps to increase efficiency, minimize errors and reduce variability [Sobek 99] p.81. Furthermore, standards represent a pivotal part of a learning organization and serve as a basis for continuous improvement [Morga 06] p.102. Only if successful procedures and methods are captured, documented and diffused throughout the organization, engineers can explicitly suggest ways for improving current best practices [Brown 07] pp.10f, [Balle 05] p.20, [Morga 06] p.24. In the following paragraphs, various elements of process standardization as suggested in the Lean PD literature shall be discussed in more detail.

From a macro perspective, a very common way of standardizing processes is to predefine a sequence of project milestones in which product development projects within the organization ought to be completed [Morga 06] p.82. Usually, as mentioned in Section 4.2.4, at the beginning of a project, the project manager outlines the schedule of the project by assigning dates to major target events. Since the nature and order of these target events is often similar between projects, it is advantageous for an organization to develop a blueprint project managers can use when planning their activities [Liker 95] p.188. Particularly in combination with other standardized tools for project planning, this can contribute to a higher reliability of plans. In addition, it provides a common structure which fosters the synchronization of the various participating functional organizations [Morga 06] pp.89, 105f. As every project follows the same general order of steps, engineers are able to develop a certain routine and get a deeper understanding of their role in the overall value stream [Morga 06] p.105. Also, in an organization where multiple projects are conducted at the same time, knowing the sequence in which tasks are completed can strongly facilitate the planning and alignment of shared resources [Morga 06] p.82.

After the project has been planned, it is of large importance that the milestones defined at the beginning of the project be met and designs be completed on time. To avoid large variations in the quality of work, individual engineers should be provided with standardized tools and procedures which support them in their creative design efforts [Balle 05] p.20, [Morga 06] p.43. These can range from standardized work instructions and design standards to standardized methods for problem solving. At Toyota, for example, besides standard checklists and trade-off curves (see Section 4.2.5) engineers make extensive use of a method called "five why" which allows them to analyze the root cause to a particular problem [Balle 05] p.20. Problem solving is supported by special decision matrices [Morga 06] p.285. Additionally, documentation and communication of information is facilitated by the use of dense and highly structured A3-reports [Morga 06] p.24, [Ward 07] p.191. By providing its engineers with standard procedures for design, problem solving and documentation, Toyota can make sure that all engineers possess the necessary methodological skills and hence can be flexibly staffed to projects [Morga 06] pp.89, 104.

Adherence to standards in many ways constitutes an important part of a Lean PD system. However, it is important to note that standards are never absolute or irrevocable and therefore should never be followed blindly. As particularly Ward and Kennedy put forward, imposing a large number of standards can quickly lead to overregulation and impair the fourth Lean PD component Responsibility-based Planning and Control. Since this has negative consequences for organizational learning and innovation, it is important to find the right balance between defining standards as guidelines and giving engineers the freedom to pursue unconventional solutions [Schuh 05]. Standards should not be seen as laws but as current best practices which are subject to continuous improvement. Even though engineers should generally follow the standards, they can deviate from them if they have a compelling reason to do so [Morga 06] p.292. They should be encouraged to continuously challenge the standards and make suggestions for their improvement [Morga 06] p.225.

4.2.11 Set-based Engineering

The last of the eleven Lean PD components to be discussed in this thesis is Set-based Engineering. In literature, this component has often been labeled as "set-based concurrent engineering". For this thesis, however, it was decided to not make use of the word "concurrent" in the title of the component to avoid confusion with "simultaneous or concurrent engineering", the Lean PD component described in Section 4.2.6. Set-based engineering and simultaneous engineering describe two considerably different paradigms of design. While simultaneous engineering is concerned with the concurrent execution of formerly subsequent tasks and early integration of functional stakeholders, set-based engineering focuses on the process of how a particular solution for a component or module is chosen.

Figure 4.8 contrasts the traditional, point-based engineering approach with the approach of set-based engineering.

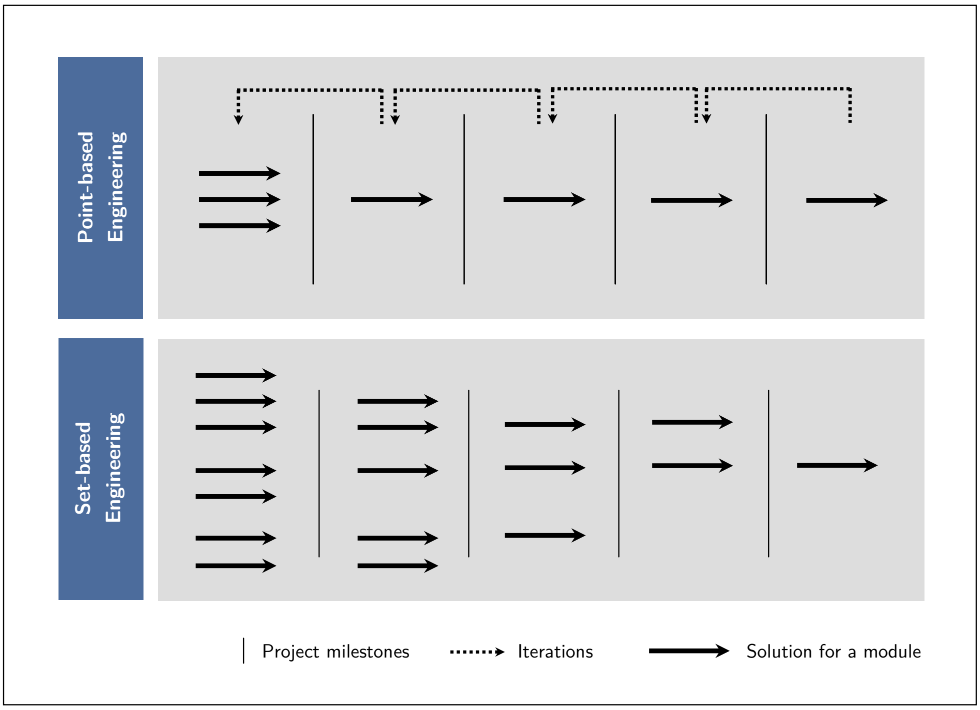


Figure 4.8: Point-based vs. set-based engineering [Kenne 03] p.122

The traditional approach to developing a product module, shown in the upper half of Figure 4.8, typically starts with breaking the product down into subsystem, defining detailed requirements for each module and deriving a small number of alternative solutions which are suited to meet the initial requirements. Engineers then quickly assess the solutions and select the most promising one to be pursued in the further product development process. For the selected solution they develop drafts, build prototypes and conduct tests to more and more specify the particular alternative. The single solutions for the modules are then integrated into a system and tested again. This process, however, rarely turns out to be linear in nature. Usually, when specifying the module, engineers discover that the particular specification chosen does not meet the requirements formulated at the beginning or cannot be integrated with other modules developed in parallel. They then go through iterative loops to either modify the concept until it satisfies their particular need or start the process over by selecting a completely different alternative. Because of its iterative nature where engineers move from point to point in the realm of possible designs, this procedure has been termed point-based engineering. [Berns 98] pp.23ff, [Liker 96] pp.165ff, [Kenne 03] p.122, [Ward 95] p.48

An alternative to the point-based engineering approach described above is set-based engineering, the general systematic of which is depicted in the lower part of Figure 4.8. Like point-based engineering, set-based engineering starts with dividing the product into small subsystems and modules. However, unlike in point-based engineering, no detailed requirements are defined for these subsystems. Instead, engineers only identify broad targets for every module. Based on these general objectives, a much larger number of alternative solutions for every component are developed early in the process. In the following phases of product development, the initial set of alternatives is not narrowed down quickly, as is the case in point-based engineering. It is kept open as long as possible to allow for a wide range of different solutions [Schuh 07-2] p.16. Engineers do not directly pick an alternative to pursue further. They design, test and analyze multiple solutions for every subsystem in parallel [Morga 06] p.19. Using extensive prototyping and testing, engineers explore failure modes and trade-offs of particular solutions and check for the compatibility with adjacent parts [Balle 05] p.111, [Morga 06] p.41. Only when, based on objective criteria, a solution has been proven to be inferior to other designs, this design is removed from the solution space [Schuh 07-2] p.16, [Adick 08] p.483. In this way, the set of alternatives is gradually narrowed down and finally converges to a single solution [Ward 07] p.111. Once the engineers have decided on a particular solution for a design, this solution remains unchanged until start of production unless altering the module is absolutely necessary [Ward 95] p.49, [Garza 05] pp.23ff.

At the first glance, the concept of simultaneously designing and testing a larger number of alternatives for a particular product module as proposed in the approach of set-based engineering appears to contradict the idea of Lean Thinking. It binds a lot of resources for exploring solutions which are subsequently discarded, thereby seemingly creating waste. In the literature, however, it has been argued that investing time and resources to explore alternatives early in the project significantly reduces uncertainties and iterations in subsequent phases of the project [Sobek 99] p.71, [Balle 05] p.18. Avoiding iterations, in turn, has been found to have positive impacts in the three major dimensions cost, schedule and quality which more than compensate for the initial investment [Adick 08] p.483.

First, it is a well-known fact in innovation management that changes in design become significantly more costly as the project proceeds towards the start of production. At the beginning of product development changes have much less of an impact than during later stages. Therefore, front-loading the product development process by exploring alternatives early in the process instead of iterating in later stages is likely to reduce the overall cost of product development [Berns 98] pp.48ff, [Kenne 03] p.130, [Ward 07] p.133, [Liker 96] p.166, [Schuh 07-2] p.16.

Second, late engineering changes are not only problematic from a cost point of view. They also pose a major threat to reliable planning and execution of the project schedule. Modifying a solution late in the product development process causes rework, often affects adjacent components and has implications for manufacturing processes. Particularly when making strong use of Simultaneous Engineering (see Section 4.2.6), therefore late changes lead to major disruptions in flow [Sobek 99] p.69. Since engineers are not sure whether a decision they make is invalidated by a later change in specifications of an adjacent part, there is a major incentive for them to delay their work [Ward 95] p.59, [Ward 07] p.114, [Liker 96] p.165. In contrast to this, set-based engineering allows for greater parallelism by solving problems of integration early on [Ward 95] p.59, [Brown 07] p.10, [Balle 05] p.20. As downstream processes become more linear and predictable, product development activities can be scheduled in a more reliable way before the start of the project. This reduces the need for communication between engineers, enhances the possibility of standardization and contributes to better flow within the workstreams [Liker 96] p.177, [Ward 95] p.49, [Balle 05] p.18.

Third, the use of set-based engineering can also increase the quality of the product to be developed. Deciding on a solution early on without exploring its benefits and drawbacks compared to alternatives increases the probability of selecting a suboptimal overall design [Sobek 99] p.69. In set-based engineering the most critical, early decisions are based on data. Trade-offs between alternative solutions are explored before potentially irrevocable decisions are made. Therefore, especially when capturing and reusing the knowledge which is generated through these early in-depth investigations, set-based engineering can possibly find more innovative and robust solutions than the point-based approach [Ward 95] p.59, [Kenne 03] p.129, [Sobek 99] pp.70f. At the same time, discussing potential problems up-front can significantly increase the probability that the single solutions for the subsystems converge to a feasible product design. As a result, set-based engineering can help lowering the risk of project failure [Ward 07] pp.128ff.

One company which makes extensive use of set-based engineering is Toyota [Sobek 99] p.68, [Ward 95] pp.43f. When designing a car, Toyota carries over a large percentage of parts from previous projects and innovates selectively by applying set-based engineering to critical components [Ward 95] p.51. For these subsystems, at the beginning of the PD process, all functional departments, e.g. body engineering, chassis engineering and production engineering, simultaneously determine the primary design constraints. Based on past experience they define feasible regions from their perspective and communicate them to the other functions [Sobek 99] p.73. Once the feasible design space of a component has been defined, product engineers and suppliers explore a large number of concepts for the design of the component, build models and conduct tests [Ward 95] p.47. The trade-offs of the solutions found by each function are then discussed in interdisciplinary design reviews which are held on a regular basis. During these reviews, the alternatives that are incompatible with the set of solutions developed by other functions are eliminated. Those which are at the intersection of feasible design sets, and therefore conceptually robust, are pursued further [Sobek 99] p.77. In the case of the Toyota Prius, for example, as many as 80 concepts for hybrid drives were scanned and slowly reduced to yield the best ten [Itaza 99] p.81. It is the role of the chief engineer to decide how many alternatives should be followed and when to narrow the set of solutions [Oppen 04] p.370. Due to Toyota's strong focus on quantified data as a selection criterion, the final decision in favour of a particular subsystem may be made as late as six months before launch [Balle 05] p. 25, [Sobek 99] p.73.

When detailing their designs, engineers commit to stay within the narrowing funnel of design sets agreed on during the review meetings. This procedure ensures that engineers simultaneously working on related components can proceed with their work without having to worry that their solution is incompatible with those developed by other engineers [Balle 05] p.20. Moreover, to guarantee that there is at least one feasible solution for every module, engineers work with fall-back designs. In case a new solution does not work by a specified deadline, the team resorts to the previously defined back-up [Sobek 99] p.80.

During the whole process of set-based engineering at Toyota, designs and testing data of all alternatives are carefully documented. Using trade-off curves and checklists (see Section 4.2.5) engineers capture the knowledge they generate by pursuing the different solutions [Ward 07] p.115, [Morga 06] p.51. Solutions which are considered unfeasible in a project are frozen and may be reused in subsequent projects when constraints have changed [Schuh 07-2] p.4, [Haque 04] p.8, [Sobek 99] p.75. Consequently, the use of set-based engineering at Toyota contributes to a constantly growing knowledge base.

To sum it up, the use of set-based engineering has been found to be one of the components that significantly contribute to the high performance of product development at Toyota. In a seemingly contradictory fashion, pursuing a large number of alternatives early in the PD process and deliberately delaying decisions enables Toyota to design better cars faster and cheaper [Sobek 99] pp. 68, 77f, [Balle 05] p.20. This counter-intuitive finding has induced Ward to label set-based engineering "the second Toyota paradox" [Ward 95] p.44.

The discussion of set-based engineering in this section concludes the description of the eleven Lean PD components derived from literature. Building on the comprehensive definition of a Lean PD system, the next chapter will discuss the interdependencies between the Lean PD components and derive hypotheses on the order in which they should be introduced.

5 Deriving Hypotheses on the Introduction of Lean Product Development

In the previous chapter, a framework consisting of eleven distinct Lean PD components was introduced. The eleven components derived from literature were described in detail and it was argued why a use of the individual elements has been found to contribute to a superior PD performance.

The following sections draw on this definition of a Lean PD system and derive hypotheses on how the eleven Lean PD components should be introduced. For this purpose, in Section 5.1 the components are investigated with regard to their interdependencies. The links between the components are subsequently translated into hypotheses on the most efficient order of introduction in Section 5.2.

5.1 Interdependencies between the Components of Lean Product Development

It has already been pointed out in Section 4.2 that, even though the components of Lean PD were presented as separate entities, this should not suggest that they are independent of each other. In fact, several authors have emphasized that many of the practices, as worthwhile as they might be, do not contribute to large efficiency gains if implemented in an isolated manner. It is claimed that only in their conjunction with other components, the full potential of the parts described in the previous chapter can be tapped [Balle 05] pp.18f, [Haque 04] p.8, [Sobek 99] p.81. In this respect, despite its different nature, Lean PD can be assumed to show strong similarities with Lean Production. Experience with Lean Production has demonstrated that implementing single parts of the production system while neglecting others yields a suboptimal performance and may even threaten operations. As an example, many companies have tried to follow the example of Toyota and implemented a just-in-time supply of material. For this purpose, they eliminated material buffers and asked their suppliers to deliver parts directly to the assembly line. However, what a lot of companies did not realize was that for just-in-time to work, they had to level their workload to avoid peaks in demand. With the reduced buffer size and remaining fluctuations in demand, the production system became vulnerable to unexpected bottlenecks in supply, causing major disruptions in production flow.

The example of just-in-time emphasizes the importance of investigating Lean PD as a system of interwoven parts rather than a collection of unrelated best practices. Particularly for the process of implementation, the interdependencies between the components may play an important role.

First, the effect a particular component on the overall system performance may differ depending on which of the other components are already in place. Second, it can be assumed that interdependencies have a major influence on how difficult a particular component is to implement at a certain point in time. Although the difficulty of implementing components is also influenced by the availability of firm-specific resources not covered by the eleven Lean PD components, the nature and strength of interdependencies between the components is likely to have the biggest impact on the question when to introduce the single components. Hence, as a starting point for deriving hypotheses on the introduction of a Lean PD system, it appears useful to theoretically investigate the interrelations between the components. For this purpose, a methodology consisting of two major steps – a qualitative analysis of the links using literature review and an evaluation of their strengths – was chosen.

In a first step, literature was scanned for quotes describing positive or negative effects that the Lean PD components have on each other. The components mentioned as well as the mechanisms serving as the links between the components were extracted from the quotes. Then, pairs of components for which no dependencies had been explicitly described in literature were investigated. Towards this end, drawing on the comprehensive descriptions of the components, potential links between each pair of components were formulated to complement the interdependencies mentioned in literature.

The result of the theoretical analysis of the qualitative interdependencies is displayed in Table 5.1. The first row and column each contain the eleven Lean PD components, spanning a table of 121 fields. The entries of the table qualitatively describe how the row element and the column element may be linked. Specifically, each entry details how the component in the row requires the component in the column. As an example, the component of Responsibility-based Planning and Control (column) contributes to the component of a Specialist Career Path (row) by enhancing individual learning through higher involvement, accountability and ownership. Vice versa, Responsibility-based Planning and Control (row) is supported by the component Specialist Career Path (column) in the way that engineers have a higher expertise to set their own goals, estimate the time they require for a particular task and are better able to achieve the goals they have defined for themselves.

In the second step of the analysis, to further understand the complex nature of the Lean PD system, the theoretical links between the components were rated according to their strength. Based on comprehensive review and consideration of the qualitative factors, each of the fields of Table 5.1 was assigned a score on a scale from 0 (not linked) to 5 (strongly linked). The resulting quantitative interdependencies, i.e. the extent to which one component requires another component, were entered into a matrix, again spanned by the eleven Lean PD components. This procedure, which is analogous to a methodology called "sensitivity model" described by Vester and Hesler [Veste 80], is inherently subjective since the score assigned to a relationship is subject to individual judgment. Considering that the scores only serve to derive hypotheses to be empirically tested later, however, the process of subjective rating was deemed appropriate and useful at this stage.

Table 5.1: Theoretical qualitative interdependencies between the components of Lean PD

How does component in row require component in column?	**Strong Project Manager**	**Specialist Career Path**	**Workload Leveling**	**Responsibility-based Planning and Control**	**Cross-project Knowledge Transfer**	**Simultaneous Engineering**	**Supplier Integration**	**Product Variety Management**	**Rapid Prototyping, Simulation and Testing**	**Process Standardization**	**Set-based Engineering**
Strong Project Manager	X	Development of qualified Strong Project Managers, reliable concept development and planning due to help of experienced engineers	Reliable project planning and progression due to reduced over-burdening of engineers, lower waiting times, clear prioritization of activities	Reliable project planning and progression through better adherence to schedule and larger motivation; reduced planning efforts for CE	More reliable project planning, cost and time estimation	More reliable proect planning and progression due to early integration of manufacturing, parallel development of product and process	More reliable project planning and progression due to early integration, careful outsourcing and high quality of delivered parts	More reliable project planning and progression due to reduced design and testing requirements	More reliable project planning and progression due to early and shorter problem-solving cycles	Faster project planning and better control through standard milestones, tools, documentation and communication	More reliable project planning and progression due to reduced late engineering changes, high robustness of solution
Specialist Career Path	Project manager as role model and mentor; learning through constant design reviews	X	Time for teaching, mentoring and reflection, increased learning through more reliable project runs	Enhancement of learning through higher involvement, accountability and ownership	Enhancement of technical expertise through ever-increasing knowledge-base	Expertise in manufacturing as important competence of product development engineers	Respectful treatment of suppliers as important competence of product development engineers	Better specialization and faster learning due to clearly separated modules	Increased and faster learning through early and shorter problem-solving cycles	Increased and faster learning through standard process logic, reduced variability through standard tools, and documentation	Increased and faster learning through consideration of wider set of technical solutions
Workload Leveling	Reduced variability in processes through better adherence to schedule, clear concept, cross-functional coordination	High availability of functional specialists for flexible planning; less iterations through standard skills, high technical expertise	X	Reduced variability through better adherence to schedule, larger motivation	Reduced variability through avoidance of unnecessary steps, iterations and learning	Reduced variability through early integration of manufacturing/ parallel development of product and process	Reduced variability through early integration, careful outsourcing, rigorous testing and fast sourcing process	Reduced variability through reduced design and testing requirements and parallel development of parts due to standard interfaces	Reduced variability through early and shorter problem-solving cycles	Improved planning through standard process logic, predictable and repeatable processes	Reduced variability through reduced late engineering changes, high robustness of solutions
Responsibility-based Planning and Control	Alignment of sub-goals to customer value; frequent control of adherence to goals and schedule	Technical expertise to set goals, estimate time required and adhere to goals set	Reliable planning of tasks and estimation of time required through clear staggering and prioritization of projects	X	More reliable planning of tasks due to availability of past experience	More reliable planning of tasks due to large amount of interaction with manufacturing	More reliable planning of tasks due to fast sourcing and high quality of delivered parts	Better planning and easier control of tasks due to clearly separated modules	More reliable planning of tasks due to early and shorter problem-solving cycles	Improved planning and control of tasks due to standard tools for design and communication	More reliable planning of tasks due to reduced late engineering changes, high robustness of solutions
Cross-project Knowledge Transfer	Clear responsibility for documentation of project knowledge; enforcement of checklists; knowledge transfer through CE	Higher ability for reflection and documentation of lessons learned	Time for reviewing past project findings before project start, time for reflection and documentation of lessons learned	Higher incentive for using past knowledge due to accountability and ownership	X	Documentation and reuse of knowledge on requirements of and design for manufacturing	Integration of supplier requirements and ratings in documentations	Better documentation of best practice of structures and designs due to lower part variability and clearly defined interfaces	Faster discovery of problems and higher rate of knowledge generation through early and shorter problem-solving cycles	Better reuse of knowledge due to similarity of subsequent projects and tools employed	Increased rate of knowledge creation and documentation through consideration of wide range of possible solutions
Simultaneous Engineering	Enforcement of early integration and synchronization of product development and manufcaturing	Better understanding of engineers for needs of manufacturing	Higher predictability of demand for functional specialists; improved synchronization	Higher incentive for cooperating with manufacturing due to accountability and ownership	Transfer of manufacturing requirements and best practice solutions	X	Early integration of manufacturing requirements in supplier contracts	Reduced complexity of parallel product and process development through standardized modules and interfaces	Early testing and optimization of design for manufacturing and assembly	Better synchronization of product and process development through standard procedures and tools	Earlier and stronger integration of manufacturing through early consideration of different alternatives
Supplier Integration	Early integration and synchronization of product development with suppliers	Clear definition of requirements; early identification of problems; mentoring and teaching of suppliers	Reliable deadlines for parts delivery	Higher incentive for integration of suppliers due to accountability and ownership	Documentation of supplier performance, preferred suppliers and their strengths and weaknesses	Improved make-or-buy decision making, precise definition of requirements, mentoring of suppliers in manufacturing strategies	X	Reduced sourcing effort through reuse; clear seperation and inter-changeability of modules through standard designs and interfaces	Faster formulation of requirements and early discovery of problems with supplied parts through early and fast testing and prototyping	Better integration of suppliers through standard procedure for contracting, partnering and sourcing	Earlier and stronger integration of suppliers through involvement in development of alternatives and frequent communication
Product Variety Management	Enforcement of reuse and modularization due to Strong Project Manager's responsibility for cost and performance	High expertise in dealing with particular part functionality, geometry and interfaces	Time for reviewing past designs and structural best practices; time for communication to increase reuse, define modules	Higher incentive for part reuse and modularization due to accountability and ownership	Knowledge on feasibility of part reuse and modularity and interface design from past projects	Integration of manufacturing requirements in modules and reuse strategy	Definition of standard designs and interfaces for suppliers; integration of suppliers in module and platform development	X	Higher robustness of parts, modules and platforms through early and fast testing and prototyping	Standardized process for increasing part reuse and developing modules and platforms	Better understanding of interdependence and higher robustness of parts, modules and platforms
Rapid Prototyping, Simulation and Testing	Coordination of testing and prototyping	Seamless cooperation between designer and testing personnel; testing competence among designers	Availability of qualified testing and prototyping personnel when needed	Autonomous development of test plans; higher incentive for early and intensive testing and prototyping due to ownership	Best practices in testing and prototyping; documentation of failure modes	Use of manufacturing expertise in prototyping and testing; early testing for manufacturing requirements and assembly	Fast sourcing of testing equipment, prototype parts and tooling; rigorous testing conducted by suppliers	Faster testing through reuse and standard designs; independent testing and prototyping through clearly separated modules	X	Systematic and faster testing and prototyping through standard procedures	Improved testing and prototyping through high use
Process Standardization	Reduced variability in processes through better adherence to schedule; reduced iterations due to clear concept	Higher adherence to schedule and linear process steps through reduced iterations	Higher acceptance of common processes due to more reliable project runs and less waiting times	Continuously improving standards; higher acceptance of common processes due to involvement of engineers in updating	Gathering of best practice milestones and procedures; best practice standard tools	Reduced variability of processes due to early integration of manufacturing	Reduced variability through early integration, careful outsourcing, rigorous testing and fast sourcing process	Reduced variability in processes through increased reuse, standard designs and interfaces	Reduced variability of processes through early and shorter problem-solving cycles	X	Reduced variability through reduced late engineering changes, high robustness of solutions
Set-based Engineering	Coordination of parallel development and driver for narrowing decisions	Expertise for developing alternative solutions, defining interfaces, weighing pros and cons, choosing and merging alternatives	Time to follow several alternatives in parallel and test them rigorously before narrowing in	Autonomous development of alternatives and accountability for results	Freezing and re-use of design sets from previous projects; generalization of solutions in trade-off curves	Consideration of alternative manufacturing processes; evaluation of alternatives for manufacturability and robustness	Development of alternative solutions and narrowing in by suppliers; frequent communication	Clearly seperated modules with standard interfaces to be developed in parallel	Rigorous testing of design sets; narrowing based on profound information base; gathering of knowledge in trade-off curves	High synchronization of parallel processes through standard procedure, tools and documentation	X

Table 5.2 shows the quantitative interdependencies between the Lean PD components gained by the second step of the theoretical analysis. As can be seen, every table entry has been assigned a designated score signaling the strength of relationship between the row and column component. Furthermore, the table contains the average values as well as the standard deviations for every column and row. Since the scores in the matrix entries indicate to what extent the component in the row requires the component in the column, the average row score is an indicator for how much a component necessitates other components. The average column score of a component, in contrast, shows how much the component is required by other components.

Table 5.2: Theoretical quantitative interdependencies of the components of Lean PD

To what extent does component in row require component in column?	Strong Project Manager	Specialist Career Path	Workload Leveling	Responsibility-based Planning and Control	Cross-project Knowledge Transfer	Simultaneous Engineering	Supplier Integration	Product Variety Management	Rapid Prototyping, Simulation and Testing	Process Standardization	Set-based Engineering	Average	Std. Deviation
Strong Project Manager	X	4	5	3	1	1	1	1	1	4	1	2.20	1.54
Specialist Career Path	2	X	5	5	3	1	1	1	2	3	1	2.40	1.50
Workload Leveling	4	3	X	2	2	2	2	1	1	5	2	2.40	1.20
Responsibility-based Planning and Control	4	5	4	X	3	1	1	1	1	2	1	2.30	1.49
Cross-project Knowledge Transfer	4	3	5	2	X	1	1	1	1	4	1	2.30	1.49
Simultaneous Engineering	4	2	2	1	1	X	1	3	1	2	1	1.80	0.98
Supplier Integration	5	4	2	2	2	1	X	3	1	2	1	2.30	1.27
Product Variety Management	4	5	5	1	5	4	4	X	1	4	1	3.40	1.62
Rapid Prototyping, Simulation and Testing	4	4	3	3	3	5	5	3	X	2	1	3.30	1.19
Process Standardization	2	2	4	1	3	1	1	1	1	X	2	1.80	0.98
Set-based Engineering	5	5	3	4	5	5	4	4	5	4	X	4.40	0.66
Average	3.8	3.7	3.8	2.4	2.8	2.2	2.1	1.9	1.5	3.2	1.2		
Std. Deviation	0.98	1.10	1.17	1.28	1.33	1.66	1.51	1.14	1.20	1.08	0.40		

The averages and standard deviations of the columns and rows of Table 5.2 can be used to build an alternative, graphical representation of the quantitative relationships. In Figure 5.1, the quantitative interdependencies are displayed in the form of a bubble chart. In this chart, the position of the bubbles represents the extent to which a particular component requires other components (abscissa) and is required by other components (ordinate). The size of each bubble reflects the average standard deviation of the component's row and column rating.

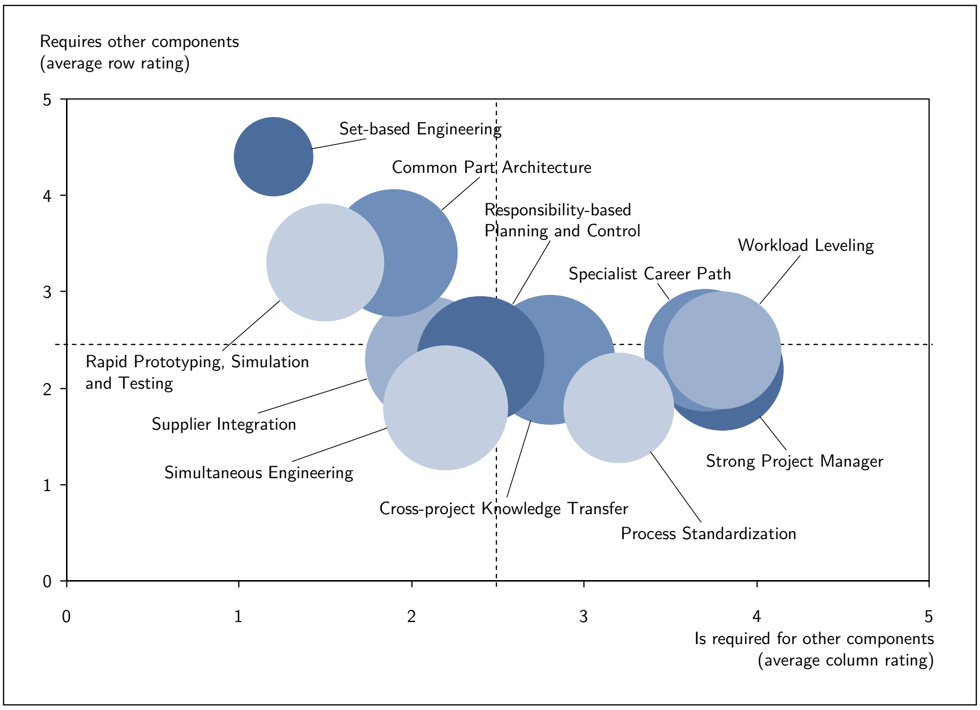


Figure 5.1: Graphical representation of the theoretical links between the Lean PD components

When taking a look at the position the single components assume in the graph of Figure 5.1, some interesting observations can be made. First, it appears that, according to the theoretical investigation, the components of the Lean PD system differ in how much they require or serve as prerequisites for other components. Second, the components are not equally distributed but seem to lie around a diagonal running from the upper left to the lower right of the graph. Some of the components, such as the Strong Project Manager, seem to require only few other components but are highly required by other components. Others, like Set-based Engineering, require other components to a much higher degree while being less required for other components. These observations can be translated into the following two definitions:

- Components requiring a lower number of other components as prerequisites but serving as prerequisites for a higher number of other components shall be labeled *lower-level components*. They are located in the lower right part of the graph in Figure 5.1.

- Components requiring a high number of other components as prerequisites but serving as prerequisites for a small number of other components shall be labeled *higher-level components*. They are located in the upper left part of the graph in Figure 5.1.

The two definitions of lower-level and higher-level components can help deriving hypotheses on the main questions of this thesis: What is the most efficient order of implementing the eleven Lean PD components to achieve a Lean PD system?

In fact, considering the observations made above, it seems intuitive to not start the process of implementation with higher-level components which presume a lot of other components and do not serve as prerequisites for the implementation of others. Instead, particularly when taking into account that resources for implementation in companies are limited, it appears much more plausible to first implement the lower-level components and then slowly move towards implementing more sophisticated parts of the Lean PD system. This is likely to yield a more systematic process of implementation where components build upon each other. Moreover, it can be assumed to avoid iterations in the implementation process which arise when components necessary for the introduction of a particular part of a Lean PD system have not yet been implemented. In sum, based on the theoretical analysis, it therefore appears reasonable to assume a most efficient order of implementing the Lean PD components as depicted in Figure 5.2.

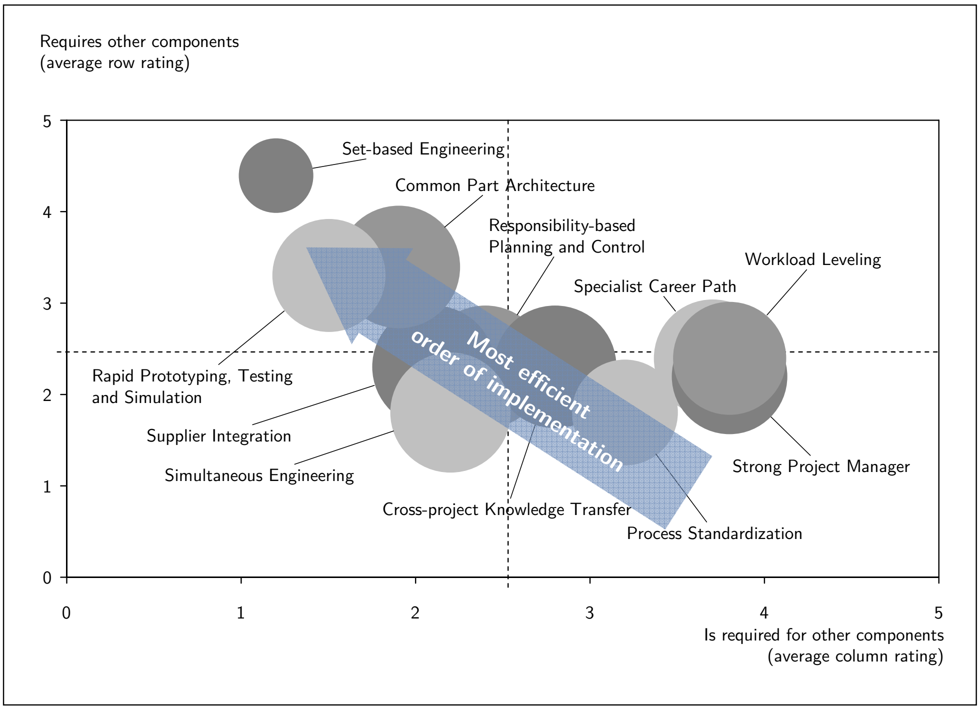


Figure 5.2: Hypothesis on the order of implementing the Lean PD components

On a micro level, the order of implementing the Lean PD components chosen by a particular company may of course deviate from the one shown in Figure 5.2. On a macro level, however, the most efficient order of implementation should be reflected in current industry practices since

- Either managers are aware of the respective prerequisites that the components have and choose their implementation strategy accordingly

- Or the implementation process is pushed into the right order as problems with implementation force the company to unintendedly implement a component on their way to implement the intended one.

The theoretical investigations described in this section can be translated into explicit hypotheses on the introduction of Lean PD. Before the hypotheses are provided in the next Section 5.2, however, it shall be pointed out again that the methods used in this section are of a partly subjective nature. It is not claimed that, if the analysis was repeated by other researchers, the position of the components shown in Figure 5.2 would be exactly the same. The goal of this section, however, was not yet to identify the rank of implementation for each of the eleven Lean PD components. Rather, the procedure served to derive more general hypotheses on the implementation of a Lean PD system to be empirically tested later.

5.2 Hypotheses on the Implementation of a Lean PD System

Based on the observations made in the previous section, a number of hypotheses on the implementation of a Lean PD system were derived. These hypotheses are:

1. The components of a Lean PD system are highly interwoven and should therefore not be implemented independently but using a process with concurrent and overlapping phases.
2. The eleven Lean PD components differ regarding the number and nature of their prerequisites, i.e. there are lower-level components and higher-level components which can be identified because, simultaneously,
    - 2a. Lower-level components are implemented to a larger extent than higher-level components.
    - 2b. Lower-level components are implemented earlier than higher-level components.
    - 2c. Lower-level components are perceived as easier to implement than higher-level components.
3. Implementing lower-level components first will facilitate the process of implementing the eleven Lean PD components, i.e.
    - 3a. Companies that make more use of lower-level components have less difficulty with implementing particular higher-level components.
    - 3b. Problems with the implementation of higher-level components are related to particular missing lower-level components.

In addition to the hypotheses derived from the theoretical analysis of the component interdependencies, it was deemed to be of particular interest in which way the process of implementing Lean PD is influenced by the financial endowment, the number of employees and the industrial sector of a company. Complementing the first three hypotheses on the structure of the implementation process, it was hypothesized:

4. Independent of the sector, due to a higher endowment of financial and human resources, larger companies will be more likely to implement the Lean PD components. In detail, this implies that
   - 4a. Companies with a higher revenue will be more likely to implement the Lean PD components.
   - 4b. Companies with a larger number of employees will be more likely to implement the Lean PD components.
   - 4c. The likelihood of implementing the Lean PD components is equal across all industry sectors.

Finally, another important question was how the process of implementing a Lean PD system can be supported by using special tools or infrastructure. To be able to investigate this question, another hypothesis with four sub-hypotheses was phrased:

5. The use of supporting tools and infrastructure will increase the probability of success of implementing the Lean PD components. Specifically,
   - 5a. Defining goals for the implementation will increase the probability of success of implementing the Lean PD components.
   - 5b. Defining a person responsible for the process of implementation will increase the probability of success of implementing the Lean PD components.
   - 5c. Using external help (e.g. consultants or sensei) will increase the probability of success of implementing the Lean PD components.
   - 5d. Conducting value stream mapping will increase the probability of success of implementing the Lean PD components.

The five main hypotheses provided in this section serve as a basis for the investigations of the implementation of Lean PD in all subsequent chapters. Building on the hypotheses, in Chapter 6 the procedure for collecting empirical data on the implementation of Lean PD is described. Chapters 7 and 8 then present the methodology and findings of a comprehensive descriptive and exploratory analysis of the data. The results of the data analyses, in turn, are used in Chapter 9 to discuss whether the hypotheses stated in this section can be corroborated or not. Finally, the insights gained by testing the hypotheses are translated into a well-grounded Lean Innovation Roadmap in Chapter 10.

6 Collection of Data on the Introduction of Lean PD

The previous chapters presented a framework consisting of eleven Lean PD components, discussed their interdependencies and derived five main hypotheses on the implementation process of Lean PD. To gain an overview of the extent to which the single practices are used in companies, back the theoretical investigations with empirical data and establish a basis for deriving a roadmap towards Lean PD, a comprehensive survey among international companies was conducted. The following Sections 6.1 and 6.2 detail the reasons for choosing this method of data collection and describe the goals and structure of the survey. Building upon this, Section 6.3 provides some information on the process of sampling.

6.1 Selection of the Method of Data Collection

In general, to shed more light on the use and implementation of the eleven Lean PD components described in the previous chapters, two different approaches are available: case studies and surveys. Case studies are typically applied to study a particular phenomenon within a small sample. Their advantage lies in the possibility to investigate an object of interest in very high detail. They are particularly useful if the factors influencing the behavior of a system are unknown and need to be identified in the course of the research. Surveys, which are used to study a phenomenon among a large sample, are less suited for this sort of investigation. In exchange, the results they produce are much more generalizable than the insights gained by case studies.

While in the past most of the investigations of Lean PD systems have been based on case studies, to collect the data for this research it was intentionally decided to make use of a survey. Previous studies mainly aimed at identifying successful PD practices, justifying the use of a case study methodology. In contrast to this, this research did not intend to identify new best practices. Instead, it sought to understand the interdependencies between the Lean PD components which had already been described in literature (see Section 4.1) as a basis for a well-grounded roadmap for their introduction. The investigation of the links between these components required a large sample. Furthermore, the roadmap to be generated needed to be based on generalizable data. For these reasons, a survey was chosen over a case study methodology in this case.

6.2 Design of the Survey on the Introduction of Lean PD

After the method of data collection had been selected, the survey needed to be developed. For this purpose, first the goals pursued with the survey were framed. In the next step, then the structure and questions of the survey were derived.

6.2.1 Goals of the Survey

The goal of the survey on the introduction of Lean PD can be divided into three parts: a descriptive, an explanatory and a prescriptive function.

Descriptive Function

As was pointed out in Section 4.1, previous investigations of Lean PD systems either focus on a small sample of companies or are limited by considering only a small set of components. In the last years, only Schuh et al. and Brown have investigated Lean PD components among a large number of companies on a broader basis. However, as shown in Table 4.1, even these studies do not cover the full range of Lean PD components described in this thesis. The only approach giving a comprehensive overview on Lean PD practices, the one by Morgan and Liker (2007), is limited to a description of PD practices at Toyota.

Considering this obvious gap in the existing literature, the first goal of the study, as a basis for all further investigations, was to give a descriptive overview of the use of Lean PD. It should be described to what extent the eleven Lean PD components mentioned in Section 4.2 are currently used in companies of different sectors. Furthermore, it should be clarified how companies structure their process of implementing the components. In this context, it was considered of interest if companies had defined explicit goals and performance measures for implementing Lean PD, had declared a person responsible for the introduction process, drew on external help for implementing the components or made use of supporting tools such as value stream mapping.

Explanatory Function

The comprehensive description of the status quo regarding the use of the Lean PD components and supporting measures as covered by the descriptive function was considered to be of great value from a scientific point of view. The intended contribution of the survey, however, went beyond a mere description of practices.

In Chapter 5, based on a comprehensive investigation of the mutual dependencies of the Lean PD components, five major hypotheses were phrased. It was hypothesized that the most efficient order in which the components are implemented in a company is determined by the interdependencies of the components. In particular, it was claimed that there are so-called lower-level components which are perceived as easier to implement, implemented earlier and used to a higher degree than higher-level components. Implementing lower-level components before higher-level components was hypothesized to facilitate the process of introducing Lean PD. Furthermore, several hypotheses regarding the effect of firm specific characteristics as well as supporting tools and infrastructure on the implementation process were derived.

It was an explicit goal of the survey to empirically verify or refute the hypotheses derived through the theoretic analysis and contribute to explanation of the governing mechanisms of a Lean PD system. By analyzing patterns in the use of the components, it should be determined whether the process of implementation in the case of the Lean PD components is indeed shaped by their interdependencies. Moreover, it should be answered how different orders of implementation impact the perceived difficulty of introducing a component.

Prescriptive Function

As stated in Section 1.3, the intended outcome of the thesis at hand is a roadmap, providing advice on the order in which the single Lean PD components ought to be implemented. The nature of this question entails that it is not sufficient to provide information on the status quo and explain underlying structures. Instead, explicit recommendations for the implementation of particular components have to be derived which assume a prescriptive rather than a descriptive or explanatory nature.

In Section 1.2 it was stressed that available roadmaps for the introduction of Lean PD tend to be vague, are not based on explicit empirical data and rarely take into account the high amount of interdependencies of the components to be implemented. In fact, in the literature on Lean PD it is rarely argued why a certain order of implementation suggested by the author is superior to alternative ways of introduction. This may be in parts due to the lack of empirical data. Thus far, a survey explicitly dealing with the process of introduction has not been conducted.

Against the background of an apparent lack of empirically sound roadmaps, the third and final goal of the survey was to gather insights on the ideal order of implementing the Lean PD components. Based on a profound understanding of the system behavior – the target of the explanatory function – the survey should identify advantages and disadvantages of alternative ways of introduction. These, in turn, should serve as a basis to derive recommendations for a successful implementation process.

It is important to note that, in contrast to most studies described in literature, the survey was not intended to measure the contribution of particular practices to a successful PD performance. The individual value of the eleven Lean PD components has been shown in previous studies (see Section 4.1) and is not subject to investigation in this thesis. In fact, as discussed in Chapter 5, one of the key claims of this thesis is that the components building a Lean PD system are highly interwoven and synergistically support each other. From this perspective, separately rating the single components according to their usefulness seems neither appropriate nor possible. The eleven Lean PD components are therefore treated as equal entities whose real value lies in their contribution to an overall system performance. In this context, the focus of the survey was to shed light on the question how the individual components are linked and can be implemented most efficiently.

6.2.2 Structure of the Survey

Based on the goals listed in the previous section, the structure and the questions of the survey were derived. The full, printed version of the survey is provided in Appendix A. An overview on the structure is given in Table 6.1. In what follows, the reasons for choosing this particular structure shall be described in more detail.

Table 6.1: Structure of the survey on the introduction of Lean PD

Content	Number of pages	Number of questions	Mode of questions
1. Introduction and Confidentiality Statement	1	-	-
2. General Questions on the Introduction Process	1	4	Mult. Choice
3. Status, Difficulty and Usefulness of Component Implementation	11	66	Mult. Choice
4. Order of Component Implementation	1	11	Mult. Choice
5. Problems during Component Implementation	1	11	Open Ended
6. Company Information	1	7	Mixed
Total	**16**	**99**	-

As shown in Table 6.1, the survey developed consists of 16 separate pages containing a total of 99 questions. It starts with an introductory page which briefly summarizes the purpose of investigation, introduces the framework of the eleven Lean PD components, lists the time required to complete the survey and reassures the potential participant that all of the information collected is treated as highly confidential (see Figure A.1 in Appendix A). After these introductory remarks, on the next page, four general questions on the introduction process are presented (see Figure A.2 in Appendix A). Specifically, it is asked whether a company has defined goals for the introduction of Lean PD, if a person responsible for implementing Lean PD has been declared, if the company is planning to use external help during the implementation process and whether value stream mapping has been used to analyze product development processes. For each of those questions, two to five answering options are provided participants can choose from. The purpose of these questions was both to first get an insight into the use of supporting measures during the process of implementation (descriptive function) and be able to measure the effect that these measures have on the success of implementation (explanatory function, see hypothesis 5).

The following eleven pages of the survey (see Figure A.3 to Figure A.13 in Appendix A) each cover one of the eleven PD components described in Section 4.2. To provide the participant with some information on the context of the questions, a short definition of the component is given at the top of each page. The first four questions then ask for the status of implementation the company has reached for the particular component. This is done by listing four characteristics that are representative of the Lean PD component. For each of these characteristics, the participant is asked to specify, on a five-item scale from "not used" to "used in every project" to what extent it is used in his company. Two further questions aim to determine as how difficult and useful the participant perceives the implementation of the respective Lean PD component. In case of the perceived difficulty, the respondent can choose between six items ranging from "very easy" to "very difficult". In case of the perceived usefulness there are six options which reach from "very low" to "very high". The questions on the status and perceived difficulty of implementation were important to test the hypotheses derived in Chapter 5 (specifically hypotheses 2c, 3a, 4 and 5). The perceived usefulness, in contrast, mainly served as a control variable. Even though, as stated in the previous section, the purpose of the survey was not to rank the components according to their contribution to a successful PD system, the subjective value assigned to each component by the participants was considered important to understand the influence of personal preferences on the implementation of the components.

With regard to the hypotheses 2b, 3, 4 and 5 as well as the Lean Innovation Roadmap to be derived, another important question is for the order in which the components have been implemented in the company of the participant. In general, the order of implementation can be inquired by asking for the point in time a component was implemented, the timeframe that has passed since the implementation or by the rank at which the component was introduced relative to the other components. The main interest of this study was not in the exact time but in the relative positions of the components. Therefore, it was decided to make use of the third option which is considerably easier to answer than the first two. Although, like the questions for status, difficulty and usefulness of implementation, the question uses the eleven Lean PD components as a basis, it was decided to not add it to the separate component pages. Instead, one extra page was created on which the participant was asked to select the rank at which of each of the components had been implemented (see Figure A.14 in Appendix A). If the question for the rank of implementation had been split up and distributed to the component pages, it would have been difficult for participants to provide a consistent, comparative ranking of the order of implementation chosen.

The majority of the survey questions were intentionally chosen to be closed in nature to facilitate both filling in and analyzing the answers. However, it was deemed important to not only measure responses to given options but capture aspects that might not have been considered when designing the answering options. Particularly with regard to hypothesis 3b, it was deemed of great interest, where the participants in the survey had experienced the biggest problems when implementing the components of Lean PD. Hence, a page was created where for each component problems could be entered in a free-form field (see Figure A.15 in Appendix A). On the one hand the insights gathered this way could be used to link problems with the implementation of a particular component with missing other components. On the other hand, this methodology served to capture external factors impacting the introduction process which are not due to the interdependencies of the components. Since it was assumed that not every of the participants had made experiences with implementing all of the components, the provision of problems was not mandatory.

Finally, the last page of the survey inquires some information on the company the participant is affiliated with (see Figure A.16 in Appendix A). The participant is asked for the industrial sector, revenue, number of employees and the geographic location of his company as well as his own position within it. On the one hand, this data was used to gain insight on the sample of the study. On the other hand, this information served as a basis for testing hypothesis 4 dealing with the influence of company characteristics on the implementation of Lean PD.

Overall, the survey was intentionally kept short to encourage a high response rate. Both questions and answering options were precisely phrased and reviewed by several researchers. Then, using the online-software EFS Survey by UNIPARK, a supplier of professional survey software for academic use, the survey was implemented in its final web-based format. In order to increase the number of potential participants, the survey was set up in two different languages, English and German, each accessible through separate URLs. Before the start of the field period, both language versions of the survey were intensively tested to ensure that all fields were formatted correctly and data entered was transferred to the database without losses.

6.3 Sampling and Data Collection

After a successful completion of the test period, the survey was announced to a sample of international companies from different industrial sectors. Using the German business platform XING, the MIT Alumni database and address databases of the Lean Advancement Initiative and the Institute for Manufacturing and Operations Research of the TU Braunschweig, the contact information of product development managers, chief engineers and development engineers was received. These three groups were considered to have the best insight into the respective PD practices of their companies and, thus, were likely to provide the most reliable data. After collecting and filtering the contact information, the persons were directly contacted via e-mail, provided with the link to the online-survey and asked to participate in the study. German companies were sent the link to the German version of the survey, companies from other countries were directed to the English version. In total, using the three channels mentioned above, a number of 910 persons were contacted. Besides directly contacting potential participants, the announcement of the survey was distributed by contacting several industry associations, such as the German Association of Engineers, local chambers of commerce and the MIT Industry Liaison Program (ILP). The associations were asked to forward the information on the survey to their members.

When selecting the companies, it was taken care that companies covered a wide range of industries to avoid bias towards the use of particular components due to industrial factors. A prerequisite for being considered as a participant in the study, however, was the existence of an own product development department within the company. This condition also has some implications for the size of the companies surveyed. While small- and medium-sized companies were explicitly included in the sample chosen, the requirement of a product development department inherently causes a bias towards larger companies.

Since one of the declared goals of this thesis is to reveal difficulties during the process of implementing the Lean PD components, it was considered useful to contact companies with different levels of experience and success in introducing Lean PD. Only surveying companies with a proven success story in Lean PD might have covered the problems laggards have to cope with. As these problems are of large importance for the derivation of a Lean Innovation Roadmap, it was tried to keep the sample as diverse as possible.

Finally, it should be noted that the unit of analysis of the survey was defined to be a division within an organization, i.e. participants in the study were asked to answer all questions considering the division of their organization in which they were placed at the time of participation. Whereas it was generally deemed preferable to contact different companies, clearly defining the unit of analysis this way allowed to have separate divisions of the same company participate in the survey without creating a bias in the results. Since in the case of the indirect distribution of the survey announcement through industry associations, chambers of commerce and ILP it was not possible to control beforehand who received the request for participation, the results were filtered ex post. Answers by participants who did not fall into one of the three target groups mentioned above or belonged to the same division of a company were deleted. In total, during the field period of only 40 days, 124 persons completed the survey, equaling a response rate of about 14 percent. Of the 124 data points, 11 data points violated the above mentioned criteria and were discarded. The remaining 113 data points were considered for the analysis of the results, described in the subsequent chapters.

7 Descriptive Analysis of the Survey Data

Following the general structure of the survey goals given in Section 6.1, the data collected through the survey was analyzed in three subsequent steps. First, to get an overview of the data and describe the status quo regarding the implementation of the eleven Lean PD components, some simple descriptive statistics were performed. The descriptive analysis, in turn, served as a basis for the second step, a more sophisticated exploratory analysis aiming to better understand the interdependencies between the components and prevailing problems of companies during the process of implementation. In a third step, finally, the findings from both the descriptive and the exploratory analysis were consolidated. This aimed at discussing the hypotheses listed in Section 5.2 and deriving implications for the most efficient order of implementing the eleven Lean PD components.

The order in which the findings of the survey are presented in this thesis reflects the steps chosen for the analysis of the survey data. The following sections of Chapter 7 provide the methodology and findings of the descriptive analysis. In Chapter 8, the procedure and results of the exploratory analysis are shown. Chapter 9 finally discusses the results of the analyses with regard to their implications for the implementation process of the Lean PD system.

7.1 Methodology of the Descriptive Analysis

As a tool for analyzing the data SPSS 17 was used. After filtering the data and deleting the invalid data points (see Section 6.3), the data generated by the two versions of the survey was brought together in a common database and analyzed using descriptive statistics. For most of the variables, e.g. the perceived difficulty or the perceived usefulness of implementing the components, this meant calculating simple averages over all of the data points. In case of the status of implementation, however, an extra step was necessary. As explained in Section 6.2.2, to inquire the use of the eleven Lean PD components, for every component the survey listed four characteristics which were considered representative of it. Although the current state of implementation of a particular component can be described by the use of its four characteristics, for the analysis it was deemed useful to have one metric summarizing the use of each component.

To be able to combine the four characteristics of each component to a single metric, the weight assigned to each of the four characteristics had to be determined. For this purpose, a factor analysis was conducted. Using principle component analysis with varimax rotation of the factor matrix, the loadings of the four characteristics were separately calculated for each of the eleven Lean PD components. Interestingly, it was found that for all of the components the four characteristics used to describe their implementation were almost equally loaded. A subsequent t-test yielded that in fact, a metric calculated by using the factor loadings of the characteristics as weights did not significantly differ from a metric calculated based on equal weights of the characteristics. Hence, for reasons of simplicity, it was chosen to determine the new variable “Use of the component” by calculating the average use of its four characteristics.

7.2 Findings of the Descriptive Analysis

The following sections display the findings of the descriptive analysis. First, the characteristics of the study participants and the data on the use of supporting tools and infrastructure during the implementation will be presented in Sections 7.2.1 and 7.2.2. Then, Sections 7.2.3 to 7.2.7 provide some comparative results regarding the implementation and use of the eleven Lean PD components.

7.2.1 Characteristics of the Study Participants

Figure 7.1 depicts the participants in the study according to their geographic location. As can be seen, 58% of the participating companies are based in Germany, 29% in the United States and 13% in the rest of the world (e.g. China, France, Italy, Spain, Australia and Sweden).

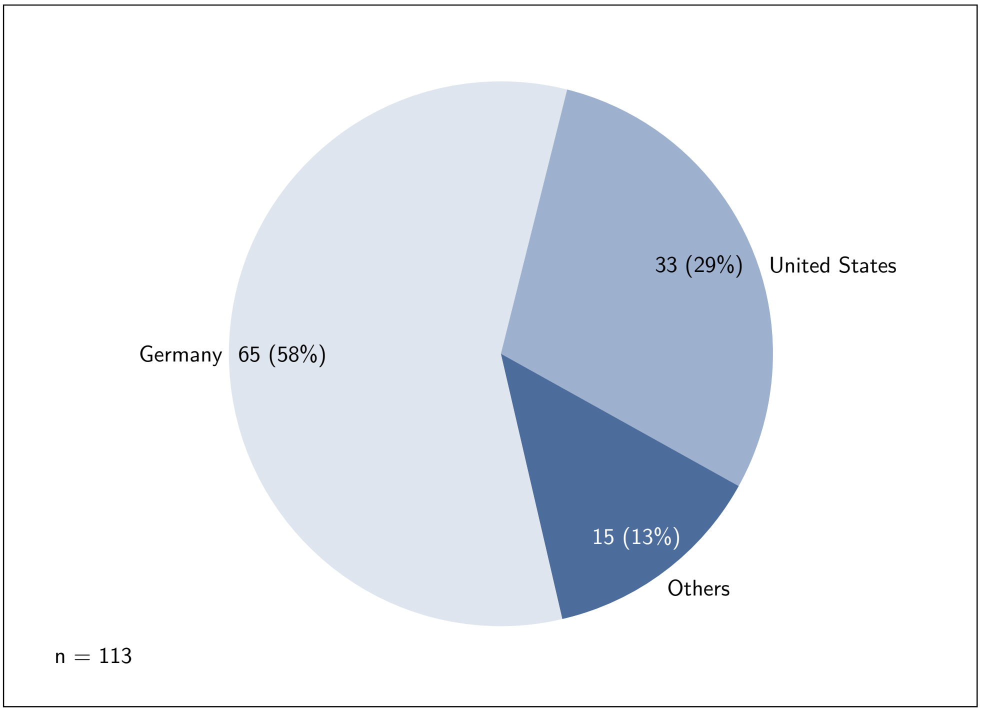


Figure 7.1: Geographic location of participating companies

The distribution of the participating companies among industry sectors is shown in Figure 7.2. The majority of the companies (39%) belong to the automotive sector, followed by 15% from the electronics sector and 14% from the industrial equipment sector. 10% of the companies have their background in aerospace manufacturing, 4% in medical devices. The rest (18%) covers a wide range of different industries, ranging from naval shipbuilding to defense.

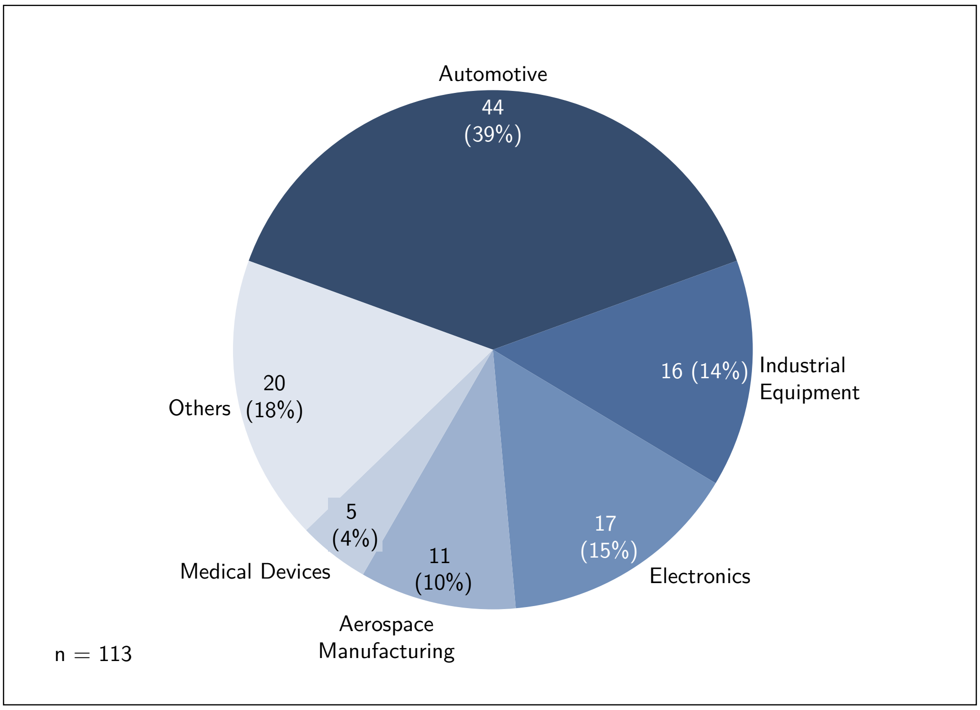


Figure 7.2: Industrial sectors of participating companies

Figure 7.3 finally shows the revenues of the participating companies generated in 2007. It becomes obvious that almost half of the firms filling in the survey had revenues of 100 million to 10 billion dollars (49.6%) in 2007. Only ten companies (8.8%) taking part in the study had revenues of less than 10 million dollars, whereas on the other side 9 companies (8.0%) had revenues of more than 100 billion dollars. As already pointed out in Section 6.3, this large number of companies with comparatively large revenues can be partly explained by the fact that, in order to be considered in the analysis, companies had to have a distinct product development department. The overrepresentation of large companies in the sample is confirmed when analyzing the companies according to their number of employees. Only ten of the companies (8.8%) taking part in the study stated to have less than 100 employees. In contrast to this, for 52 companies (46.0%) the number of employees exceeded 10,000 with 36 companies (31.9%) lying in the range from 10,000 to 100,000 and 16 firms (14.2%) surpassing the number of 100,000.

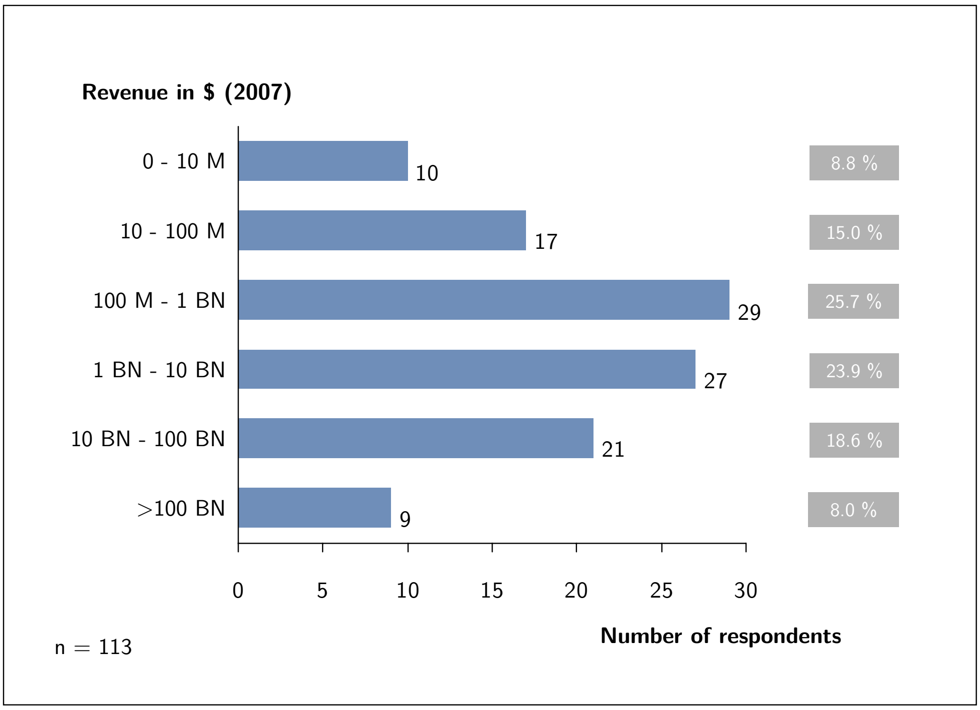


Figure 7.3: Revenues of participating companies in 2007

7.2.2 Use of Supporting Infrastructure and Tools during the Implementation Process

As explained in Section 6.2.2, the first part of the survey contained some general questions on the measures companies use to support their process of implementing Lean PD. Specifically, companies were asked whether the had defined goals and performance measures, were making use of special human resources and external help and had conducted value stream mapping.

Figure 7.4 describes to what extent the firms answering the survey have set goals for their introduction process. It shows that about a quarter of the companies (25.1%) have not defined any goals for the implementation of Lean PD, eight of which (7.1%) are not planning to develop any in the future. Of the 84 companies that have taken the effort to define goals, 35 so far only have formulated an overall strategy but not defined lower-level goals and performance measures supporting the strategy yet. Only 27 companies (23.9% of the total sample or 32.1% of the companies that have defined goals) have actually derived an overall strategy, measurable lower-level goals and the according performance measures.

Regarding the use of human resources during the implementation of Lean PD the survey shows mixed results as well. As indicated in the left part of Figure 7.5, the minority of the companies (46%) in the sample responded to have declared a person responsible for implementing Lean principles in product development. Asked whether their organization was planning to use or was already using external help during the implementation process, only 37% percent of the participants responded that they were considering this option.

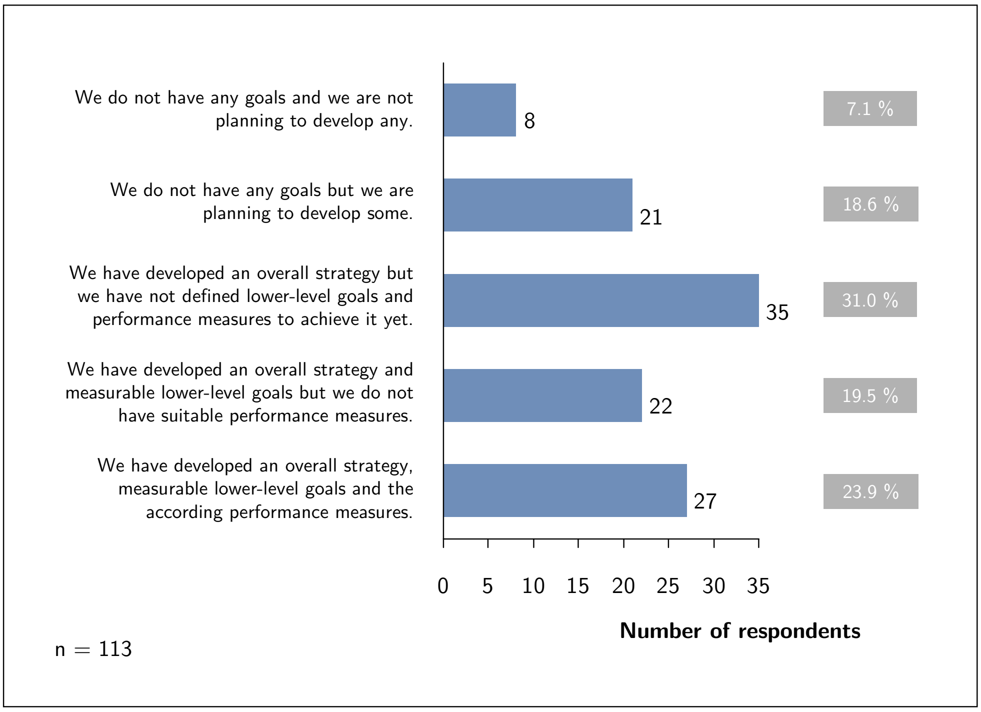


Figure 7.4: Goals for the implementation of Lean PD

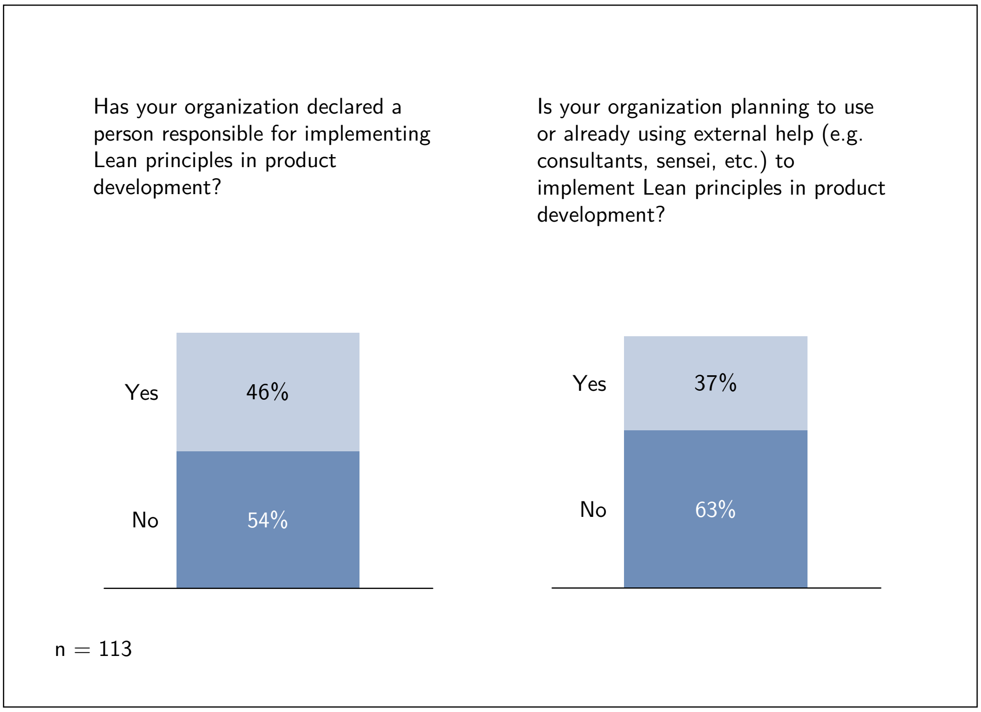


Figure 7.5: Human resources for the implementation of Lean PD

The answers of the participating companies concerning the use of value stream mapping as a supporting tool during the implementation process are shown in Figure 7.6. Most of the firms in the sample (57.6%) have conducted value stream mapping. However, it is striking, that among these companies, the vast majority (63.1% of the companies that used value stream mapping) so far has limited their efforts to only a small number of processes. Furthermore, it is interesting to see that almost a quarter (24.8%) of the total sample neither has conducted nor plans to use value stream mapping. Considering that value stream mapping, particularly in the domain of production, is one of the key tools of Lean, this finding is surprising and will be elucidated further in Section 8.2.4.

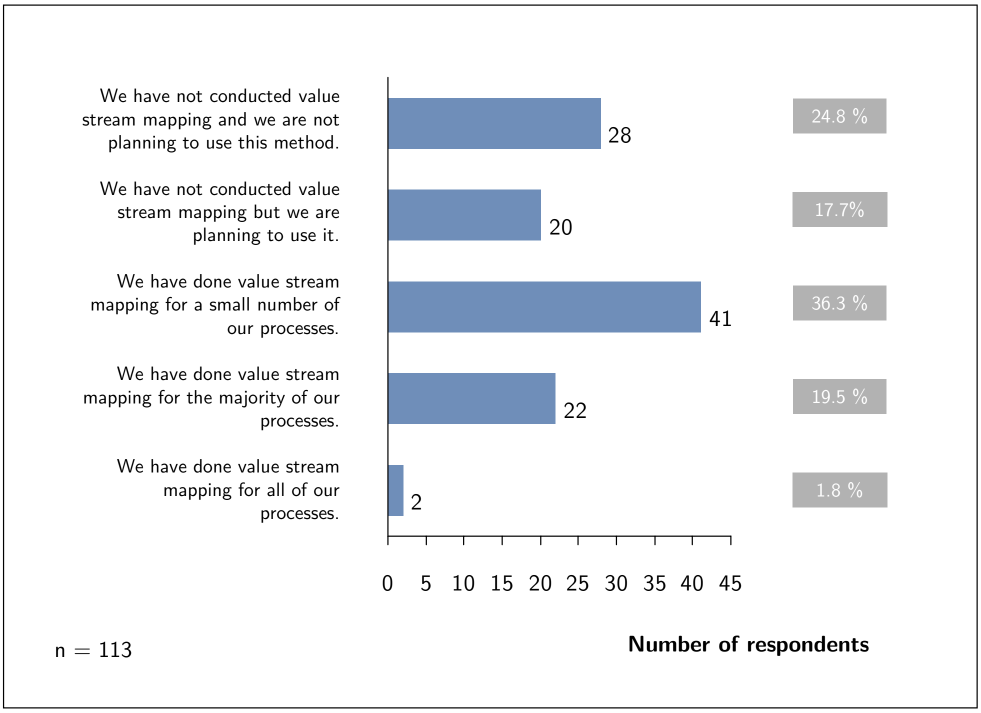
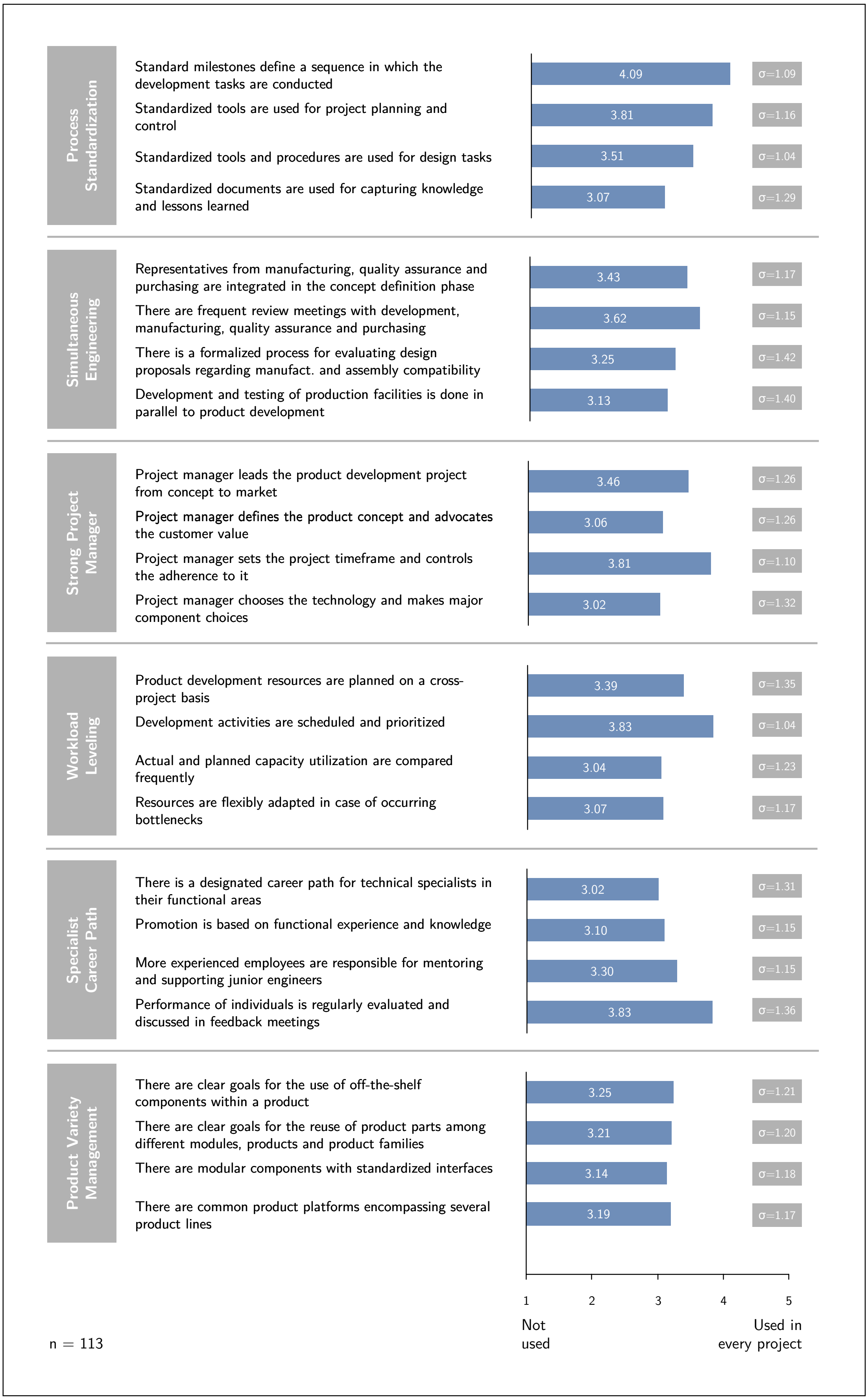


Figure 7.6: Use of value stream mapping during the implementation of Lean PD

7.2.3 Use of the Lean PD Components

After the general questions on the implementation process, the survey participants were asked to rate the use of each of the eleven Lean PD components in their company. As detailed in Section 6.2.2, for each of the components four specific characteristics were defined. The participant was then asked to rate the use of these characteristics on a five-item scale from "not used" (1) to "used in every project" (5). The averages and standard deviations of the ratings for the characteristics are shown on the next two pages in Figure 7.7.


Process Standardization
Standard milestones define a sequence in which the development tasks are conducted
4.09
σ=1.09
Standardized tools are used for project planning and control
3.81
σ=1.16
Standardized tools and procedures are used for design tasks
3.51
σ=1.04
Standardized documents are used for capturing knowledge and lessons learned
3.07
σ=1.29
Simultaneous Engineering
Representatives from manufacturing, quality assurance and purchasing are integrated in the concept definition phase
3.43
σ=1.17
There are frequent review meetings with development, manufacturing, quality assurance and purchasing
3.62
σ=1.15
There is a formalized process for evaluating design proposals regarding manufact. and assembly compatibility
3.25
σ=1.42
Development and testing of production facilities is done in parallel to product development
3.13
σ=1.40
Strong Project Manager
Project manager leads the product development project from concept to market
3.46
σ=1.26
Project manager defines the product concept and advocates the customer value
3.06
σ=1.26
Project manager sets the project timeframe and controls the adherence to it
3.81
σ=1.10
Project manager chooses the technology and makes major component choices
3.02
σ=1.32
Workload Leveling
Product development resources are planned on a cross-project basis
3.39
σ=1.35
Development activities are scheduled and prioritized
3.83
σ=1.04
Actual and planned capacity utilization are compared frequently
3.04
σ=1.23
Resources are flexibly adapted in case of occurring bottlenecks
3.07
σ=1.17
Specialist Career Path
There is a designated career path for technical specialists in their functional areas
3.02
σ=1.31
Promotion is based on functional experience and knowledge
3.10
σ=1.15
More experienced employees are responsible for mentoring and supporting junior engineers
3.30
σ=1.15
Performance of individuals is regularly evaluated and discussed in feedback meetings
3.83
σ=1.36
Product Variety Management
There are clear goals for the use of off-the-shelf components within a product
3.25
σ=1.21
There are clear goals for the reuse of product parts among different modules, products and product families
3.21
σ=1.20
There are modular components with standardized interfaces
3.14
σ=1.18
There are common product platforms encompassing several product lines
3.19
σ=1.17
1
2
3
4
5
Not used
Used in every project
n = 113

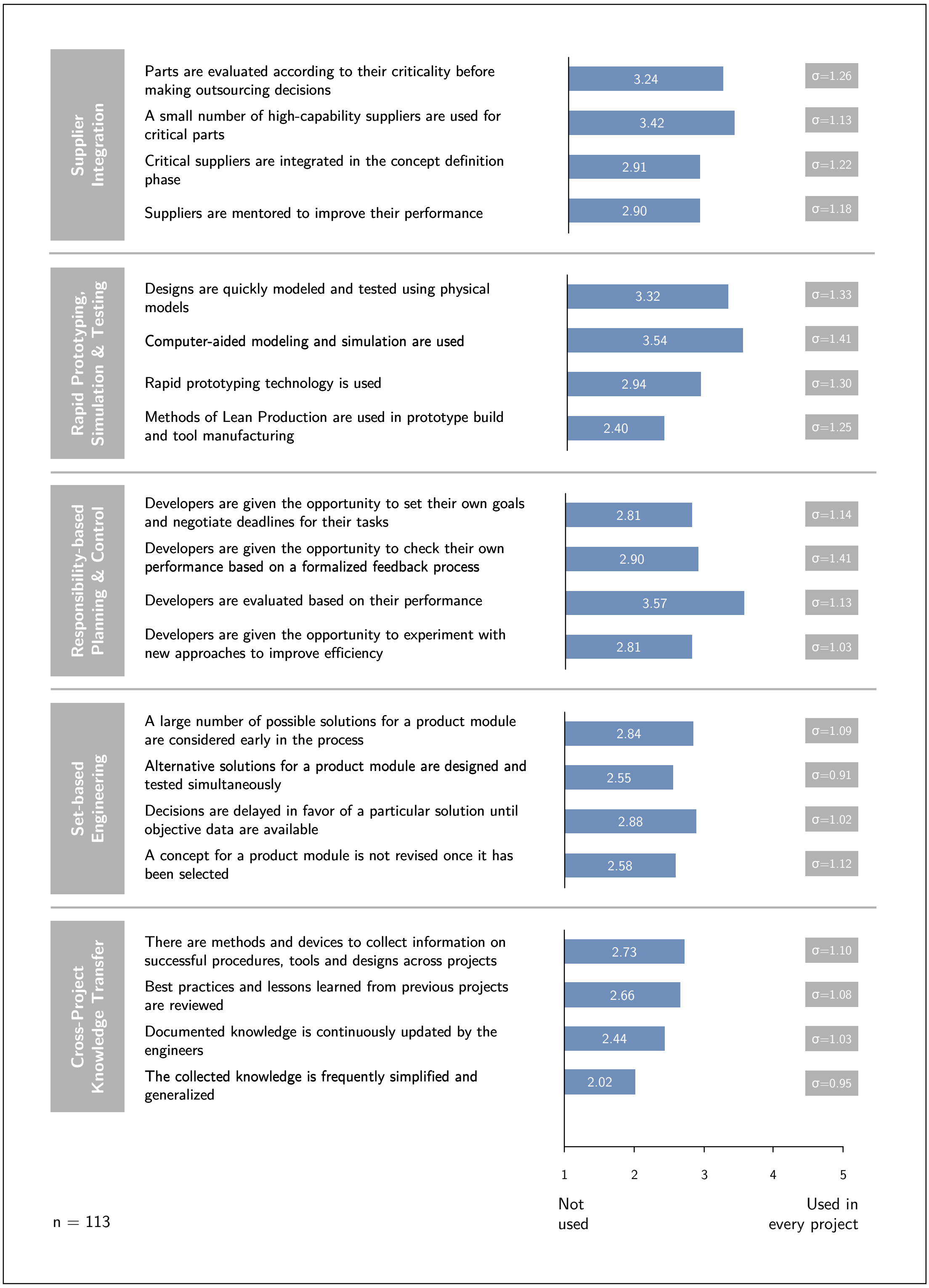


Figure 7.7: Use of the Lean PD components according to specific characteristics

The results of the analysis displayed in Figure 7.7 illustrate that the use of the single characteristics varies widely from an average rating of 4.09 for the use of "standard milestones defining a sequence for PD projects" to a minimum rating of 2.02 for a "frequent simplification and generalization of knowledge". While for some components, such as Process Standardization, the Strong Project Manager or Rapid Prototyping, Simulation and Testing, there are large differences in the use of their characteristics, for others, such as Product Variety Management, the use of the characteristics within the component is relatively constant.

To be able to compare the use of the eleven Lean PD components, rather than only its characteristics, the average ratings of the characteristics for each component were summarized as described in Section 7.1 to build an aggregated metric for each component. The outcome of this analysis is depicted in Figure 7.8. As can be seen, the components used most by the surveyed companies are Process Standardization, Simultaneous Engineering, a Strong Project Manager, Workload Leveling and a Specialist Career Path, the latter four of which obtain quite similar ratings. The components used least by the participating companies are Set-based Engineering and Cross-project Knowledge Transfer. While the average rating for most of the components lies within a range of 3 and 3.4 and therefore relatively close together, there is a comparably large gap to Set-based Engineering and Cross-project Knowledge Transfer as the components which are used the least.

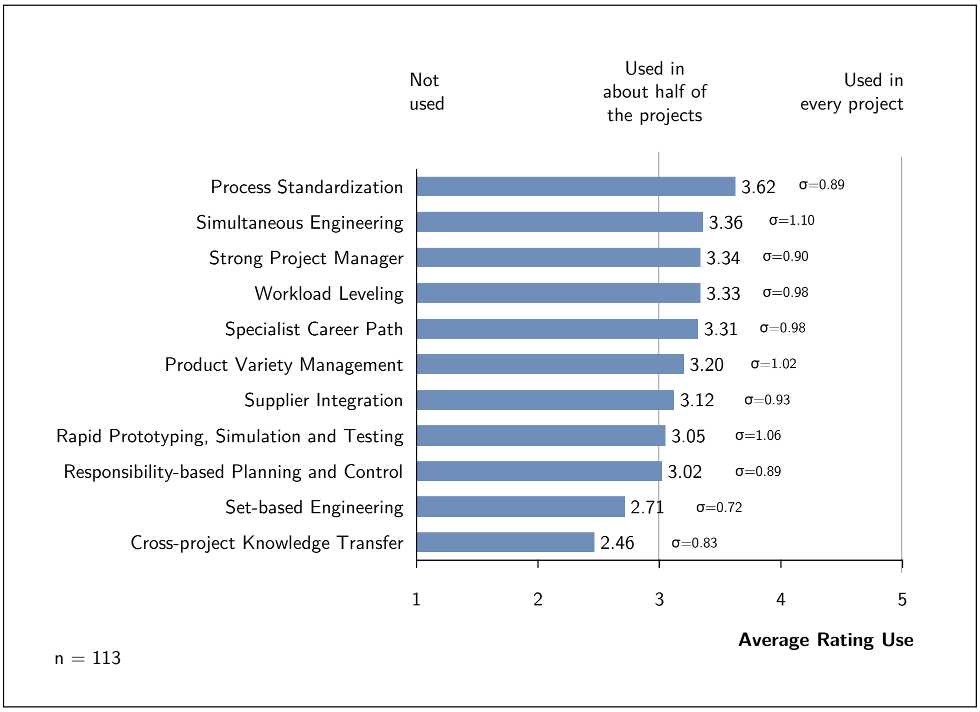


Figure 7.8: Use of the Lean PD components

7.2.4 Time of Implementation of the Lean PD Components

Besides for the use of every component, the survey participants were asked to rank the eleven Lean PD components according to the order in which they were implemented in their company on a scale from 1 (first implemented) to 11 (last implemented). The average rank assigned to each of the components is displayed in Figure 7.9 and shows some similarities with the average use given in Figure 7.8. In fact, the three components which, according to the survey, have on average been implemented first are the Strong Project Manager (average rank: 3.46), Process Standardization (3.50) and Simultaneous Engineering (4.29), which are the same three components that are most widely used. Furthermore, Set-based Engineering and Cross-project Knowledge Transfer are the components which on average are ranked highest. Whereas with an average rating of 5.55 the rank of implementing Set-based Engineering does not significantly differ from the one of a Specialist Career Path and Supplier Integration, Cross-project Knowledge Transfer (6.96) can clearly be identified as the component which companies on average have implemented last. Considering that the overall span between the average ranks of the eleven components amounts to 3.5, the gap between Set-based Engineering and Cross-project Knowledge Transfer of 1.41 points is particularly noteworthy. The late implementation of Cross-project Knowledge Management will be taken on in later chapters when discussing the implications for the most efficient order of implementation.

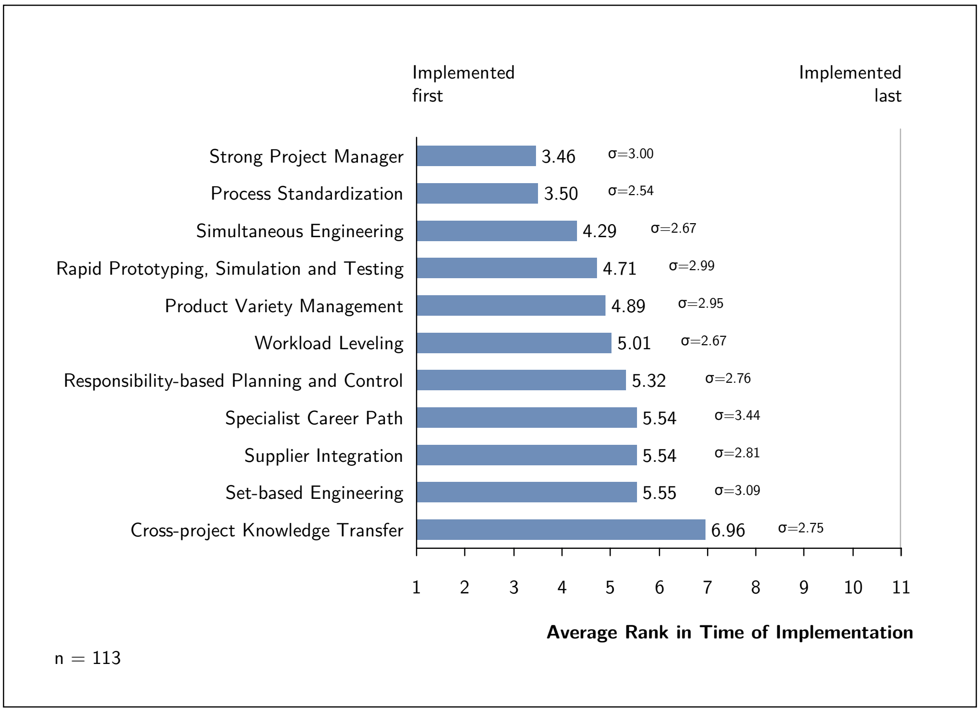


Figure 7.9: Rank of implementation of the Lean PD components

7.2.5 Perceived Difficulty of Implementing the Lean PD Components

For each of the eleven Lean PD components, the survey posed the question of how difficult the respondent perceived its implementation. Figure 7.10 illustrates the answers by listing the average rating for the perceived ease of implementation.

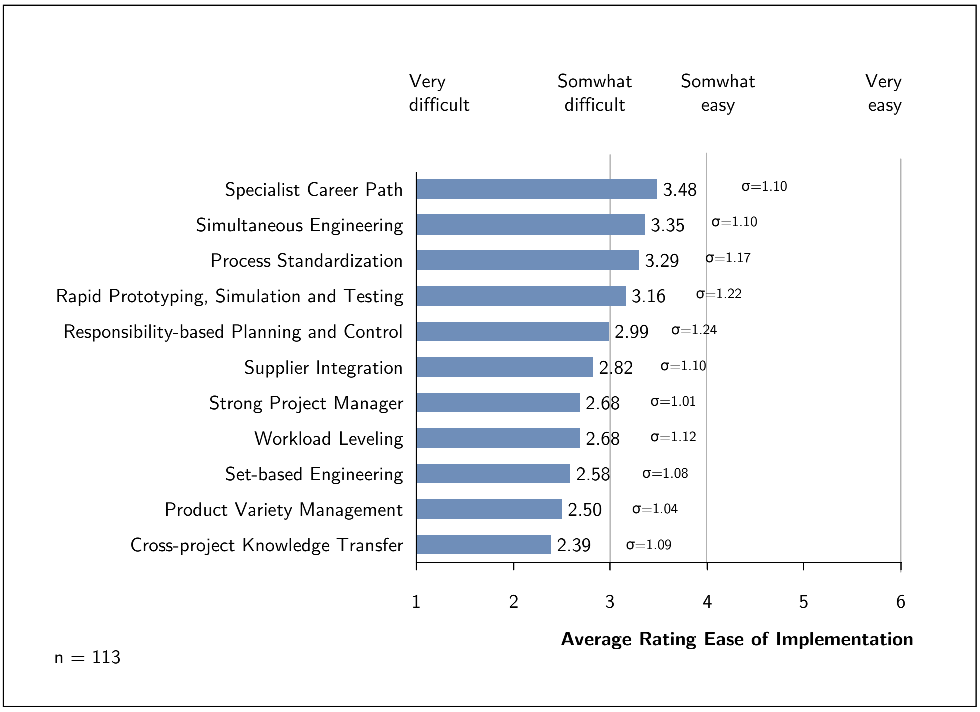


Figure 7.10: Perceived difficulty of implementing the Lean PD components

Again, Simultaneous Engineering and Process Standardization can be found among the top three components with average ratings of 3.35 and 3.29 on a scale from 1 (very difficult) to 6 (very easy). Interestingly, however, the Strong Project Manager which on average has been implemented first is considered to be comparably difficult to implement (average rating of 2.68). The component perceived as the easiest to implement is the Specialist career Path (3.48). Set-based Engineering and Cross-project Knowledge Transfer, which regarding their use and time of implementation were ranked last, are also perceived as relatively difficult to implement (average ratings of 2.58 and 2.39 respectively). This is also the case for Product Variety Management receiving an average rating of 2.50 although being quite widely used and among the first five components to be implemented.

7.2.6 Perceived Usefulness of Implementing the Lean PD Components

Finally, as stated in Section 6.2.2, the survey as a control variable inquired the perceived usefulness of implementing the Lean PD components. The average values for each of the components on a scale from 1 (very low usefulness of implementation) to 6 (very high usefulness of implementation) are shown in Figure 7.11. The component which is perceived the most useful is Simultaneous Engineering (average rating 5.14) followed by Process Standardization (4.90) and Product Variety Management (4.85). A Specialist Career Path (4.38) and Responsibility-based Planning and Control (4.34) are the components perceived least useful.

In general, compared to the results obtained for the use of the components or the difficulty of implementation, the span between the ratings for the components perceived most useful and least useful is relatively low (0.8 points). This finding is in line with the general assumption underlying this research that the components are highly interwoven and only in their concurrency contribute to a successful PD performance. From this point of view, as was pointed out in 6.2.1, separately rating the single components according to their usefulness seems neither appropriate nor possible. The claim that which of the components is most important for a successful PD system cannot be said with certainty seems to be, at least in parts, reflected in the comparatively small differences in the rating of the components.

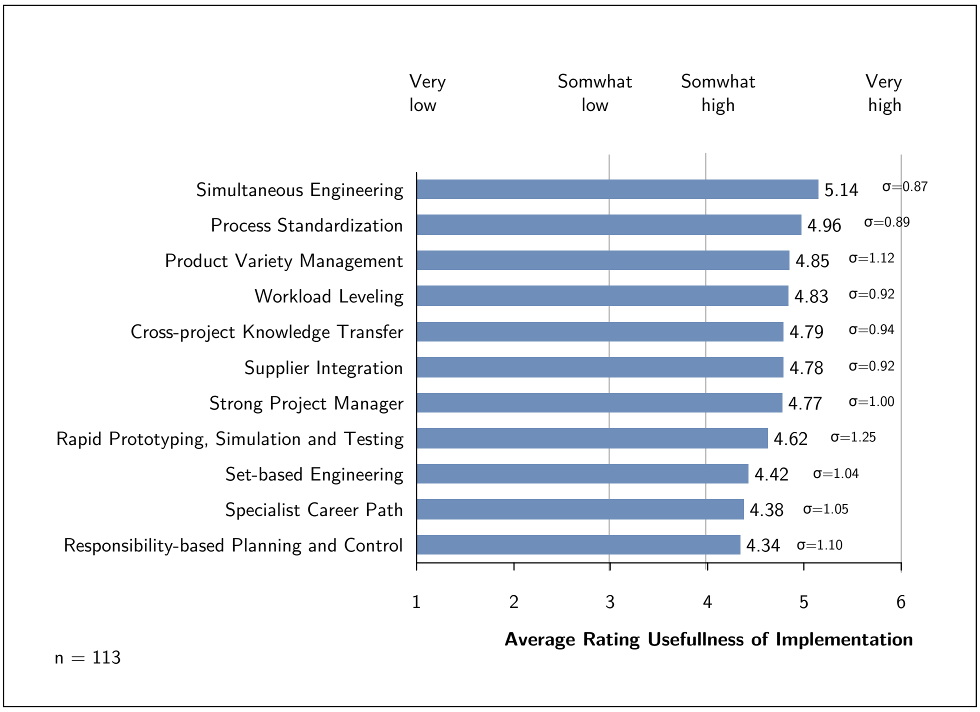


Figure 7.11: Perceived usefulness of implementing the Lean PD components

7.2.7 Cross-categorical Comparison of the Lean PD components

To conclude the descriptive presentation of the survey results, Table 7.1 juxtaposes all eleven PD components regarding their use, time of implementation, ease of implementation and usefulness of implementation. For each of the categories, the table lists the rank of the component on a scale from 1 to 11. The order in which the components are listed reflects the ranking of their use within the companies of the sample.

Table 7.1: Cross-categorical comparison of Lean PD components

	Use	Time of Implementation	Perceived Ease of Implementation	Perceived Usefulness of Implementation
Process Standardization	1	2	3	2
Simultaneous Engineering	2	3	2	1
Strong Project Manager	3	1	7-8	7
Workload Leveling	4	6	7-8	4
Specialist Career Path	5	8	1	10
Product Variety Management	6	5	10	3
Supplier Integration	7	9	6	6
Rapid Prototyping, Simulation and Testing	8	4	4	8
Responsibility-based Planning and Control	9	7	5	11
Set-based Engineering	10	10	9	9
Cross-project Knowledge Transfer	11	11	11	5

When comparing the ranks each component assumes in the different categories, first potential explanations for why they are highly or poorly used in companies can be derived. To get more of an in-depth understanding of the system and investigate the problems which arise during the process of implementation, the following Chapter 8 describes the methodology and results of a comprehensive exploratory analysis of the survey data.

8 Exploratory Analysis of the Survey Data

The previous chapter outlined the methodological approach and the findings of the descriptive survey data analysis. It was described how the companies of the sample can be characterized, which tools and infrastructure they use to support the implementation process of Lean PD, to which extent they have implemented the eleven Lean PD components and how difficult and useful they perceive their implementation. Building on this general overview of the status quo concerning Lean PD, in a second step, a more sophisticated exploratory analysis was conducted. The methodology of this exploratory analysis will be detailed in the subsequent Section 8.1. Section 8.2 will then present the findings which, in turn, serve as a basis for discussing the implications for the implementation of Lean PD in Chapter 9.

8.1 Methodology of the Exploratory Analysis

The exploratory analysis conducted to gain a thorough understanding of the data and its patterns can be divided into four major steps. First, the component-specific data gathered on the use, order of implementation, perceived difficulty and perceived usefulness was explored using a comprehensive analysis of the correlations. Second, a content analysis was employed to investigate the problems participants had experienced when trying to implement the particular Lean PD components. Third, again using correlation analysis, it was tested whether company size, revenues, industry sector and location have an impact on the responses given by the participants. Fourth, drawing on t-tests, the influence of supporting tools and infrastructure on the process of implementation was studied. The exact methodology used during each of the four stages is described in the following Sections 8.1.1, 8.1.2, 8.1.3 and 8.1.4.

8.1.1 Correlation Analysis on the Interdependencies between the Lean PD Components

It was pointed out in Chapter 5 that one of the primary goals of this thesis is to shed more light on the interdependencies that exist between the single components. Towards this end, at the beginning of the exploratory analysis, the data was investigated to identify potential correlations. Following a systematic approach, the information on each of the eleven Lean PD components, i.e. their use, the rank they were implemented at, the perceived difficulty of implementation and the perceived usefulness, was tested for correlations. On the one hand, this included tests to reveal how the components were correlated within each of these categories, e.g. how the use of a Strong Project Manager was correlated with the use of Set-based Engineering. On the other hand, the data was tested for correlations across the categories, e.g. how the use of a Strong Project

Manager was related to the perceived difficulty of implementing this component or Set-based Engineering. To cover all possible combinations of the four data categories for each of the components, a total of 10 separate correlation analyses were performed. These analyses, which have been assigned letters from A to J, are shown in Table 8.1.

Table 8.1: Correlation analyses on the interdependencies between the Lean PD components

No.	Data Categories	1	2	3	4
1	Use of the Lean PD components	A	-	-	-
2	Time of the implementation of Lean PD components	B	E	-	-
3	Perceived difficulty of implementing the Lean PD components	C	F	H	-
4	Perceived usefulness of implementing the Lean PD components	D	G	I	J

As noted in Section 6.2.2, the data for each of the categories listed in Table 8.1 was inquired using multiple choice. The scales of the answering options were intentionally designed to be ordinal with equal intervals. Hence, Pearson correlation coefficients, which are particularly suited to describe correlations in cardinal data, were used to determine the correspondence between the categories for the single components. Since the time of implementation was expressed using ranks, correlation analyses B, E, F and G were repeated using Spearman's method which does not postulate interval scales. However, since in every case Pearson's method produced more conservative, i.e. less significant, results, this thesis only presents the correlation coefficients according to Pearson.

For each of the analyses shown in Table 8.1, a correlation matrix spanned by the eleven Lean PD components was calculated. Since the use of the Lean PD components is defined by four characteristics (see Section 7.2.3), correlations for the analyses A and C were not only calculated on a component basis but also determined for the 44 characteristics. All of the correlations calculated during the 10 analyses were tested for significance on a 5 percent and 1 percent level.

Due to the large number of calculations, in a first step only bivariate relationships between the components were identified. However, once it was found that a correlation was significant and of interest regarding the goals of this research, the analysis was extended to include potentially interfering components. Using these components as control variables, partial correlations were calculated to check whether the correlation remained significant if effects from other components were excluded. In essence, therefore, all variables considered during the analysis by turns served as dependent and explanatory variables. This procedure seemed plausible from a conceptual point of view because relations between the components were hypothesized to be bidirectional and not clearly understood before conducting the exploratory analysis.

8.1.2 Content Analysis on the Problems during the Implementation

For most of the survey questions a set of answering options were provided that participants could choose from. Nevertheless, as explained in Section 6.2.2, the survey also contained one page with free-form fields where the representatives from the sample companies could enter the problems they had experienced when trying to implement the respective Lean PD components. Although filling in these fields was intentionally marked as voluntary, almost half of the participants in the survey provided comments on at least one of the components.

To analyze the qualitative answers and be able to clearly illustrate them, a content analysis was conducted. The individual problems listed by the survey participants for each of the eleven components were consolidated in a list. Then, each list entry was assigned a category describing the more abstract problem it referred to. After all of the problems had been subsumed under specific categories, in an iterative process the categories were tweaked and further refined to guarantee that they were mutually exclusive. The number of times problems from each category were mentioned by the participants was counted and translated into graphical representations of the answers. The according graphs, giving insights into which problems companies frequently experience, will be presented in Section 8.2.2.

8.1.3 Correlation Analysis on the Influence of Company Characteristics

As the third step of the exploratory analysis, it was investigated whether firm-specific factors such as company size, revenue and industry sector play a role for the implementation of the Lean PD components. While company size and revenue as quantitative data can be directly tested for correlations with the component variables using Pearson's method, this is not possible with the variables defining industry sector. To be able to conduct a correlation analysis with the latter data, six dummy variables were introduced which describe the affiliation of the company with an industrial sector. Using Figure 7.2 as a basis, each dummy variable represents one industry sector (Automotive, Industrial Equipment, Electronics, Aerospace Manufacturing, Medical Devices, Other Sectors). If the company is part of a particular industry, the respective dummy variable for this firm takes the value "1". The other five dummy variables for the company are zero.

Using the dummy variables, correlations between the data on the components of Lean PD and the industrial sector can be calculated. It is important to note, however, that the dummy variables are binary variables which do not correspond to real-scaled values. Therefore, to determine the correlations, Spearman's rank correlation coefficients instead of Pearson correlation coefficients were used.

8.1.4 T-test on the Effect of Supporting Tools and Infrastructure

Section 7.2.2 summarized the results of the survey regarding the use of supporting infrastructure and tools during the implementation process of Lean PD. The descriptive analysis showed to what extent companies have defined particular goals for the implementation, have defined a person responsible, draw upon external help and have conducted value stream mapping. From the descriptive analysis, however, it remains unclear if the use of these practices has an impact on the implementation of certain components of Lean PD. Therefore, in the last of the four steps of the exploratory analysis, t-tests were conducted to investigate this question.

In contrast to the answering options employed to inquire use, time of implementation, perceived difficulty and usefulness of implementation for the single components, the scales used when asking for the supporting tools and infrastructure are non-linear. In case of the questions on the definition of goals and the use of value stream mapping, the distances between the respective options participants could choose from are not equal. The question of whether a person has been declared responsible for the implementation process and whether external help is employed could only be answered with "yes" or "no", leading to binary data. To achieve a consistent data basis for the analysis on the effects of supporting tools and infrastructure on the implementation process, two more binary dummy variables were introduced. The first variable takes the value "0" if a company has not defined goals for the introduction of Lean PD and "1" if at least a general strategy has been derived. The second dummy variable is "0" if a company has not yet conducted value stream mapping and assumes a value of "1" if value stream mapping has at least been conducted for a small number of PD processes.

With the definition of the dummy variables, the responses to all four questions concerning supporting tools and infrastructure can be displayed as binary data. This, in turn, allows splitting the participants up in two groups which can be compared regarding their use, time of implementation, perceived difficulty and perceived usefulness of implementing the Lean PD components. For each of these categories and the four binary data variables, a t-test was used to examine whether companies relying on supporting tools and infrastructure differed from those that did not. Depending on whether the variances of the two groups to be compared differ, different t-tests have to be conducted. Hence, prior to the t-test a Levene's test for equality of variances was performed. In case that the Levene's test found that at a level of significance of less than 10% the groups showed the same variance in data, a t-test for groups with equal variances was used. Else, a t-test for groups with different variances was conducted. The findings of the t-tests will be discussed in Section 8.2.4.

8.2 Findings of the Exploratory Analysis

In the next sections, the findings of the four phases of the exploratory analysis rendered in Section 8.1 are described. The presentation of the results follows the same order as the actual analysis. First, Section 8.2.1 portrays the insights gained by the correlation analysis explained in Section 8.1.1. Second, Section 8.2.2 discusses the problems experienced by the companies during the implementation process which were identified using content analysis. Third, in Section 8.2.3 the impact of firm-specific characteristics such as company size, revenue and industry sector is described. Section 8.2.4 finally deals with the effects of supporting tools and infrastructure on the implementation process.

8.2.1 Interdependencies between the Lean PD Components

As depicted in Table 8.1, to investigate the interdependencies between the eleven Lean PD components, a total of 10 separate correlation analyses, labeled with letters from A to J, was conducted. Table 8.2 summarizes the major findings of the analyses. The most striking results, which have been found in the analyses A, C and E will be subsequently discussed in more detail. The correlation matrices for the analyses B, D, F, G, H, I and J are provided in Appendix B.

Table 8.2: Major findings of the correlation analyses on the interdependencies between the Lean PD components

Analysis	Major Findings (in brackets: Pearson correlation coefficient, * p<0.05, ** p<0.01)
A	• Generally strong correlation between the use of the single Lean PD components • Use of a Strong Project Manager largely independent of the use of other components
B (Table B.5)	• Early implementation of components goes along with stronger use (effect not significant for Product Variety Management and Cross-project Knowledge Transfer) • High use of Responsibility-based Planning and Control correlated with early implementation of Set-based Engineering (0.277*) • High use of Simultaneous Engineering goes along with late implementation of a Strong Project Manager (0.306**) and Specialist Career Path (0.233*) • Late implementation of Cross-project Knowledge Transfer correlated with high use of a Strong Project Manager (0.214*), a Specialist Career Path (0.357**), Supplier Integration (0.279**) as well as Rapid Prototyping, Simulation and Testing (0.293**)
C	• Use of a component positively correlated with its perceived ease of implementation (effect not significant for Supplier Integration) • Perceived ease of implementing Set-based Engineering positively correlated with use of Workload Leveling (0.220*), Supplier Integration (0.202*), Responsibility-based Planning and Control (0.250**) and Cross-project Knowledge Transfer (0.331**) • Use of Strong Project Manager negatively correlated with perceived ease of implementing Cross-project Knowledge Transfer (-0.258**), Product Variety Management (-0.191*) and Set-based Engineering (-0.244**) • Perceived ease of implementing Specialist Career Path positively correlated with use of Set-based Engineering (0.205*) Cross-Project Knowledge Transfer (0.280**) and Product Variety Management (0.245**)
D (Table B.9)	• Use of Rapid Prototyping, Simulation and Testing (0.515**), Supplier Integration (0.278**), Simultaneous Engineering (0.262**). Strong Project Manager (0.248**), Responsibility-based Planning and Control (0.233*), Specialist Career Path (0.232*) and Process Standardization (0.232*) positively correlated with their perceived usefulness • Perceived usefulness of Set-based Engineering negatively correlated with use of Product Variety Management (-0.366**), Process Standardization (-0.287**), Cross-project Knowledge Transfer (-0.216*) and Workload Leveling (-0.206*)

Analysis	Major Findings (in brackets: Pearson correlation coefficient, * p<0.05, ** p<0.01)
E	• Later implementation of Process Standardization goes along with later implementation of Product Variety Management (0.264*) and Cross-project Knowledge Transfer (0.247*) • Delay in Supplier Integration goes along with delay in Product Variety Management (0.230*), Responsibility-based Planning and Control (0.254*) and Simultaneous Engineering (0.281**) • Early implementation of Strong Project Manager goes along with late implementation of Simultaneous Engineering (-0.228*)
F (Table B.10)	• Perceived ease of implementation negatively correlated with rank of implementation for Set-based Engineering (-0.262*), Cross-project Knowledge Transfer (-0.277**) and Rapid Prototyping, Simulation and Testing (-0.256*) • Late implementation of Strong Project Manager goes along with high perceived ease of implementing Set-based Engineering (0.311**) • Simultaneous Engineering is perceived as easier to implement when Supplier Integration (-0.301**) and Cross-project Knowledge Transfer (-0.250*) are implemented early
G (Table B.11)	• High perceived usefulness of implementation goes along with early implementation in case of Rapid Prototyping, Simulation and Testing (-0.451**), Strong Project Manager (-0.286**), Responsibility-based Planning and Control (-0.228*) and Simultaneous Engineering (-0.205*) • Early implementation of Cross-project Knowledge Transfer goes along with low perceived usefulness of implementing Product Variety Management (0.356**), Supplier Integration (0.310**), Set-based Engineering (0.218*) and a Specialist Career Path (0.213*)
H (Table B.12)	• Strong positive correlation between perceived difficulty of implementing Process Standardization, Workload Leveling, Supplier Integration and Simultaneous Engineering with perceived difficulty of implementing respective other components • Perceived difficulty of implementing Strong Project Manager positively correlated with perceived difficulty of implementing Process Standardization (0.289**), Simultaneous Engineering (0.269**) and Workload Leveling (0.215*) • Perceived difficulty of implementing Set-based Engineering positively correlated with perceived difficulty of implementing Responsibility-based Planning and Control (0.355**), Cross-project Knowledge Transfer (0.213*), Product Variety Management (0.200*) and Process Standardization (0.187*) • Perceived difficulty of implementing Cross-Project Knowledge Transfer positively correlated with perceived difficulty of implementing Product Variety Management (0.430**). Workload Leveling (0.404**), Supplier Integration (0.338**), Simultaneous Engineering (0.238*) and Set-based Engineering (0.213*)
I (Table B.13)	• Lower perceived usefulness of implementing the components of Product Variety Management, the Strong Project Manager and Set-based Engineering goes along with higher perceived difficulty of implementing a large number of other components • Perceived usefulness of implementing Cross-project Knowledge Transfer and Supplier Integration not significantly correlated with perceived difficulty of implementing any other component • High perceived difficulty of implementing Cross-project Knowledge Transfer goes along with low perceived usefulness of implementing Simultaneous Engineering (-0.300**), Workload Leveling (-0.287**), Product Variety Management (-0.284**) and a Strong Project Manager (-0.249**)
J (Table B.14)	• Perceived usefulness of implementing Simultaneous Engineering positively correlated with perceived usefulness of all other components except for Strong Project Manager and Product Variety Management • Perceived usefulness of implementing Strong Project Manager only correlated with perceived usefulness of implementing Process Standardization (0.258**), Product Variety Management (0.244**) and Set-based Engineering (0.213*)

Correlation Analysis A

Analysis A, as shown in Table 8.1, aimed at exploring the correlations between the use of the eleven Lean PD components. The two major findings of the analysis have already been listed in Table 8.2. Due to the importance that these findings have with regard to a better understanding of the Lean PD system, however, the following paragraphs shall give a more detailed description of the results.

Table 8.3 depicts the correlation matrix generated in analysis A which is spanned by the eleven Lean PD components. The matrix entries at the intersection of two components contain the Pearson correlation coefficients which indicate to what extent the use of the respective components is correlated. Correlations that are significant at a 5 percent level of significance are marked with one star and colored bright blue. Correlations significant at the 1 percent level of significance are marked with two stars and shaded in dark blue.

Table 8.3: Correlations between the use of the Lean PD components (Analysis A)

	Use of Strong Project Manager	Use of Set-based Engineering	Use of Process Standardization	Use of Specialist Career Path	Use of Product Variety Management	Use of Workload Leveling	Use of Supplier Integration	Use of Responsibility-based Planning and Control	Use of Cross-project Knowledge Transfer	Use of Rapid Prototyping, Simulation and Testing	Use of Simultaneous Engineering
Use of Strong Project Manager	1	.246**	.154	.102	.076	.299**	.194*	.175	.101	.157	.185
Use of Set-based Engineering	.246**	1	.204*	.421**	.326**	.279**	.438**	.399**	.385**	.427**	.373**
Use of Process Standardization	.154	.204*	1	.392**	.428**	.443**	.436**	.232*	.492**	.235*	.407**
Use of Specialist Career Path	.102	.421**	.392**	1	.313**	.417**	.547**	.422**	.416**	.332**	.434**
Use of Product Variety Management	.076	.326**	.428**	.313**	1	.334**	.539**	.226*	.463**	.286**	.350**
Use of Workload Leveling	.299**	.279**	.443**	.417**	.334**	1	.433**	.443**	.423**	.219*	.439**
Use of Supplier Integration	.194*	.438**	.436**	.547**	.539**	.433**	1	.474**	.489**	.425**	.519**
Use of Responsibility-based Planning and Control	.175	.399**	.232*	.422**	.226*	.443**	.474**	1	.361**	.161	.336**
Use of Cross-project Knowledge Transfer	.101	.385**	.492**	.416**	.463**	.423**	.489**	.361**	1	.266**	.430**
Use of Rapid Prototyping, Simulation and Testing	.157	.427**	.235*	.332**	.286**	.219*	.425**	.161	.266**	1	.422**
Use of Simultaneous Engineering	.185	.373**	.407**	.434**	.350**	.439**	.519**	.336**	.430**	.422**	1

* p<0.05 ** p<0.01

The fact that Table 8.3 has a largely dark blue color indicates that the eleven Lean PD components are highly positively correlated regarding their use. Obviously, companies which make extensive use of Lean PD use a large number of the components simultaneously, whereas those with less experience in Lean PD seem to make less use of almost all components. This finding is interesting since, alternatively, it could have been assumed that leaders in the field of Lean PD simply focus on different components than laggards. The strong correlations among the use of the components, however, suggest that this is not the case. Instead, it can be seen that in practice companies advance by extending the use of almost all the Lean PD components at the same time.

The only apparent exception to this rule is the Strong Project Manager. Regarding their use all other components are significantly correlated with at least 9 other components. The use of a Strong Project Manager, however, is only significantly correlated with the use of three other components, namely Set-based Engineering (Pearson correlation coefficient: 0.246**), Workload Leveling (0.299**) and Supplier Integration (0.194*). The positive correlation with the use of Workload Leveling remains significant when controlling for the use of all other components (0.230*). When calculating partial correlation coefficients for the relation between the use of a Strong Project Manager and the use of Set-based Engineering and Supplier Integration, however, no significant relationships can be found. The finding that the use of a Strong Project Manager is largely independent of the use of the other Lean PD components is particularly striking when considering that it is the component most frequently described in the literature on Lean PD (see Table 4.1).

More detailed insights on the correlations between the use of the components can be gained when splitting the components up into their four characteristics which were defined to inquire their use. The correlations between the use of the 44 characteristics are provided in Table B.1 to Table B.4 in Appendix B. Like in Table 8.3, significant correlations are marked with stars and colored in bright (5 percent level of significance) and dark (1 percent level of significance) blue. It shows that some of the correlations which were significant on a component level, e.g. between the use of Process Standardization and Set-based Engineering, lose their significance when displayed for the single characteristics. Conversely, for some components which were not correlated regarding their use in Table 8.3, e.g. Responsibility-based Planning and Control and Rapid Prototyping, Simulation and Testing, there are correlations on a characteristic level.

It is worth mentioning that for the component of a Strong Project Manager, the use of which showed few correlations on the component level, there are also a very few significant correlations on the characteristic level. In fact, strongly significant correlations can mainly be observed between Workload Leveling and "a project manager who leads the project from concept to market" as well as between Workload Leveling and Simultaneous Engineering and "a project manager who sets the project timeframe and controls the adherence to it". The use of "a project manager who defines the product concept and advocates customer value", which is often described as crucial for a Lean PD system, is correlated with none of the 40 characteristics of the other ten Lean PD components.

Correlation Analysis C

Subject of analysis C was to explore the relationship between the use of particular Lean PD components and the perceived difficulty of implementation. Two main questions were considered of particular interest: First, the analysis aimed to explore how the perceived difficulty of implementing a particular component is correlated with the use of *that same* component. Second, it was deemed interesting to elucidate how the use of a component is connected with the perceived ease of implementing *others*. The latter question was regarded as particularly useful to investigate in which way certain components serve as predecessors for others by facilitating their implementation.

Not surprisingly, the first part of the analysis yielded that for almost all components their use is positively correlated with their perceived ease of implementation (see Table 8.4). While the effect was found to be not significant for Supplier Integration, it is plausible that companies make higher use of components they perceive as relatively easy to implement.

Table 8.4: Correlations between the use and the perceived difficulty of implementing the Lean PD components (Analysis C)

	Ease of Implementation Strong Project Manager	Ease of Implementation Set-based Engineering	Ease of Implementation Process Standardization	Ease of Implementation Specialist Career Path	Ease of Implementation Product Variety Management	Ease of Implementation Workload Leveling	Ease of Implementation Supplier Integration	Ease of Implementation Responsibility-based Planning and Control	Ease of Implementation Cross-project Knowledge Transfer	Ease of Implementation Rapid Prototyping. Simulation and Testing	Ease of Implementation Simultaneous Engineering
Use of Strong Project Manager	.312**	-.244**	-.034	-.095	-.191*	-.080	-.140	-.080	-.258**	-.077	-.097
Use of Set-based Engineering	.091	.391**	-.021	.205*	-.144	-.114	-.008	.144	-.086	.022	-.039
Use of Process Standardization	.187*	.155	.242**	.147	.126	.021	-.039	.025	-.044	.007	.080
Use of Specialist Career Path	-.025	.178	-.056	.487**	-.124	-.045	-.093	.087	-.089	-.070	-.103
Use of Product Variety Management	-.046	.184	.118	.245**	.257**	-.045	.051	.028	-.044	.064	-.068
Use of Workload Leveling	.120	.220*	.062	.066	-.002	.372**	.001	.079	.065	.117	-.052
Use of Supplier Integration	.069	.202*	-.038	.178	-.019	-.013	.173	.084	-.106	.133	.024
Use of Responsibility-based Planning and Control	.179	.250**	.068	.044	.084	.134	.138	.365**	.046	.052	.046
Use of Cross-project Knowledge Transfer	.232*	.331**	.196*	.280**	.117	.156	.136	.097	.219*	-.018	.039
Use of Rapid Prototyping. Simulation and Testing	-.021	.054	.037	.124	-.096	-.180	-.010	.051	-.230*	.353**	-.045
Use of Simultaneous Engineering	-.037	.154	-.030	.133	-.134	.044	.021	.105	-.100	.024	.235*

* p<0.05 ** p<0.01

Regarding the link between the use of components and the perceived difficulty of implementing others, it is particularly striking that Set-based Engineering is perceived as easier to implement when several other components are used to a higher degree. The perceived ease of implementation is positively correlated with the use of Workload Leveling (0.220*), Supplier Integration (0.202*) as well as Responsibility-based Planning and Control (0.250**). Most obviously, however, a high use of Cross-project Knowledge Transfer goes along with an implementation process of Set-based Engineering which is perceived as less difficult (0.331**). To gain further insights, partial correlation coefficients were calculated which describe the correlation between the use of a particular component and the perceived ease of implementing Set-based Engineering while controlling for the use of all other components. Interestingly, even though the components still show strong positive correlation coefficients, in this case Supplier Integration and Responsibility-based Planning and Control lose their significance. Workload Leveling and Cross-project Knowledge Transfer are only significant on a 6.9 and 8.8 percent level respectively. This indicates that the use of no single component has a strongly significant effect on the ease of implementing Set-based Engineering. A higher use of several other components in conjunction, however, is measurably positively correlated with the perceived ease of implementing this component.

Beyond its link to Set-based Engineering, a high use of Cross-project Knowledge Transfer in seems to be connected with an easier implementation of a larger number of components. Besides Set-based Engineering, the perceived ease of implementing a Strong Project Manager (0.232*), Process Standardization (0.196*) and a Specialist Career Path (0.280*) was found to be positively correlated with a stronger use of this component. The relationship between the use of Cross-project Knowledge Transfer and the perceived ease of implementing a Strong Project Manager remains significant (0.238*) when testing for partial correlations.

In contrast to the findings for Set-based Engineering, the use of a Strong Project Manager, in a seemingly contradictory fashion, is negatively correlated with the perceived ease of implementing Cross-project Knowledge Transfer (-0.258**), Product Variety Management (-0.191*) and Set-based Engineering (-0.244**). The negative correlations become even more significant when using partial correlations. The partial correlation coefficients for Cross-project Knowledge Transfer, Product Variety Management and Set-based Engineering are -0.275**, -0.174** and -0.430** respectively. The Strong Project Manager is the only Lean PD component which shows a constant negative relationship between its use and the perceived ease of implementing other Lean PD components. This finding is remarkable and shall be further discussed in the subsequent Chapter 9.

To get a more detailed insight into the correlations between the use and the perceived difficulty of implementation Table B.6 to Table B.8 in Appendix B display the correlations for the single characteristics of all the eleven Lean PD components. While the diagonal of the matrix shows the relations between the use and perceived difficulty of implementing a particular characteristic, off-diagonal entries describe to what extent the use of a certain characteristic is correlated with the perceived difficulty of implementing others.

Correlation Analysis E

The third correlation analysis to be discussed in more detail in this thesis is analyses E. Analysis E explored correlations between the time of implementing the single Lean PD components. The basis for the analysis was given by the ranks of implementation in which the participating companies had implemented the eleven Lean PD components. These ranks were tested for correlations to identify if late implementation of particular components can be linked to the time at which other components are introduced.

The results of analysis E are shown in Table 8.2. Three major insights were gained. First, it was found that a late implementation of Process Standardization goes along with a later implementation of Product Variety Management (0.264*) and Cross-project Knowledge Transfer (0.247*). A similar result was obtained for Supplier Integration for the time of implementation is positively correlated with the rank of Product Variety Management (0.230*), Responsibility-based Planning and Control (0.254*) and Simultaneous Engineering (0.281**). Last, an early implementation of a Strong Project Manager was found to go along with a late implementation of Simultaneous Engineering (-0.228*). Except for the latter, which became even more significant (-0.452**), all relations lost their significance when controlling for the ranks of all other components while calculating the partial correlation coefficient of one pair.

The results for the first two components can potentially be interpreted in the way that the respective components are highly interwoven, leading to a situation where a delay in implementing one of the components might cause a delay in the one. Contrariwise, the negative correlation between the rank of implementing a Strong Project Manager and Simultaneous Engineering alludes to a potential conflict between those components. Apparently, companies either choose to implement a Strong Project Manager early and delay the introduction of Simultaneous Engineering or focus on an early introduction of Simultaneous Engineering while delaying the implementation of a Strong Project Manager.

Table 8.5: Correlations of the ranks of implementing the Lean PD components (Analysis E)

	Rank Strong Project Leader	Rank Set-based Engineering	Rank Process Standardization	Rank Specialist Career Path	Rank Product Variety Management	Rank Workload Leveling	Rank Supplier Integration	Rank Responsibility-based Planning and Control	Rank Cross-project Knowledge Transfer	Rank Rapid Prototyping, Simulation and Testing	Rank Simultaneous Engineering
Rank Strong Project Leader	1	.020	.088	-.021	.024	.202	-.075	.062	-.029	-.035	-.228*
Rank Set-based Engineering	.020	1	.030	.072	.024	.230	.052	.076	.003	.151	-.007
Rank Process Standardization	.088	.030	1	.105	.264*	.081	-.010	-.165	.247*	-.089	-.131
Rank Specialist Career Path	-.021	.072	.105	1	-.039	.092	.155	.229	-.011	-.078	.066
Rank Product Variety Management	.024	.024	.264*	-.039	1	.091	.230*	.078	.103	.086	.014
Rank Workload Leveling	.202	.230	.081	.092	.091	1	.172	.257*	-.003	-.036	.006
Rank Supplier Integration	-.075	.052	-.010	.155	.230*	.172	1	.254*	-.035	.147	.281**
Rank Responsibility-based Planning and Control	.062	.076	-.165	.229	.078	.257*	.254*	1	.109	.027	-.018
Rank Cross-project Knowledge Transfer	-.029	.003	.247*	-.011	.103	-.003	-.035	.109	1	.156	.019
Rank Rapid Prototyping, Simulation and Testing	-.035	.151	-.089	-.078	.086	-.036	.147	.027	.156	1	.278*
Rank Simultaneous Engineering	-.228*	-.007	-.131	.066	.014	.006	.281**	-.018	.019	.278*	1

* $p<0.05$ ** $p<0.01$

8.2.2 Problems During the Implementation of the Lean PD Components

As explained in Section 8.1.2, the second major step of the exploratory analysis consisted in a systematic examination of the problems experienced by the surveyed companies during the implementation of the eleven Lean PD components. In the following, the results of the content analysis are displayed in the form of graphs. Peculiarities in the answers shall be pointed out and illustrated by giving exemplary quotes.

Problems during the Implementation of a Strong Project Manager

Figure 8.1 shows the results of the content analysis for the component of the Strong Project Manager. It can be seen that the by far most prominent difficulty when implementing the component is the lack of qualified project managers. 52.3 percent of all answers given by the participants in the survey fall into this category. Other problems mentioned are functional organizations which oppose the introduction of a strong project manager role (18.2%), lack of support by upper management (9.1%), an inability to prioritize PD tasks (9.1%), cultural resistance (6.8%) or conflicts with standardization of projects (4.5%).

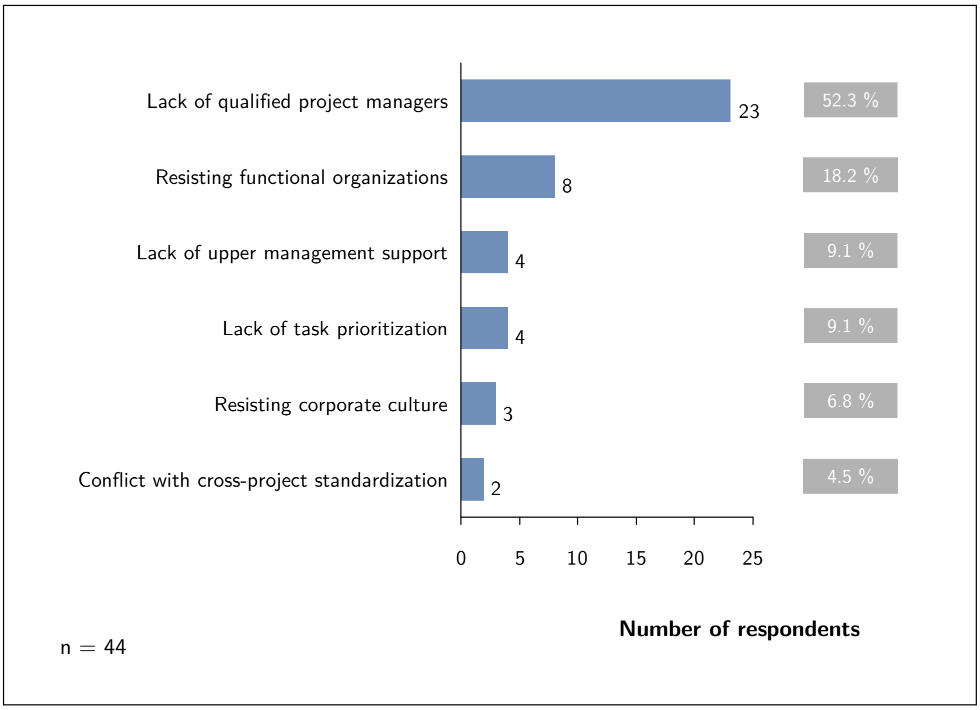


Figure 8.1: Problems during the implementation of a Strong Project Manager

As one respondent points out, a "good project leader needs a broad knowledge base, good people skills and other desired qualities. It is hard to find and train such individuals." In line with this answer, another person alludes to the fact that it "takes about 15 years do develop" a strong project manager. Since strong project managers are hard to find, there is a "temptation to overload the good ones with all your key projects". At the same time, "line managers fight the new competitor" which makes it "hard for strong project managers to assert themselves". Interestingly, some respondents also see a conflict between standardization of projects and strong project managers. It is pointed out that "strong project leaders optimize for their product, not the platform or the portfolio of products. This can lead to too many unique parts, new user interfaces, etc., that increase total cost and time."

Problems during the Implementation of a Specialist Career Path

An overview of the problems experienced when trying to implement the component of a Specialist Career Path is given in Figure 8.2. The most frequently mentioned problem is a resisting corporate culture which covers half of the answers given by the respondents. 18.2% of the respondents furthermore name a lack of upper management support as an important problem, followed by conflicts with a flat hierarchy (13.0%), a lack of qualified developers (9.1%) and an increased complexity of human resource management (9.1%).

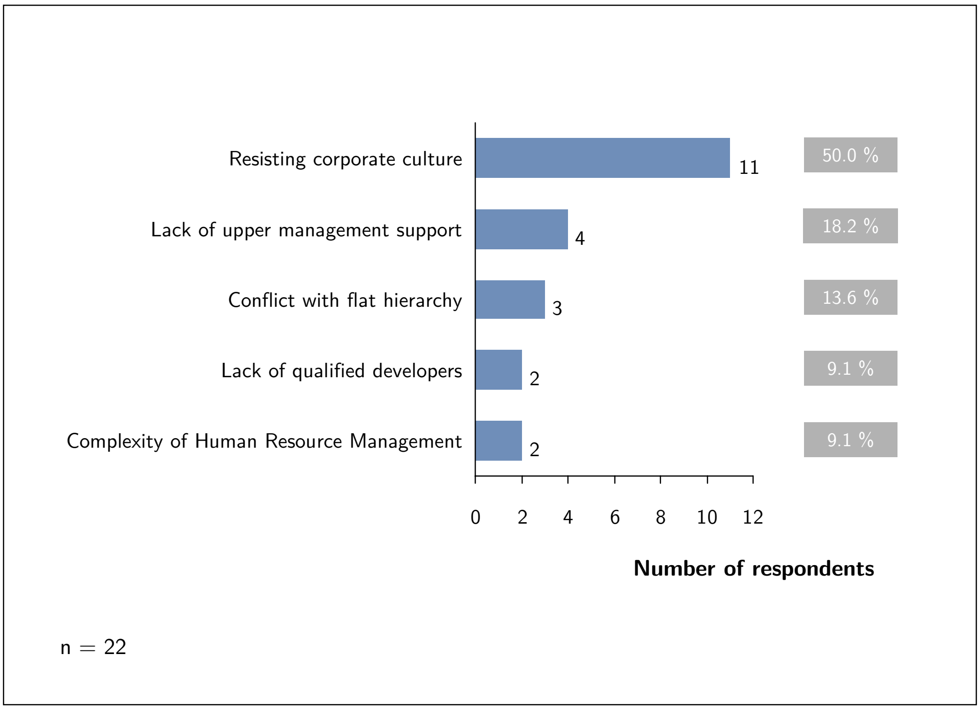


Figure 8.2: Problems during the implementation of a Specialist Career Path

The fact that most participants in the survey see cultural issues as the biggest hurdles for the implementation of a Specialist Career Path can be exemplified by a number of quotes covering a variety of different cultural aspects. One respondent mentions that "eventually engineers have to become managers in this company". Others state that a Specialist Career Path is "possible but not as highly recognized as a management career" or simply "not in the blood of company culture". Referring to company guidelines and the management culture, it is mentioned that "lip service is paid to the concept, but it has not been implemented in practice". At the same time, however, legitimate doubts in the concept are expressed when participants note that a "flat organization does not allow all mentioned in this area", "budgets suppress [a] realistic pyramid structure" and the component leads to a high "complexity of the roles with multiple functions".

Problems during the Implementation of Workload Leveling

With regard to the implementation of Workload Leveling, the analysis of the qualitative problems provided by the survey participants yielded the categories depicted in Figure 8.3. With a 30% share of all responses, changes in schedule represent the largest group of problems mentioned. A lack of cross-project coordination (16.7%) and supporting tools (13.3%), an excess number of projects (10.0%) and the lack of reliable data (10.0%) are further problems which a lot of companies experience.

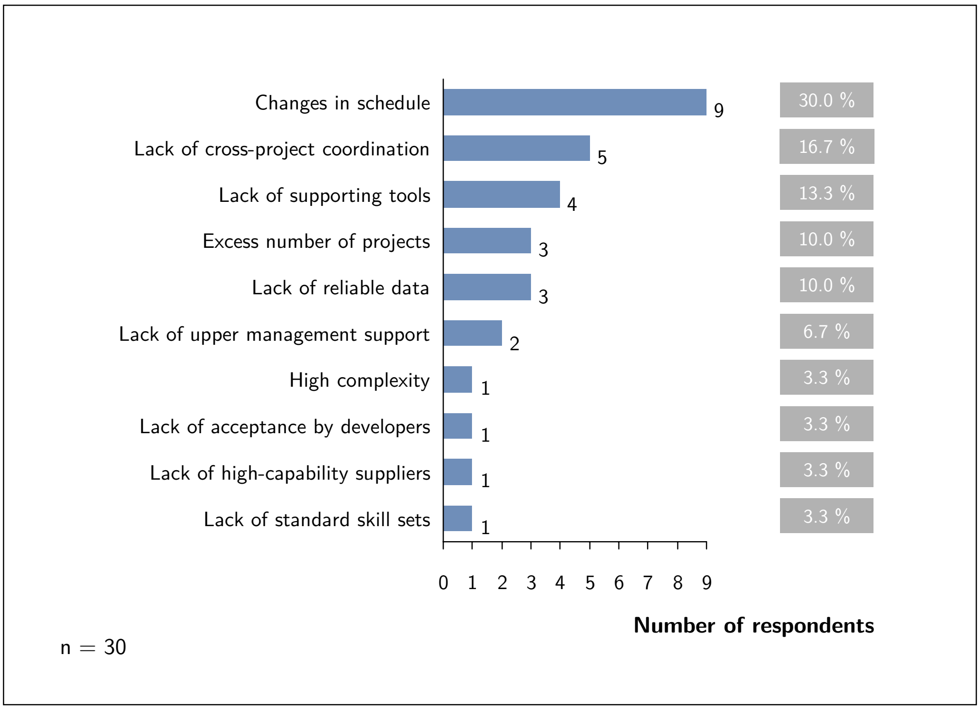


Figure 8.3: Problems during the implementation of Workload Leveling

Participants in the survey point to the "rapidly changing business climate" causing "constant change of priorities" and "schedule variability [which] prohibits cross program sharing" of resources. It is mentioned that in general "cooperation across different priorities and projects can become cumbersome", particularly in the light of prevailing "departmental egoism" where "programs tend to hoard their best resources". As is emphasized, useful tools to support the difficult task of workload leveling are rare. One respondent utters that "[w]e have some alleged workload planning tools. They don't do capacity planning between projects. They are mainly used for Earned Value. As workload leveling tools, they are a waste of time." In a similar fashion, another person states that "we have tried many ways to do this but it is so dynamic that every method that we have tried is either not accurate enough or too time consuming to maintain so it dies on the vine". Some persons complain that engineers in their companies are "overworked [...] at 100% capacity" or "everyone says he is busy", making a systematic use of Workload Leveling very difficult.

Problems during the Implementation of Responsibility-based Planning and Control

The results of the content analysis of the problems during the implementation of Responsibility-based Planning and Control are provided in Figure 8.4. The main problem identified by the participants in the survey are a resisting management culture (25.0%), a lack of qualified developers (20.0%), conflicts with process standardization (15.0%) and a potential loss of the holistic project view (10.0%).

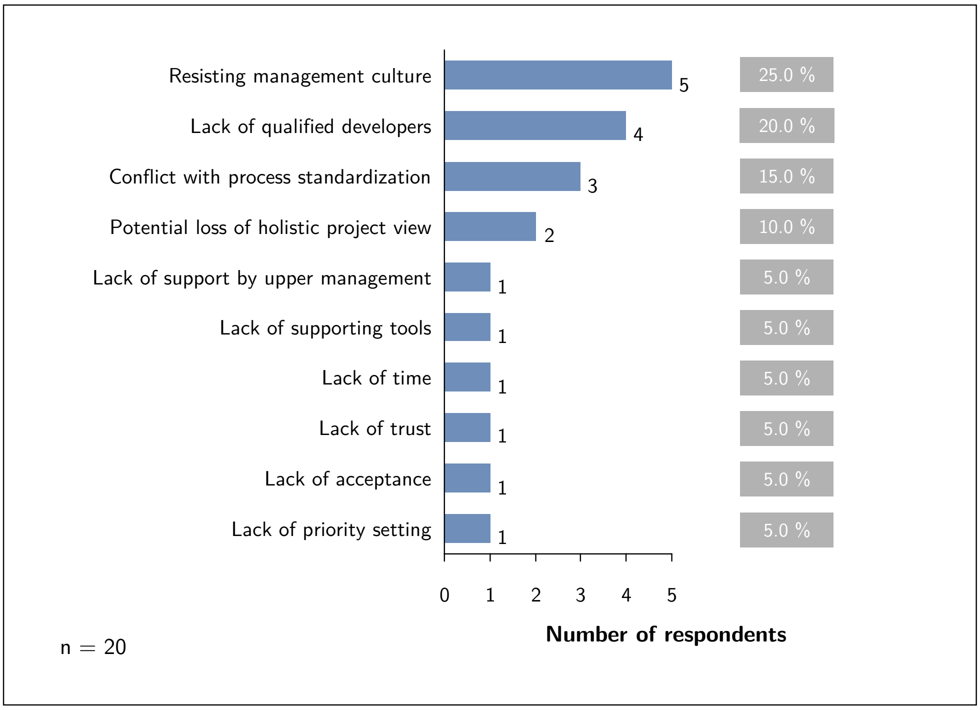


Figure 8.4: Problems during the implementation of Responsibility-based Planning and Control

Several of the respondents point out that in their company there still is a "strong command and control culture" with "too many chiefs and too few Indians", resulting in a situation where Responsibility-based Planning and Control "doesn't always get the attention it needs". On the other hand, however, it is recognized that the implementation of the component requires an according qualification of the development engineers. One respondent points out that "I encourage my project managers and design engineers to take as much responsibility as they can, but people's abilities are mixed." Furthermore, some persons spot a contradiction between an empowerment of the individual and efforts towards process standardization, alluding to a "high creativity of the developers".

Problems during the Implementation of Cross-project Knowledge Transfer

Figure 8.5 summarizes the major problems experienced by the surveyed companies concerning the implementation of Cross-project Knowledge Transfer. Besides a lack of acceptance by developers (34.4%), many participants regard a lack of supporting tools (25.0%), a lack of time (9.4%) or a large amount of information (9.4%) as a hindrance to introducing this component.

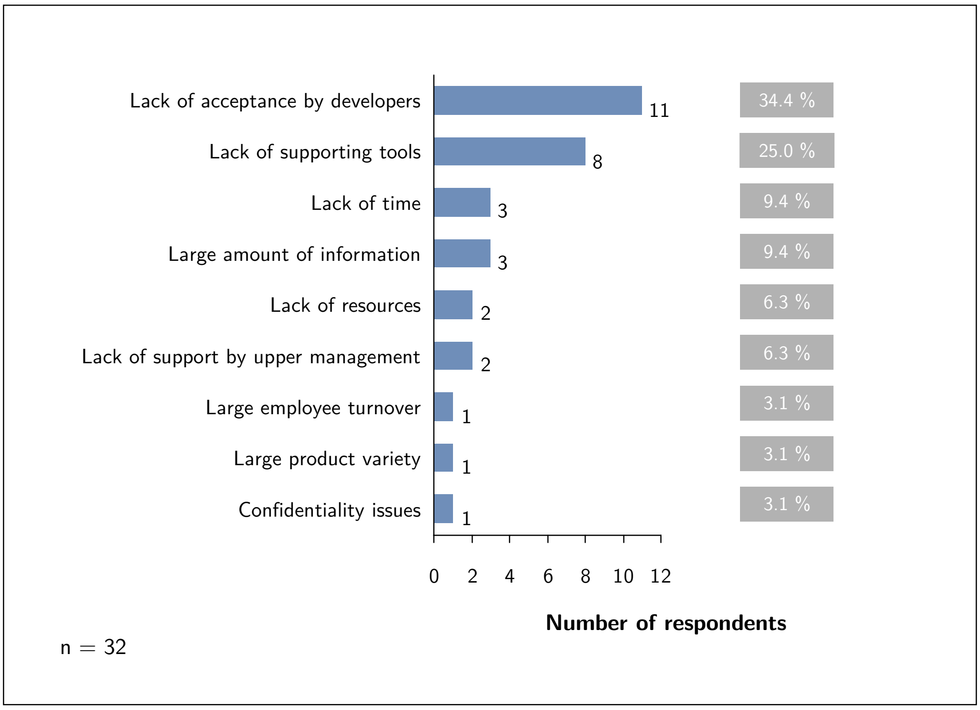


Figure 8.5: Problems during the implementation of Cross-project Knowledge Transfer

With regard to the lack of acceptance by the developers, several respondents explicitly mention that in their companies they experience the "not invented here" syndrome, meaning that already existing knowledge is not reused simply because it has been generated by a different person or department. Some state that a culture of mutual learning in their company has yet to be "accepted as something positive" and observe a lack of willingness among engineers to "go back and document" knowledge. Moreover, like in the case of Workload Leveling, many respondents claim to be "lacking the appropriate tools" as well as "funding and time" to establish an effective Cross-project Knowledge Transfer. It is pointed out that "the large amount of information quickly leads to a large complexity and therefore limited possibilities to access relevant knowledge". A key issue mentioned by two participants therefore is how to achieve a "compact but detailed and generalizable description" when documenting knowledge.

Problems during the Implementation of Simultaneous Engineering

The categorized problems companies experience during the implementation of Simultaneous Engineering are shown in Figure 8.6. The most frequently mentioned problem is the lack of acceptance by functional organizations (29.4%). Further problems are a lack of resources (23.5%), capacity conflicts between manufacturing and ramp-up (11.8%), a geographical distance between the functions (11.8%) and a lack of synchronization (11.8%).

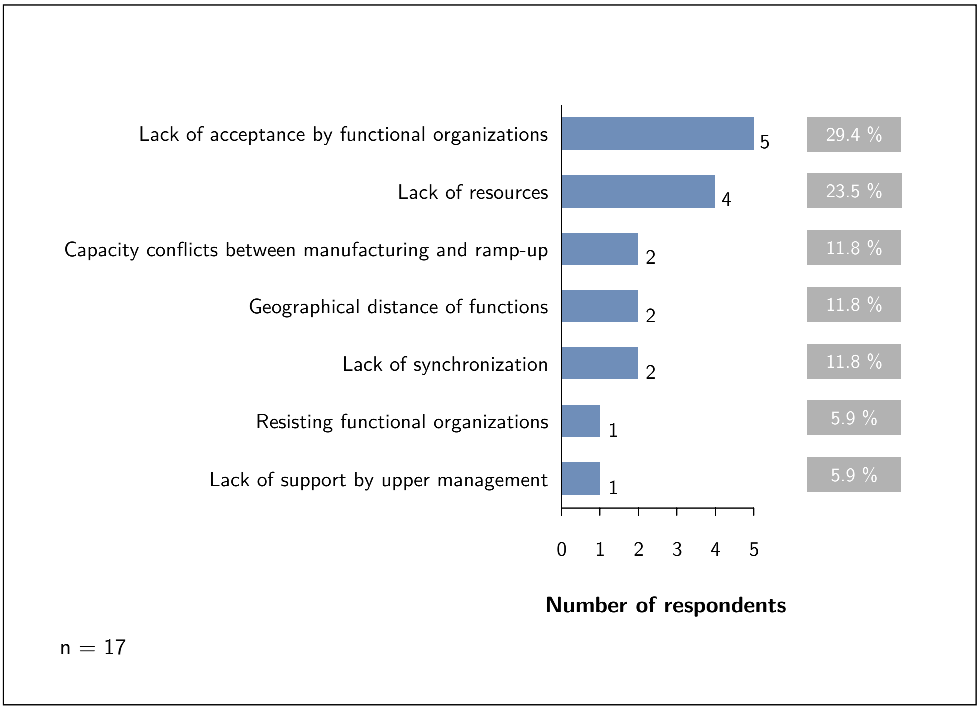


Figure 8.6: Problems during the implementation of Simultaneous Engineering

The fact that a lack of acceptance by functional organizations plays an important role as an obstacle to implementing Simultaneous Engineering is reflected in the answers of the participants who see a "lack of buy in from other groups", express that the "integration of production plants is often difficult" and quote excuses of production representatives who state that "without complete drawings we can do nothing at all". As one respondent brings into attention, departmental egoism can cause resource bottlenecks when the "respective employees are charged to full capacity by their line managers". Related to this, conflicts between manufacturing and ramp-up occur when "existing facilities are fully utilized [and] therefore cannot be reconfigured until new product roll out". Finally, implementing Simultaneous Engineering is perceived as "difficult in case of geographic separation".

Problems during the Implementation of Supplier Integration

Figure 8.7 shows the results of the content analysis regarding the problems during the implementation of Supplier Integration as provided by the survey participants. It is apparent, that compared to the results presented in the previous paragraphs, for the component of Supplier Integration, there is a larger number of different problems with a small number of mentions each. The problem most often reported is the fear of losing intellectual property (17.4%), closely followed by the risk of dependency on suppliers (13.0%) and a lack of resources for implementation (13.0%). Apart from that, companies see hurdles for introducing Supplier Integration in a large geographical distance to their the suppliers (8.7%), a resisting corporate culture (8.7%), a too large supplier base (8.7%), a high supplier turnover (8.7%) and a potential increase in the price of supplied parts in case of closer cooperation (8.7%).

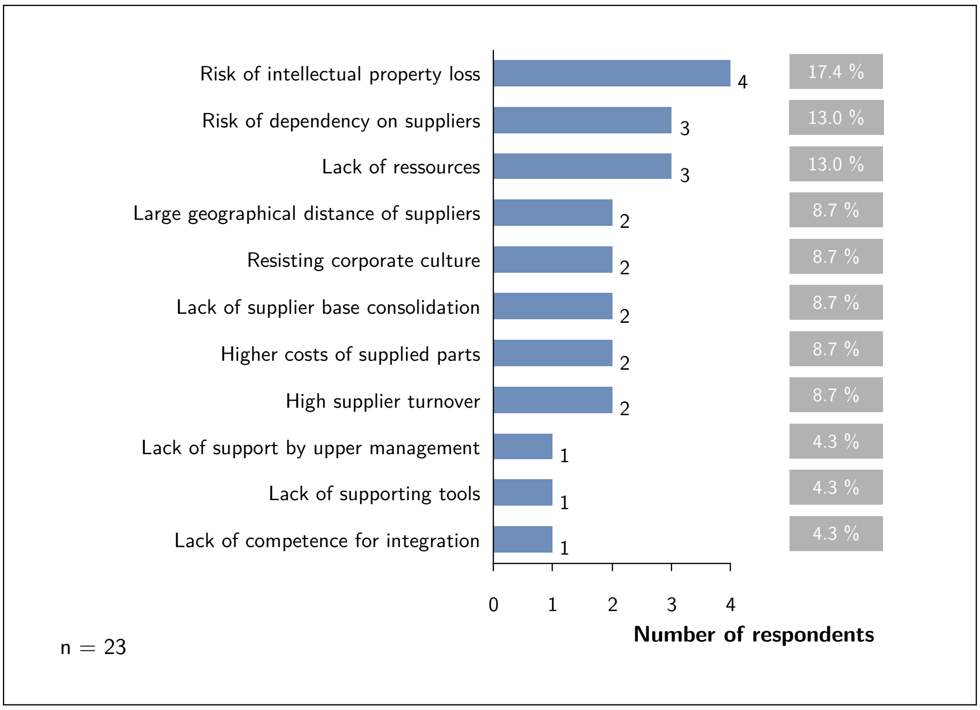


Figure 8.7: Problems during the implementation of Supplier Integration

The risk of losing intellectual property is addressed by several respondents and can be exemplified by the quote of one of the respondents who mentions that "proprietary concerns limit inclusion of multiple suppliers early on". While some of the participants in the survey warn of an "early dependency on suppliers" others refer to a "high supplier turnover" and "a kingdom mentality" of purchasing as major obstacles to a close integration of suppliers. As one person points out, "our supply base has moved further and further from home base and become less sophisticated so control is a big issue". Another one sees the main challenge in engaging suppliers "when product and components are still 'fuzzy'" to overcome the "'don't bother me until you've finished your design' syndrome".

Problems during the Implementation of Product Variety Management

The major problems when implementing the eighth of the eleven Lean PD principles, Product Variety Management, are shown in Figure 8.8. 23.8 percent of the persons that answered the question on problems with implementing the component state that the diversity of customer requirements represent the main hurdle for implementation. In addition, like in the case of Workload Leveling, participants mention that Product Variety Management lacks acceptance by developers (14.3%), is very complex (14.3%), requires cross-project knowledge transfer (14.3%) and supporting tools (9.5%) which are lacking.

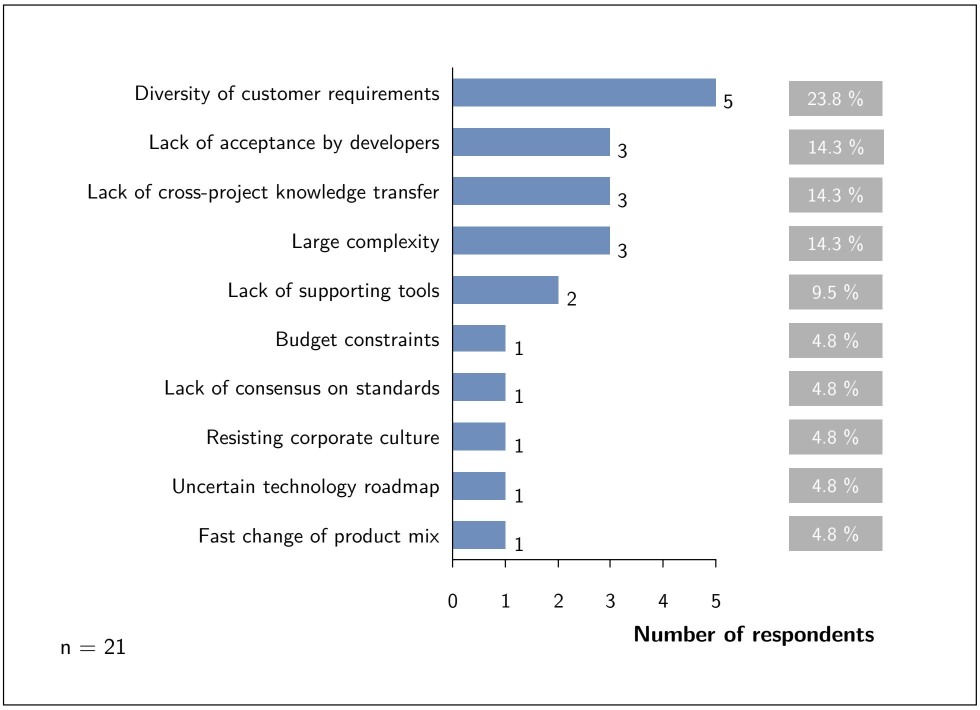


Figure 8.8: Problems during the implementation of Product Variety Management

As several participants in the survey point out, companies are “bound to customer design requirements” which “drive too many design changes”. What’s more, there is a “high creativity of the developers” making it difficult “getting engineers to agree”. One of the respondents states that there is a general reluctance to standardize from major program to program”, particularly “strong projects ignore standards”. Another one points to a lack of Cross-project Knowledge Transfer when stressing that “we do standardize between platforms under common VPs. Cooperation between different Program VP domains is lacking. We'd communicate more with the commercial programs if they were run by space aliens.”

In general, it is acknowledged that “modular concepts are complex to use” and appropriate tools supporting the process of definition have not been found by every company. As one participant in the survey points out “we attempt to do this, but most MRP and document control systems are not good at attribute searching for existing components.”

Problems during the Implementation of Rapid Prototyping, Simulation and Testing

An overview of the problems experienced when trying to implement the component of Rapid Prototyping, Simulation and Testing is given in Figure 8.9. In comparison with the other components, the number of responses provided by the survey participants is relatively low. Of the 13 persons that answered the question, 30.8% see budget constraints as the major issue. 23.1% refer to a high complexity as a reason for problems during the implementation process of Rapid Prototyping, Simulation and Testing.

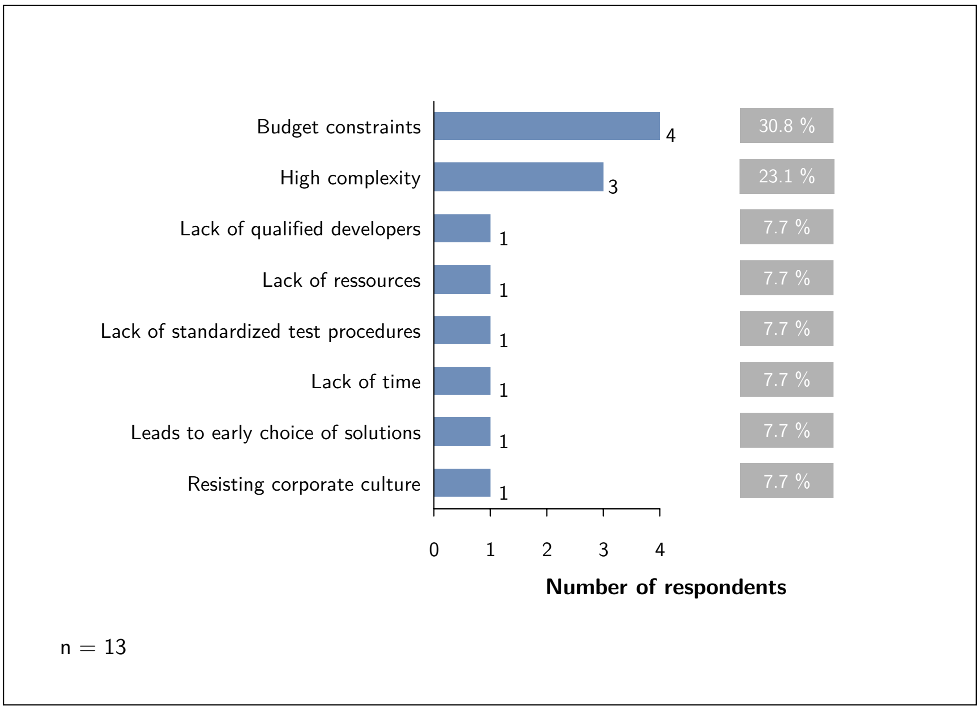


Figure 8.9: Problems during the implementation of Rapid Prototyping, Simulation and Testing

Some respondents point to the fact that the use of this component is "often not possible due to budget and resource constraints" or mention "physical limitations". Others warn of potential negative effects since Rapid Prototyping, Simulation and Testing "sometimes makes 'promises' too early, locks in solutions".

Problems during the Implementation of Process Standardization

Figure 8.10 displays the main problems the survey companies have experienced when implementing the component of Process Standardization. Most of the problems occur because an implementation of the component stands in contrast with flexibility requirements of the company's PD processes (35.3%), followed by a lack of acceptance by the developers (29.4%). Other problems mentioned include administrative requirements which go along with standardization (8.8%), difficulties with finding a consensus on which standards to choose (5.9%) and a lack of willingness to document knowledge (5.9%).

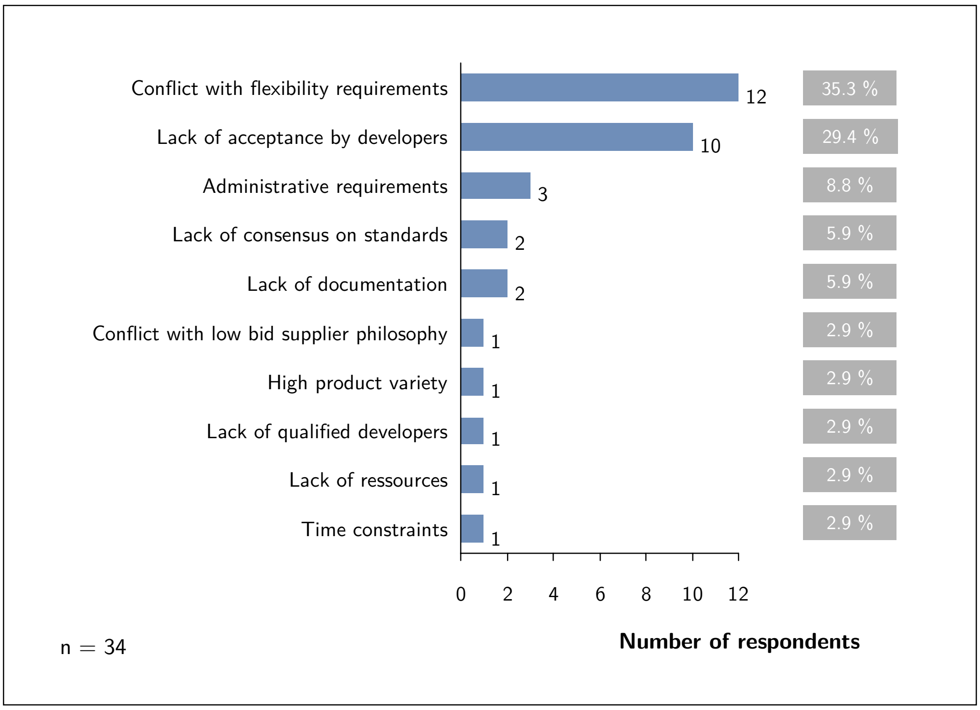


Figure 8.10: Problems during the implementation of Process Standardization

A large number of the persons answering the questions emphasize that they have "very different projects", a "multitude of processes" and "many exceptions". As one participant stresses, "product development is not a deterministic process and is therefore hard to squeeze into a process corset". Therefore, as two respondents put it, the "tricky part is balancing standardization with flexibility" and maintain "flexibility to tailor case by case project uniqueness". In addition, it is pointed out that there is a “lack of acceptance” and “discipline” among the development engineers. Several respondents state that developers still see themselves as “artists” for who “processes are seen as hindrance to the work” so that “deviations from processes become the rule”. At the same time, however, it is avowed that Process Standardization requires “large documentation and implementation efforts”, binding a lot of resources. One respondent mentions that “everybody has strong and different opinions on this so it is very hard to come to consensus on which processes we should standardize”. For another person this leads to the conclusion that the implementation of the component cannot be done “by enterprise consensus” but requires a “strong leadership to standardize”.

Problems during the Implementation of Set-based Engineering

The last of the eleven Lean PD components of which the results of the content analysis shall be discussed is the component of Set-based Engineering. The categorized problems provided by the surveyed companies regarding Set-based Engineering are shown in Figure 8.11. 32.0% of the problems reported are due to the fact that among developers there is a lack of acceptance regarding the component. An additional 24.0% name a lack of capacity as a problem during their implementation process. 16.0% and 8.0% refer to time and budgets constraints as hindrances to a successful implementation respectively.

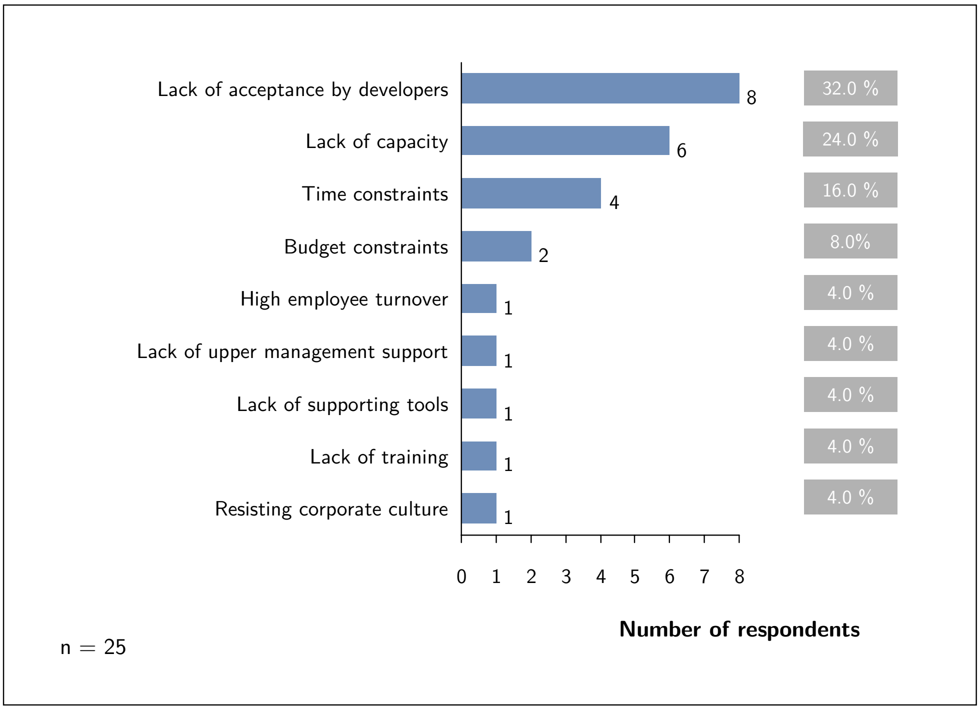


Figure 8.11: Problems during the implementation of Set-based Engineering

Among the survey participants it is observed that there is a "strong inertia of iterative design process". A respondent states that their "team gets one idea set in motion" leading to a situation where "options [are] not really considered equally". In line with this answer one participant points out that engineers in his company "tend to jump at [the] first thing that looks good, often have to backtrack". As another person puts it, therefore the "challenge is to shake up engineers to try multiple approaches before falling in love with one".

For some companies Set-based Engineering raises questions of resource consumption, both during implementation and use. Several respondents indicate that they have "limited resources for parallel solutions", that "budget constraints limit the number of solutions" and "the concrete implementation under limited resources remains unclear".

8.2.3 Influence of Company Characteristics on the Implementation of the Lean PD Components

The third step of the exploratory analysis consisted in a comprehensive investigation of links between the Lean PD components and company characteristics such as revenue, number of employees and industrial sector. It was deemed of large interest whether companies with higher revenues, more human resources or from a specific industrial sector are more likely to adapt Lean PD components. Furthermore, it should be examined how the perception regarding difficulty of implementation and usefulness varies among companies which differ according to the before mentioned criteria.

As explained in Section 8.1.3, to investigate these questions, correlation analyses were conducted. After introducing six dummy variables for the industrial sectors use, rank of implementation, perceived usefulness and perceived ease of implementation were separately tested for correlations with revenue, number of employees and the industrial sector. The results of these analyses shall be subsequently discussed.

Influence of Company Characteristics on the Use of Lean PD Components

Table 8.6 shows the findings of the correlation analysis regarding the influence of company characteristics on the use of the Lean PD components. The first column lists the eleven Lean PD components. The fields to the right of the component name provide the correlation coefficients, describing how the use of the particular component is correlated with the company characteristics shown in the first row. It is noteworthy that, for revenue and number of employees, the correlation coefficients have been calculated Pearson's method. The coefficients given for the six categories describing the influence of the industrial sector are Spearman Rank correlation coefficients. As in previous sections, correlations significant at a five percent level of significance are marked with one star and colored bright blue. Those significant at a one percent level of significance are accentuated by two stars and a dark blue shading.

When looking at the data of Table 8.6, it becomes obvious that depending on revenue, number of employees and industrial sector differences in the use of the eleven Lean PD components can be observed. Specifically the revenue of a company is significantly and positively correlated with a use of the majority of the Lean PD components. For the number of employees, fewer significant correlations with the use of the Lean PD components can be found. While the use of a Strong Project Manager, Set-based Engineering and Product Variety Management is correlated with revenue, these components are not significantly correlated with the number of employees. On the one hand, this may allude to a particular importance of financial resources for the implementation of these components. On the other hand, it is possible that, even though larger companies are more likely to implement a Lean PD system, for these particular components the larger number of employees complicates their successful implementation.

Table 8.6: Influence of company characteristics on the use of Lean PD components

	Revenue	Number of Employees	Industrial Sectors					
			Automotive	Industrial Equipment	Electronics	Aerospace Manufacturing	Medical Devices	Other Sectors
Strong Project Manager	.213*	.109	-.158	-.016	.114	-.022	.091	.029
Set-based Engineering	.225*	.166	.103	-.031	.152	-.086	-.071	-.051
Process Standardization	.096	.053	.060	-.099	.160	.092	-.172	-.104
Specialist Career Path	.297**	.344**	-.037	-.195*	.131	.153	.040	-.045
Product Variety Management	.312**	.174	.295**	-.016	.101	-.052	-.197*	-.299*
Workload Leveling	.067	.013	.016	.027	.145	-.084	.003	-.055
Supplier Integration	.334**	.295**	.172	-.211*	.118	.164	-.085	-.236
Responsibility-based Planning and Control	.019	.058	-.038	-.057	.092	-.053	-.128	.299*
Cross-project Knowledge Transfer	.182	.157	.109	-.166	.143	.068	-.151	-.123
Rapid Prototyping, Simulation and Testing	.278**	.199*	.157	-.202*	.174	.002	.179	-.381**
Simultaneous Engineering	.309**	.196*	.200*	-.186*	.106	-.080	.058	-.099

* $p<0.05$ ** $p<0.01$

Differences regarding the use of the eleven Lean components can also be found when dividing the survey data into groups of respondents from different industry sectors. The affiliation of a company with the automotive sector is significantly and positively correlated with the use of Product Variety Management and Simultaneous Engineering. In contrast to this, companies belonging to the industrial equipment sector make significantly less use of a Specialist Career Path, Supplier Integration, Rapid Prototyping, Simulation and Testing as well as Simultaneous Engineering. In general, it shows that particularly the automotive and electronics sector tend to make more use of the Lean PD components than the other sectors. This is little surprising, considering that Lean Thinking has its roots in the automotive industry. The application of Lean principles to sectors such as industrial equipment and medical devices is comparably new which might be reflected in a lesser use of Lean PD components. Furthermore, when comparing the use of the components across different sectors, it should be considered that the products the sectors produce differ significantly. Factors such as complexity and size of the products have an important impact on both production and product development and may therefore favor the use of particular Lean PD components in certain sectors.

Influence of Company Characteristics on the Rank of Implementing the Lean PD Components

The influence of company characteristics on the rank of implementing the respective Lean PD components is shown in Table 8.7. As can be seen, the correlation analysis yielded only few significant results. Of all eleven Lean PD components, only Supplier Integration is significantly correlated with the revenue or number of employees. The negative correlation denotes that companies with higher revenues introduce Supplier Integration significantly earlier.

Table 8.7: Influence of company characteristics on the rank of implementing the Lean PD components

	Revenue	Number of Employees	Industrial Sectors					
			Automotive	Industrial Equipment	Electronics	Aerospace Manufacturing	Medical Devices	Other Sectors
Strong Project Manager	-.027	-.125	.206*	-.055	-.097	-.103	-.018	.120
Set-based Engineering	.100	-.043	-.045	.152	-.054	-.070	.120	-.258
Process Standardization	-.030	-.070	.039	.018	-.246*	.084	.141	.007
Specialist Career Path	.038	-.101	.182	.160	.030	-.127	-.067	-.301*
Product Variety Management	-.005	-.026	-.155	.046	.016	-.005	.157	.025
Workload Leveling	.083	.069	.170	-.154	-.027	-.056	-.192	.080
Supplier Integration	-.208*	-.203	-.113	.198	-.009	-.154	.074	.088
Responsibility-based Planning and Control	.046	-.078	-.087	-.112	.132	.003	.194	-.141
Cross-project Knowledge Transfer	.121	.139	-.066	.022	-.045	.180	.196	-.194
Rapid Prototyping, Simulation and Testing	-.012	-.037	-.169	.146	.033	.144	-.164	.097
Simultaneous Engineering	-.090	-.178	-.096	.151	.138	-.068	.020	-.116

* $p<0.05$ ** $p<0.01$

Regarding differences in the time of implementing the components among different industrial sectors, the analysis shows that in the automotive sector, a Strong Project Manager on average has been implemented significantly later than in other sectors. The rank of implementing Process Standardization, in turn, is found to be negatively correlated with an affiliation of the company with the Electronics sector. Hence, the companies of the Electronics sector implement Process Standardization, relative to the other components, significantly earlier than the companies of the other sectors.

Influence of Company Characteristics on the Perceived Ease of Implementing the Lean PD Components

In Table 8.8 the correlations between the company characteristics and the perceived ease of implementing the eleven Lean PD components are depicted.

Table 8.8: Influence of company characteristics on the perceived ease of implementing the Lean PD components

	Revenue	Number of Employees	Industrial Sectors					
			Automotive	Industrial Equipment	Electronics	Aerospace Manufacturing	Medical Devices	Other Sectors
Strong Project Manager	-.111	-.034	.105	-.043	.032	-.049	-.058	-.022
Set-based Engineering	-.063	-.021	.089	-.053	.057	.060	-.173	.001
Process Standardization	-.185	-.133	-.003	-.002	.025	.049	-.023	-.029
Specialist Career Path	.221*	.292**	.029	-.114	-.024	.140	-.023	-.086
Product Variety Management	-.282**	-.173	.070	-.013	.114	.060	-.144	-.236
Workload Leveling	-.105	-.031	-.098	-.009	.044	.050	-.052	.119
Supplier Integration	-.006	-.011	.100	.020	.103	.022	-.124	-.237
Responsibility-based Planning and Control	-.037	-.068	-.003	.055	.013	-.024	-.190*	.234
Cross-project Knowledge Transfer	-.208*	-.117	-.087	.037	.088	.091	-.025	-.068
Rapid Prototyping, Simulation and Testing	-.026	.025	.103	.026	.083	.017	.044	-.352**
Simultaneous Engineering	-.114	-.071	.103	-.175	-.021	.008	.016	.073

* p<0.05 ** p<0.01

It could have been assumed that implementing Lean PD components is perceived as less difficult by companies with a large revenue. The results of the analysis, however, demonstrate that with the exception of a Specialist Career Path, companies with higher revenues perceive the implementation of the components as more difficult. Particularly, for the components of Product Variety Management and Cross-Project Knowledge Transfer the perceived ease of implementation is significantly negatively correlated with the revenues the companies generate. Similarly, the Specialist Career Path is the only component which is perceived as easier to implement in a company with a larger number of employees.

Both the negative correlations for Product Variety Management and Cross-project Knowledge Management as well as the positive correlations for a Specialist Career Path seem plausible when considering the goals which are pursued with their implementation. Product Variety Management and Cross-project Knowledge transfer yield at bundling and standardizing formerly decentralized, heterogeneous patterns. Thus, the implementation of both of these components requires strong coordination efforts among a large number of employees, making implementation more difficult for larger firms. In contrast, a Specialist Career Path, as already indicated by the name, premises a high specialization of the employees. This specialization, however, is much more likely to be found in larger companies with a multitude of different functional domains.

Influence of Company Characteristics on the Perceived Ease of Implementing the Lean PD Components

Concluding the presentation of the correlations between company characteristics and a Lean PD system, Table 8.9 gives an overview of the findings concerning the perceived difficulty of implementing the eleven Lean PD components.

Table 8.9: Influence of company characteristics on the perceived usefulness of implementing the Lean PD components

	Revenue	Number of Employees	Industrial Sectors					
			Automotive	Industrial Equipment	Electronics	Aerospace Manufacturing	Medical Devices	Other Sectors
Strong Project Manager	.001	.032	-.106	.026	.069	.056	.008	-.096
Set-based Engineering	.052	.153	-.088	-.021	-.080	.082	.194*	-.048
Process Standardization	-.161	-.171	-.003	.093	-.028	-.073	.048	-.051
Specialist Career Path	.133	.133	-.076	.141	-.151	.106	-.051	.052
Product Variety Management	.063	.068	.074	.086	-.154	-.007	.112	-.148
Workload Leveling	.058	.023	-.086	-.031	.107	.003	.032	-.030
Supplier Integration	.219*	.239*	.077	-.040	-.008	.065	.157	-.283*
Responsibility-based Planning and Control	.004	.061	-.096	.025	.026	-.086	-.078	.205
Cross-project Knowledge Transfer	.028	.137	.079	.001	-.109	-.085	-.198*	.150
Rapid Prototyping, Simulation and Testing	.177	.130	.056	-.105	.095	.090	.141	-.263*
Simultaneous Engineering	.232*	.187*	.056	-.083	-.057	.157	.174	-.267*

* $p<0.05$ ** $p<0.01$

Here, it shows that revenue and number of employees have a predominantly positive influence on how useful the Lean PD components are perceived. The perceived usefulness of Supplier Integration and Simultaneous Engineering is positively correlated with both revenue and the number of employees. The investigation of differences between the single industry sectors yields rather mixed results with only two significant correlations for the sector of medical devices.

8.2.4 Influence of Supporting Tools and Infrastructure on the Implementation Process

In Section 7.2.2 it was described to what extent the companies of the sample make use of the definition of goals, define persons responsible for the process of implementation, draw on external help and conduct value stream mapping. For this research, it is of particular interest if these supporting tools and infrastructure have an identifiable influence on the process of implementing the eleven Lean PD components. Therefore, as described Section 8.1.4, in the fourth and last major phase of the exploratory analysis, t-tests were performed to analyze the effect of these measures on use, time of implementation, perceived difficulty of implementation and the perceived usefulness of implementing the components. In what follows, the results of these tests shall be presented separately for each of the four supporting measures.

Influence of the Definition of Goals on the Implementation Process

To identify whether the definition of goals has a measurable effect on the use, time of implementation, perceived difficulty and perceived usefulness of implementing the eleven Lean components, the data points of the survey were separated into two groups. As detailed in Section 8.1.4, one group consisted of the companies that had not defined any goals for the implementation process while members of the other had defined goals. Using a t-test the two groups were then compared regarding their use and perception of the eleven Lean PD components.

Table 8.10 encapsulates the results of the t-test conducted to examine the effect of defining distinct goals for the implementation of Lean PD. The first column lists the eleven Lean PD components. For each of these components, the table then describes the differences that exist among the two groups, with and without goals, regarding its use, its time of implementation, its perceived ease of implementation and its perceived usefulness of implementation. The columns labeled "Mean Difference" contain the average difference in points between the answers given by the two groups for the particular category. The column "Sig. (2-tailed)" provides the level of significance. For values less than 5%, there is a significant difference between the answers provided by the two groups (marked bright blue). Values less than 1% indicate strongly significant findings and are colored dark blue.

As can be seen from the table, particularly regarding the extent to which the eleven Lean components are used, there are differences between the group of companies that have defined goals and the group of firms that have not. In fact, the mean difference is positive for the use of all components, indicating that companies with goals in place make higher use of Lean PD components. Of these results, however, only those for the components of Supplier Integration, Responsibility-based Planning and Control, Rapid Prototyping, Simulation and Testing, the Specialist Career Path, Workload Leveling and Cross-project Knowledge Transfer are significant. Regarding the time, perceived ease and usefulness of implementation, much less significant differences between the two groups can be observed. In case of the time of implementation, there is a significant positive mean difference for the component of Process Standardization. This indicates that the group with designated goals for the implementation of Lean PD on average has started to implement the component at a later point in time. At the same time, defining goals does not seem to strongly positively influence the perceived ease of implementation. The only component for which a significant and positive relation between the definition of goals and perceived ease of implementation could be found is Rapid Prototyping, Simulation and Testing.

Table 8.10: Results of the t-test on the effect of the definition of goals

	Use		Time of Implementation		Perceived Ease of Implementation		Perceived Usefulness of Implementation	
	Sig. (2-tailed)	Mean Difference	Sig. (2-tailed)	Mean Difference	Sig. (2-tailed)	Mean Difference	Sig. (2-tailed)	Mean Difference
Strong Project Manager	.637	.10447	.897	-.102	.793	-.057	.436	-.170
Set-based Engineering	.165	.21613	.975	.029	.702	.090	.634	.108
Process Standardization	.130	.32605	.015	1.187	.521	-.164	.806	-.048
Specialist Career Path	.016	.53561	.312	-.981	.454	.179	.538	.141
Product Variety Management	.400	.18668	.241	.907	.898	-.029	.378	.215
Workload Leveling	.049	.42621	.480	-.516	.964	-.011	.469	.145
Supplier Integration	.003	.58682	.914	.077	.578	.133	.013	.491
Responsibility-based Planning and Control	.003	.56322	.250	-.870	.829	-.058	.357	.220
Cross-project Knowledge Transfer	.034	.37849	.396	.615	.801	.060	.243	-.239
Rapid Prototyping, Simulation and Testing	.005	.63372	.448	.584	.016	.632	.120	.509
Simultaneous Engineering	.059	.44735	.774	-.185	.267	-.266	.787	.051

It should be noted that the findings of this analysis do not necessarily imply that for certain components there is a positive effect of defining goals on the level of use. Instead, the results should be interpreted in the way that companies which have defined goals at the same time make higher use of some of the eleven Lean PD components. Besides a potentially positive effect of clearly defined goals, this observation could also be due to better general management capabilities or a higher resource endowment of the firm which enable the firm to independently implement the components and set goals to a larger extent.

Influence of the Definition of a Responsible Person on the Implementation Process

The procedure chosen to investigate the effect of defining a responsible person for the process of implementing the Lean PD components is analogous to the one described for the definition of goals. Table 8.11 shows the results of the t-test on the influence that using a responsible person has on the use, time, perceived ease and perceived difficulty of implementing the components.

Table 8.11: Results of the t-test on the influence of the definition of a responsible person

	Use		Time of Implementation		Perceived Ease of Implementation		Perceived Usefulness of Implementation	
	Sig. (2-tailed)	Mean Difference	Sig. (2-tailed)	Mean Difference	Sig. (2-tailed)	Mean Difference	Sig. (2-tailed)	Mean Difference
Strong Project Manager	.351	.16078	.991	-.007	.918	.020	.355	.177
Set-based Engineering	.481	.09639	.885	-.103	.352	-.191	.376	.175
Process Standardization	.610	.08630	.957	-.026	.354	.207	.150	.244
Specialist Career Path	.412	.15243	.156	-1.091	.885	-.030	.303	-.206
Product Variety Management	.565	.11207	.704	.244	.890	-.027	.639	.101
Workload Leveling	.429	.14707	.645	-.262	.572	-.122	.884	.026
Supplier Integration	.492	.12122	.488	.407	.838	.043	.611	.089
Responsibility-based Planning and Control	.003	.48447	.661	-.265	.148	-.340	.453	.161
Cross-project Knowledge Transfer	.288	.16764	.887	.085	.707	-.080	.993	.002
Rapid Prototyping, Simulation and Testing	.457	.15030	.641	-.303	.677	.097	.436	-.186
Simultaneous Engineering	.950	.01293	.905	-.066	.456	-.157	.621	-.084

While, again, there is a positive mean difference for all components when comparing the groups with and without a responsible person, the effect is only significant for Responsibility-based Planning and Control. A possible explanation for this might be that companies which make strong use of Responsibility-based Planning and Control, i.e. put strong emphasis on responsibility and accountability in their PD activities, are more likely to also have designated responsibilities in their implementation process. Regarding time, perceived ease and usefulness of implementation, defining a responsible person does not seem to have a positive impact on any of the components.

Influence of the Use of External Help on the Implementation Process

The third t-test aimed at shedding more light on the question whether companies that plan to use or are already using external help differ from others with respect to the use, time of implementation, perceived ease and perceived usefulness of implementing the eleven Lean PD components. Table 8.12 presents the results of the analysis. It is apparent that there are almost no significant differences between the group which makes use of external help and the group that does not. In fact, it shows that, despite being not significant, the mean differences for the use of the components are mostly negative. Hence, companies that draw on external help, such as senseis and consultants, tend to be those with a lower maturity level in Lean PD. The positive influence that external help might have on the use of the components is therefore overlayed and covered by the phenomenon that firms which are still at the beginning of the implementation have a higher need for external help.

Table 8.12: Results of the t-test on the influence of using external help

	Use		Time of Implementation		Perceived Ease of Implementation		Perceived Usefulness of Implementation	
	Sig. (2-tailed)	Mean Difference	Sig. (2-tailed)	Mean Difference	Sig. (2-tailed)	Mean Difference	Sig. (2-tailed)	Mean Difference
Strong Project Manager	.210	.22267	.952	.040	.488	-.137	.522	-.126
Set-based Engineering	.754	-.04435	.080	-1.226	.126	-.323	.037	.423
Process Standardization	.097	-.28840	.274	.563	.126	-.351	.591	.094
Specialist Career Path	.477	-.13649	.530	-.503	.475	-.154	.997	.001
Product Variety Management	.092	-.33585	.661	.277	.146	-.296	.821	.050
Workload Leveling	.517	-.12433	.535	-.371	.951	.014	.370	-.187
Supplier Integration	.414	-.14873	.403	.507	.249	-.249	.490	.125
Responsibility-based Planning and Control	.423	-.13942	.213	.839	.096	-.403	.613	-.118
Cross-project Knowledge Transfer	.167	-.22435	.905	.074	.950	-.013	.552	.111
Rapid Prototyping, Simulation and Testing	.934	.01727	.304	.682	.670	-.102	.760	.075
Simultaneous Engineering	.143	-.31464	.138	.827	.045	-.412	.834	-.036

Influence of Value Stream Mapping on the Implementation Process

Finally, the role of value stream mapping as a tool supporting the implementation of the eleven Lean PD components shall be elucidated. Like for the measures discussed in the previous paragraphs, the sample was split up into two groups, one of which had already conducted value stream mapping for at least a small number of its processes while the other had not done value stream mapping. The results of the comparison of these two groups are provided in Table 8.13.

Table 8.13: Results of the t-test on the influence of value stream mapping

	Use		Time of Implementation		Perceived Ease of Implementation		Perceived Usefulness of Implementation	
	Sig. (2-tailed)	Mean Difference	Sig. (2-tailed)	Mean Difference	Sig. (2-tailed)	Mean Difference	Sig. (2-tailed)	Mean Difference
Strong Project Manager	.600	.09447	.211	-.804	.080	.337	.075	.328
Set-based Engineering	.578	.07444	.981	.017	.596	-.110	.021	-.449
Process Standardization	.415	-.13910	.824	.113	.198	.289	.262	-.192
Specialist Career Path	.319	-.18013	.462	.574	.992	.002	.095	-.336
Product Variety Management	.826	.04319	.555	-.384	.561	.116	.332	-.209
Workload Leveling	.926	.01683	.463	-.426	.581	.119	.827	.039
Supplier Integration	.273	-.19479	.830	-.128	.144	.308	.084	-.304
Responsibility-based Planning and Control	.947	-.01130	.901	-.076	.500	.160	.883	.031
Cross-project Knowledge Transfer	.196	-.19720	.913	-.066	.905	-.025	.719	-.065
Rapid Prototyping, Simulation and Testing	.125	-.31098	.606	-.346	.254	.266	.387	-.208
Simultaneous Engineering	.017	-.49631	.683	.236	.494	.145	.209	-.210

It is striking that, similar to the use of external help, there are almost no differences between the companies which have conducted value stream mapping and the firms that have not. Among the different categories tested, only two yielded significant results. Contrary to the assumption that value stream mapping has a positive effect on the process of implementing the Lean PD components, one of these results shows that the group of firms which have conducted value stream mapping indeed make significantly less use of Simultaneous Engineering. What's more, most of the mean differences for the use of the Lean PD components are negative, implying that in general companies that have not conducted value stream mapping have a higher maturity level in Lean PD. The finding that value stream mapping does not have any significant positive effect on the implementation of a Lean PD system will be taken on and further discussed in the following chapter.

The presentation of the results on the influence of supporting tools and infrastructure on the implementation of Lean PD concludes the chapter on the exploratory analysis of the survey data. After in the Chapters 7 and 8 the patterns found in the survey data have been described in great detail, the following Chapter 9 will discuss their implications for the introduction of a Lean PD system. In particular, it will be examined whether the hypotheses derived in Chapter 5 can be confirmed or need to be refuted.

9 Implications of the Survey Data Analyses for the Hypotheses on the Introduction of Lean PD

The two previous chapters presented the results of a comprehensive descriptive and exploratory analysis of the survey data. Besides providing an overview of the current use and perception of the Lean PD components in practice, one of the main goals of the analyses was to build a basis for investigating the hypotheses on the implementation of a Lean PD system derived in Chapter 5. Therefore, in this chapter, the hypotheses shall be taken on and discussed in the light of the survey results. Following a systematic approach, each of the following sections is dedicated to one of the five hypotheses. Each of the hypotheses is first verified or refuted. Then, the implications of the test results for the implementation of a Lean PD system are discussed. In this way, a foundation shall be laid to derive the Lean Innovation Roadmap in the subsequent Chapter 10.

9.1 Implications of the Survey Data Analyses for Hypothesis 1

The first of the five hypotheses on the implementation of a Lean PD system was based on the theoretical investigation of the component interdependencies. It was claimed that the components of a Lean PD system are highly interwoven and should therefore not be implemented independently but using a process with concurrent and overlapping phases.

Testing of Hypothesis 1

The results of the analyses described in the two previous chapters seem to support hypothesis 1. In fact, as Table 8.3 and Table B.1 to Table B.4 show, the use of the eleven Lean PD components is highly correlated. As stated, companies do not advance in their Lean PD practices by making more use of a few, particular components but by extending the use of almost all components simultaneously. Leaders in Lean PD show a high use of almost all components, laggards make less use of almost all of them. This clearly indicates that Lean PD should not be regarded as a loose collection of practices but a complicated system the performance of which depends on a concurrent use of practices.

The fact that in practice the Lean PD components are not implemented in a strict linear, subsequent way is also underlined by the descriptive analysis of the use of the characteristics detailing them. As was shown in Figure 7.7, the use of the four characteristics within one component varies strongly. While a component may on average be used more than another component, this does not mean that this is necessarily the case when looking at the characteristics. As an example, one of the characteristics of Responsibility-based Planning and

Control, which on average is the third least used component, shows a higher use than two of the characteristics of Process standardization, the component most widely used by the surveyed companies.

Discussion

In sum, the results of the analyses militate for an understanding of Lean PD as a system of highly interwoven components which should not be implemented in an isolated manner. This observation is not surprising and has been made by several authors before. So, Karlsson and Ahlstrom state that "[i]mplementing one or a few of the techniques contained in the total concept is not sufficient for achieving Lean Product Development. The emphasis lies on a coherent whole." [Karls 96] p.285 Similarly, Sobek et al. emphasize that "[m]any factors contribute to the efficacy of the Toyota product development system; no one secret explains its success" [Sobek 99] p.72.

While the general notion of Lean PD as a complex system therefore is in line with literature, the analysis of the system interdependencies also yielded a result which seems to contradict the current understanding of a Lean PD system. As pointed out in Section 8.2.1, the use of the component of a Strong Project Manager was found to be largely independent of almost all other components. This finding is particularly striking because several authors consider the Strong Project Manager to be one of the most important Lean PD components. Morgan and Liker, for example, utter: "Key decisions, mentoring, lobbying for resources, building a shared vision, pushing the product to higher levels, and achieving quality, safety, cost and timing targets all start with the chief engineer. This makes the CE system stand out as a pivotal part of Toyota's PD system" [Morga 06] p.138.

The finding of this research that in fact the Strong Project Manager seems to be the only component the use of which is not strongly connected to the use of all others seems to at least partly question the statement by Morgan and Liker. It is not doubted that using a Strong Project Manager can decisively contribute to a successful PD system. Nevertheless, the fact that there are companies which seem to make use of almost all other components while not making use of a Strong Project Manager indicates that the component does not serve as a prerequisite for a Lean PD system as much as it has been argued in literature.

9.2 Implications of the Survey Data Analyses for Hypothesis 2

As the second hypothesis derived in Section 5.2 it was claimed that, even though the interdependencies require a concurrent implementation, the eleven Lean PD components differ regarding the number and nature of their prerequisites. Specifically, it was hypothesized that among the components there are some which can be identified as lower-level and higher-level components. Lower-level components are components which, at the same time, are easy to implement, are implemented early and are used to a high degree. Higher-level components, in contrast, are hard to implement, implemented late and used less.

Testing of Hypothesis 2

The findings of the analyses appear to confirm hypothesis 2. Table 7.1 in Section 7.2.7 provided a cross-categorical comparison of all eleven Lean PD components. It can be seen that for most of the components the ranks differed among the three categories use, time of implementation and perceived ease of implementation. However, it is striking that particularly for the components ranked highest and lowest, the ranks are fairly constant across the categories. Process Standardization and Simultaneous Engineering rank high in all three categories use, time of implementation and ease of implementation. In contrast to this, Set-based Engineering and Cross-project Knowledge are simultaneously used little, implemented late and considered hard to implement. According to the definition mentioned above, Process Standardization and Simultaneous Engineering can therefore be labeled as lower-level components. Set-based Engineering and Cross-project Knowledge are identified as higher-level components. An unequivocal classification of the other components seems not possible. The component of a Strong Project Manager, for example, is both highly used and implemented early. However, as Figure 7.10 illustrates, it is perceived as comparatively difficult to implement, preventing an explicit labeling as a lower-level component.

Discussion

While the general assumption that in a Lean PD system there are lower-level and higher-level components is supported by the findings, it should be noted that the exact components found to be lower-level and higher-level components deviate from those expected to fall into these categories. As depicted in Figure 5.1, based on the theoretical analysis Set-based Engineering analysis had in fact been assumed to be a higher-level component. The categorization of Process Standardization as a lower-level component is not surprising either. What is striking, however, are the findings on Simultaneous Engineering and Cross-project Knowledge Transfer. Simultaneous Engineering, based on the investigation of the interdependencies, had been hypothesized to require several other components as prerequisites and had therefore been placed in the middle of the graph shown in Figure 5.2. Similarly, Cross-project Knowledge Transfer was assumed to be neither lower-level nor higher-level component since it was expected to serve as an important prerequisite for a number of other components (e.g. Product Variety Management and Set-based Engineering, see Table 5.2). Hence, the result that Simultaneous Engineering can be clearly classified as a lower-level component while Cross-Project Knowledge Transfer is a higher-level component was quite astonishing.

In case of Simultaneous Engineering, a possible explanation for its high use, early implementation and little perceived difficulty might lie in the fact that, since its first description in the late 1980s, this component has received a lot of attention. As was pointed out in Section 4.1, the component has long been considered to be one of the main differentiating factors of a PD system, leading both researchers and practitioners to invest large efforts into developing concepts for its implementation. These endeavors have not only resulted in a high spreading of this practice but can also be assumed to have positively influenced its perceived importance for a successful PD system. This is reflected by the fact that Simultaneous Engineering, as shown in Figure 7.11, is perceived as the most useful of all eleven Lean PD components.

To find a plausible explanation for the classification of Cross-project Knowledge Transfer as a higher-level component seems more difficult. It appears reasonable to assume that its strikingly little use and exceptionally late implementation are not due to the fact that companies *do not see the value* of the component as a prerequisite but are rather *not able* to implement the component. In this case, the gap between the importance of the component and its current implementation in companies would allude to a central role of Cross-project Knowledge Transfer for achieving the status of a truly learning organization. Companies which find a way to succeed in implementing the component can potentially take a major step on their way towards a Lean PD system and gain significant advantages over their competitors.

9.3 Implications of the Survey Data Analyses for Hypothesis 3

The third hypothesis derived from the investigation of the component interdependencies stated that implementing lower-level components before higher-level components will facilitate the process of implementing a Lean PD system. More specifically, it was hypothesized that companies which make more use of lower-level components have less difficulty with implementing particular higher-level components (hypothesis 3a). Furthermore, it was claimed that, problems companies had experienced when trying to implement higher-level components are at least to some part, caused by particular missing lower-level components (hypothesis 3b).

Both sub-hypotheses 3a and 3b, can be supported only for some of the four lower-level and higher-level components identified in the previous section. For others they need to be rejected. In the following, the four components, i.e. Process Standardization, Simultaneous Engineering, Set-based Engineering and Cross-project Knowledge Transfer, shall be discussed concerning the two sub-hypotheses.

Testing of Hypothesis 3a

Insights regarding hypothesis 3a can be gained when taking a look at the results of correlation analysis C and correlation analysis E of Section 8.2.1. Analysis C investigated to what extent the use of certain Lean PD components is correlated with the perceived ease of implementing other components. For the components labeled as lower-level components in Section 9.2, Process Standardization and Simultaneous Engineering, hypothesis 3a, if supported, would imply that their use contributes to an easier implementation of other, more sophisticated components. In fact, on a component basis, the use of Process Standardization is positively correlated with the perceived ease of implementing the component of a Strong Project Manager (see Table 8.4). The rest of the correlations, although predominantly positive, are not significant. The use of Simultaneous Engineering is not positively correlated with the perceived use of any other component.

Analysis E of Section 8.2.1 examined the correlations between the time of implementation among the different components. Strong positive correlations allude to relationships where the component are highly dependent on each other. The investigation yielded that a late implementation of Process Standardization goes along with a later implementation of Product Variety Management and Cross-project Knowledge Transfer. The time of implementing Simultaneous Engineering was found to be significantly positively correlated with the time of implementing Product Variety Management but, at the same time, negatively correlated with the time of implementing a Strong Project Manager. While Process Standardization therefore is connected with the implementation of other components, the role of Simultaneous Engineering remains controversial. In sum, therefore, hypothesis 3a can be confirmed for the component of Process Standardization and cannot be supported for Simultaneous Engineering.

For the component of Set-based Engineering, in correlation analysis A of Section 8.2.1 it was found that there is a strong positive link between its perceived ease of implementation and the use of other, less sophisticated components, such as Workload Leveling, Supplier Integration and Responsibility-based Planning and Control. Except for the use of a Strong Project Manager, all correlation coefficients between the use of other components and the perceived ease of implementing Set-based Engineering are positive. Therefore, since this component was identified as a higher-level component in Section 9.2, hypothesis 3a can be clearly corroborated for Set-based Engineering.

Regarding Cross-project Knowledge Transfer, the second of the two higher-level components identified in the previous Section, correlation analysis C yielded that the perceived ease of implementation is not positively influenced by the use of any other component. In contrast, Cross-project Knowledge Transfer is even perceived as harder to implement when a Strong Project Manager or Rapid Prototyping, Simulation and Testing are used to a higher degree. Consequently, hypothesis 3a has to be rejected for Cross-project Knowledge Transfer.

Testing of Hypothesis 3b

Hypothesis 3b can be tested based on the insights gained from the content analysis of Section 8.2.2. When analyzing the problems companies experienced during the implementation of the single components, it was found that many problems result from organizational resistance against new concepts. At the same time, however, as stated in hypothesis 3b, several of the major problems listed by the survey participants for a respective component refer to lacking other components. For example, four respondents point to a lack of task prioritization, a part of Workload Leveling, when naming problems with the implementation of a Strong Project Manager. A lack of Process Standardization is explicitly mentioned for Product Variety Management as well as Rapid Prototyping, Simulation and Testing and may be implicitly contained in answers such as "lack of acceptance by developers". A lack of Simultaneous Engineering, in contrast, was not among the answers given by the responding companies. Hence, again, hypothesis 3b can be weakly confirmed for Process Standardization and cannot be supported for Simultaneous Engineering.

For two higher-level components Set-based Engineering and Cross-Project Knowledge Transfer the content analysis yielded results which allude to both internal and external factors as problems during the process of implementation. Among the top answers for Set-based Engineering, a "lack of capacity" and "time constraints" and "high employee turnover" were mentioned. These responses are well in line with the finding of correlation analysis A that Workload Leveling and Responsibility-based Planning and Control may facilitate its implementation. Similar problems, e.g. a "lack of time", "lack of resources", "large employee turnover" and "large product variety", were identified for the implementation of Cross-project Knowledge Transfer. Hypothesis 3b can therefore be confirmed for both Set-based Engineering and Cross-project Knowledge Transfer.

Discussion

Overall, the finding that the data supports hypotheses 3a and 3b for the component of Set-based Engineering suggests a certain path dependency for the implementation of this component. Based on the empirical data, Set-based Engineering appears to be a component which, as already hypothesized in Figure 5.2, should not be implemented at an early stage. Rather, it seems strongly dependent on several prerequisites which facilitate its implementation and favor a late introduction.

Process Standardization, in contrast, shows many of the features expected from a lower-level component. Even though empirical evidence for hypothesis 3 is not as strong as expected, results point to a role of Process Standardization as a predecessor for rather than a successor of other components.

Finally, the finding that hypothesis 3 could not be confirmed for Simultaneous Engineering and Cross-project Knowledge Transfer requires some explanation. Apparently, Simultaneous Engineering is implemented early and used to a high degree but does not significantly facilitate the use of other components. The latter observation may indicate that an early use of Simultaneous Engineering, from a systems design perspective, is in fact not a strict necessity. It is possible that, in contrast to Process Standardization, companies do not implement Simultaneous Engineering as a prerequisite for other, more sophisticated components. Instead, the finding that hypothesis 3 cannot be corroborated for Simultaneous Engineering, may back the interpretation provided in the previous section that the classification of Simultaneous Engineering as a higher-level component is partly due to a high popularity.

Even more striking than the results for Simultaneous Engineering are the findings for Cross-project Knowledge Transfer. From its classification as a higher-level component it would have been expected that the use of other components has a positive impact on its perceived ease of implementation. The data indicates that this is not the case. On the contrary, as shown in correlation analysis A, Cross-project Knowledge Transfer itself seems to facilitate the implementation of several other components. In this sense, Cross-project Knowledge Transfer behaves like one would expect from a lower-level component, despite being the component implemented last and used by far least. From a conceptual point of view, this is interesting because the former observation is well in line with the original hypothesis that Cross-project Knowledge Transfer serves as an enabler for many other components (see Table 5.2 and discussion in the previous section). Hence, the findings with regard to hypothesis 3 underpin the theory that for Cross-project Knowledge Transfer there is a large gap between its current and ideal use. In sum, therefore, Cross-project Knowledge Transfer, more than any other component, may play an important role as a differentiating factor of a Lean PD system.

9.4 Implications of the Survey Data Analyses for Hypothesis 4

While the first three hypotheses were based on the theoretical observation of the interdependencies, hypothesis 4 aimed at investigating the influence of company-specific characteristics on the process of implementing a Lean PD component. It was hypothesized that companies with a higher endowment of financial and human resources with higher revenues will be more likely to implement a Lean PD system. To test this, three detailed sub-hypotheses were phrased. It was claimed that companies with higher revenues (hypothesis 4a) and a larger number of employees (hypothesis 4b) are more likely to implement the Lean PD components whereas the likelihood of implementing the Lean PD components is equal across all industry sectors (hypothesis 4c). The analyses dealing with the influence of company characteristics on the implementation process of Lean PD were presented in 8.2.3. Subsequently, the implications of the findings shall be discussed separately for the three sub-hypotheses.

Testing of Hypothesis 4a

Section 8.2.3 presented the correlation coefficients for the link between the revenues of the surveyed companies and the use, the rank of implementation, the perceived ease and the perceived usefulness of implementing the single Lean PD components. It was found that the use of Lean PD components is significantly correlated with revenues for the majority of the Lean PD components. Regarding the ranks of implementation, the perceived ease and usefulness, the analysis yielded only few significant results. However, the signs of the correlation coefficients in almost all cases indicated a positive relationship between revenues and the implementation of Lean PD. Even though for most components, the implementation was perceived as more difficult by companies with higher revenues, this apparently did not prevent them from actually implementing the components. In sum, therefore, hypothesis 4a can be confirmed.

Testing of Hypothesis 4b

The results on the correlations between the number of employees and the implementation of Lean PD are comparable to those for the revenues. Almost all correlation coefficients show the same positive tendency. In general, however, the links found are less significant for the number of employees than for the revenues. Hence, hypothesis 4b can be weakly corroborated.

Testing of Hypothesis 4c

Hypothesis 4c cannot be confirmed based on the empirical findings. In Table 8.6 it was shown that there are significant differences between the use of the Lean PD components among the different industry sectors. For example, automotive companies employ Product Variety Management and Simultaneous Engineering to a larger degree than those from other sectors. By and large, as can be seen from the sign of the correlation coefficients, automotive companies make more use of Lean PD components while companies from industrial equipment show a relatively weak level of implementation. Regarding the ranks of implementation, perceived ease and usefulness there are only few significant correlations with the affiliation of a company to an industry sector. Nevertheless, all in all, hypothesis 4c needs to be refuted.

Discussion

The fact that hypotheses 4a and 4b can be confirmed allow for two possible interpretations. On the one hand, this might be an indicator that the better endowment of a company with financial and human resources has a positive impact on the implementation of a Lean PD system. It seems plausible that companies with higher revenues and more employees can dedicate more resources to the implementation process. On the other hand, however, the results to some part may simply be due to the fact that in smaller companies there is simply a smaller need for a complex and sophisticated PD system. As first evidence for this assumption, the correlations between revenue or number of employees and the perceived usefulness of implementing the components are positive for almost all Lean PD components.

Potential explanations for the result that the implementation of Lean PD components differs among different industries have already been provided in Section 8.2.3. First, it can be argued that the automotive sector shows a higher use of Lean PD components because of a higher experience with Lean in general. The methodology of Lean Thinking has its roots in this industry and its application to sectors such as Industrial Equipment is relatively new. Second, it may be the case that in fact Lean PD components in some industries are not as beneficial as in others. Considering that among the automotive sector and the industrial equipment sector there are no significant differences for the perceived usefulness of the components, however, the first interpretation appears to be more likely. It shows that the use of a Lean PD system is not limited to the automotive sector. Instead, the Lean PD components might in fact be applicable to a wide range of different industries.

9.5 Implications of the Survey Data Analyses for Hypothesis 5

The last of the five hypotheses listed in Section 5.2 deals with the impact of supporting tools and infrastructure on the implementation of a Lean PD system. It was hypothesized that defining goals for the implementation (hypothesis 5a), defining a person responsible for the process of implementation (hypothesis 5b), using external help, such as consultants or sensei (hypothesis 5c), and conducting value stream mapping (hypothesis 5d) will increase the probability of success of implementing the Lean PD components. Since the influence of the single supporting measures was already pointed out in Section 8.2.4, the following paragraphs only briefly summarize the findings before discussing their implications in more detail.

Testing of Hypothesis 5a

The results of the t-test on the influence of defining goals for the implementation process were shown in Table 8.10. It was found that the definition of goals is positively correlated with the use of most of the Lean PD components. A significant impact on the time of implementation, perceived ease of implementation and perceived usefulness, however, could be observed for only few components. Overall, therefore, hypothesis 5a can be weakly confirmed.

Testing of Hypothesis 5b

Regarding the definition of a responsible person, the t-test of Section 8.2.4 yielded very few significant results. In fact, only the component of Responsibility-based Planning and Control was found to be significantly more used when a responsible person had been defined for the implementation process. Hence, based on the data hypothesis 5b cannot be confirmed.

Testing of Hypothesis 5c

The use of external help, as illustrated in Table 8.12, was not found to not have any significantly positive effect on the use of the eleven Lean PD components. On the contrary, mean differences between the group drawing on external help and the group not drawing on external help were predominantly negative. This indicates that companies making use of external help tend to be those with a low implementation level of Lean PD. Therefore, the data does not support hypothesis 5c.

Testing of Hypothesis 5d

Table 8.13 summarized the results of the t-test on the influence of value stream mapping on the implementation of the eleven Lean PD components. Similar to the use of external help, almost no significant differences between companies making use of value stream mapping and those which are not using the component could be identified. The component of Simultaneous Engineering was even significantly less used in the group of companies that used value stream mapping. As a result, hypothesis 5d is not supported by the data either.

Discussion

The finding that of the supporting measures tested only the definition of goals is linked to a higher use of the Lean PD components in a measurable way is remarkable and calls for some further discussion.

In the literature, defining goals has often been mentioned as an important first step for changing organizational structures in general and achieving a Lean Enterprise in particular. Henderson lists a "strategic vision of what the organization is moving toward and will become" as well as "aggressive Lean Enterprise performance targets and tracking" as two of five key factors of Lean Enterprise success [Hende 03] p.234. Morgan and Liker state that one of the main tasks of leaders to support the process of implementing Lean PD is to "create common objectives and reward the right behaviors" [Morga 06] p.346. Hence, it is not surprising that a positive relationship between the definition of goals for the implementation process and the maturity level of the companies was found. As already mentioned in Section 8.2.4, this finding, however does not necessarily imply that defining goals has a positive effect on the implementation of Lean PD. Instead, it could also be the case that some companies can draw on a larger amount of resources for the process of implementation. These slack resources may then enable the companies to both better implement the components and simultaneously define goals without the first being a direct effect of the latter.

Defining a responsible person for the implementation process is also a frequently reported supporting measure in the literature on organizational transformation and Lean. In their book Lean Thinking, Womack and Jones use the word "internal change agent" to describe the role of a person who drives the change process towards a Lean Enterprise [Womac 03]. Morgan and Liker take on this definition and, akin to Womack and Jones, recommend to declare and develop such a person as the first step of the change process [Morga 06] p.335. Considering their statement that "it is important that someone in the organization truly own this effort", it is striking that for the companies surveyed no comprehensive positive effect of this measure on the implementation of Lean PD could be observed. This raises the question whether making use of an internal change agent really does not contribute to the success of implementing Lean PD or whether the impact is covered by other factors overlaying the effect. In general, there are two broad possibilities for who leads the implementation of Lean PD. On the one hand, as proposed by Womack, Jones, Morgan and Liker, a distinct person can be identified who champions the implementation effort. On the other hand, the responsibility for implementing Lean could be distributed to a larger number of managers who integrate this task into their daily decision making. It seems plausible that having a single person who is very committed to the idea lead the process can be helpful. Nevertheless, it may also be argued that such a role, if not designed carefully, may lead to conflicts with those of the general managers and PD departments. The challenge of implementing Lean PD requires the commitment of all employees. A distinct internal change agent may be seen as an external force, increasing skepticism among the employees and managers and hindering a bottom-up implementation of the components. Hence, to fully understand the effect that declaring an internal change agent has during the process of implementing Lean PD, further research seems necessary.

Like internal change agents, the use of external help is commonly regarded as an important helping factor for implementing a Lean PD system. Liker states that "[i]f you want a lean organization, you need to get lean knowledge into your company, either by hiring experts with a minimum of five years' lean experience or by hiring outside experts as consultants" [Liker 04] p.306. Similarly, Garza points out that "[i]t is recommended that a sensei, 'coach' or 'mentor' in Japanese, aid in the process" of implementing Lean PD [Garza 05] p.91. As the refutal of hypothesis 5c showed, the importance of external help, however, is not supported by the empirical data gathered through the survey. It was found that particularly companies with a low maturity level in Lean PD make use of external help. This effect can be mainly attributed to the fact that among these companies there is larger need for help than for companies which have already achieved a higher level of implementation. Since a potential positive effect of external help is probably overlayed by this dominant relationship, it cannot be said whether using external help actually significantly contributes to a more successful implementation of the Lean PD components.

The finding that value stream mapping does not have any positive impact on the implementation of a Lean PD system is both surprising and important. In the literature on Lean PD, several authors, such as Morgan, Locher and Oppenheimer, put strong emphasis on value stream mapping as a tool to increase PD performance and even build their definition of Lean PD around it [Morgan 02], [Loche 08] pp.55ff, [Oppen 04] pp.359ff. The results of the analysis suggest that the current perception of the opportunities value stream mapping offers in PD is at least partly distorted and requires some adjustment. Indeed, value stream mapping is a powerful tool to document processes and identify waste, i.e. reduce the amount of unnecessary inputs in the graph depicted in Figure 3.2. In production, where the desired output is clearly defined beforehand and processes are largely linear, the reduction of waste is the dominant mechanism to increase performance [Liker 06] pp.33ff. In contrast to this, as was already pointed out in Section 3.2, rather than only combating waste, product development offers large potential for increasing value. A value-creating Lean PD system, however, cannot be achieved when the traditional system structure remains unchanged. Elimination of waste may be the first step to increase awareness of inefficiencies in current processes and generate short-term improvements. [Kenne 03] p.229 To tap the full potential of Lean PD, however, conducting value stream mapping seems not sufficient. Instead, it appears necessary to go beyond the reduction of non-value added activities, implement the value-enhancing eleven Lean PD components and thereby fundamentally change the structure of the system itself. Value stream mapping, as the refusal of hypothesis 5d showed, is not particularly well suited to support this process. In sum, value stream mapping can therefore be assumed to play a much less prominent role in Lean PD than it does in Lean Production.

10 Derivation of the Lean Innovation Roadmap

In the previous Chapter 9 the findings of the survey data analyses of Chapters 7 and 8 were discussed in the light of the hypothesis derived in Chapter 5. This chapter builds upon all previous chapters and combines the insights gained from the theoretical and empirical analyses in a single roadmap for the introduction of Lean PD. In Section 10.1 the methodology used for deriving the Lean Innovation Roadmap is presented. Section 10.2 provides a comprehensive description of the roadmap and its phases. Section 10.3 explains the differences between the Lean Innovation Roadmap derived in this thesis and alternative roadmaps for Lean PD described in literature. Finally, in Section 10.4 some limitations of the Lean Innovation Roadmap are pointed out.

10.1 Methodology of Deriving the Lean Innovation Roadmap

Chapter 9 tested five major hypotheses on the implementation of a Lean PD system and discussed which conclusions can be drawn from the fact that particular hypotheses are confirmed or refuted. The comprehensive analysis yielded a number of important insights on the factors which influence the process of implementation. These insights serve as a basis for a systematic derivation of a Lean Innovation Roadmap which is subsequently described. First, in Section 10.1.1 four explicit requirements for the Lean Innovation Roadmap are formulated. Then, in Section 10.1.2 the actual process of deriving the Lean Innovation Roadmap is detailed.

10.1.1 Definition of Requirements

The first and very important finding of Chapter 9 was that the components of a Lean PD system are highly interwoven and should therefore not be implemented independently but concurrently. It was pointed out that the four characteristics describing each of the eleven components are not equally used but show different maturity levels even for the same component. As a result of this, when deriving the roadmap it seems insufficient to only map the eleven lean PD components. Instead, the roadmap should explicitly detail the time of implementation for each of the 44 characteristics, leading to a much more precise representation of the implementation process. Two first requirements for the roadmap can be phrased:

Requirement 1: The roadmap should show the time of implementation for each of the 44 characteristics which detail the eleven Lean PD components.

Requirement 2: To reflect reality, the implementation of the eleven Lean PD components as shown in the roadmap must be overlapping and concurrent instead of strictly subsequent.

Section 9.2 showed that among the eleven Lean PD components, there are so-called lower-level components which are generally perceived as easier to implement, implemented early and used to a high degree. Other components, labeled as higher-level components, are perceived as harder to implement, implemented comparatively late and used to a much smaller degree. In Section 9.3 it was demonstrated that, particularly for the components of Process Standardization and Set-based Engineering, the classification as lower-level and higher-level components has important implications for the degree to which they serve as prerequisites for other components. While Process Standardization is likely to facilitate the implementation of several other components, Set-based Engineering was found to be easier to implement with other components in place. It can be assumed that ignoring the different nature of the Lean PD components leads to a less efficient process of implementation. In sum, therefore, two further requirements for the roadmap can be formulated:

Requirement 3: The order in which the components are shown in the roadmap should consider their classification as lower-level and higher-level components.

Requirement 4: The order in which the components are shown in the roadmap should consider to what extent the single components facilitate the implementation of others.

10.1.2 Derivation of the Roadmap

In order to generate a roadmap fulfilling all of the four requirements two alternative approaches were followed: Design Structure Matrix (DSM) and Adjusted Past Implementation (API).

Design Structure Matrix (DSM)

The Design Structure Matrix is a tool which allows to analyze and design complex systems based on a structured representation of the relationships between its elements. Similar to the cause-effect matrix displayed in Table 5.2, a DSM is a square matrix spanned by an arbitrary number of system components. As its elements it contains information on how the components are linked. Using specific algorithms, the relations between the system elements can then be analyzed and used to derive insights on the system as a whole. Due to its general nature, in the past DSM has been applied in a variety of different fields. It can be equally employed to examine relations between physical components of a product, investigate the structure of teams and manage the flow of information between separate units. [Brown 01] pp.292ff

One of the possible applications of DSM explicitly mentioned in literature is the sequencing and scheduling of activities. As suggested by Browning and Eppinger, information such as the strength of dependencies between tasks or the volume of information exchanged between different units can be used to build a DSM. From the DSM, it can be seen whether the dependencies between the activities are one-directional, bi-directional or whether the tasks are fully independent. Then, trough triangulation and clustering algorithms, the sequence of activities is re-arranged so that iterations in the process are minimized. [Brown 02] pp.428ff

Considering that the main challenge for deriving the Lean Innovation Roadmap in fact is to determine the ideal sequence of introduction for the components and characteristics, DSM was considered to be an appropriate method to develop the Lean Innovation Roadmap. Particularly since the system had already been divided into clearly distinguishable elements and empirical data on the dependencies between the elements were available, DSM suggested itself as a means. To meet requirement no. 1 stated in the previous section, it was decided to make use of the 44 Lean PD characteristics to build the DSM. The correlation coefficients described in Table B.1 to Table B.4 in Appendix B lent themselves as elements of the DSM matrix, representing the dependencies between the characteristics.

A considerable number of software tools are available which aid the process of building the DSM and run the analyses on its elements. For the derivation of the Lean Innovation Roadmap, a MATLAB macro developed by Thebeau was considered to be the ideal choice [Thebe 01]. In contrast to most of the other DSM tools, this software allows to describe the dependencies between system elements using numerical instead of only binary data. Considering the fact that the correlation coefficients fall into the first category, this was deemed an important requirement for the DSM software. The correlation coefficients were imported into the MATLAB file. In a next step, using the algorithm provided by the software, the characteristics were clustered into groups of highly correlated characteristics. Depending on the choice of parameters for the algorithm 6 to 16 clusters were built. According to the theory of DSM, the characteristics belonging to the same cluster ought to be implemented simultaneously, giving some first ideas on how to structure the process of implementation for a Lean PD system.

While DSM was found to be easy to apply, it turned out that the insights gained when using this method for the derivation of the Lean Innovation Roadmap were very limited. Two major problems when using DSM to derive the Lean Innovation Roadmap were experienced.

First, in order to generate good results, DSM requires a detailed, prior analysis of the system element dependencies. Ideally, cause-effect mechanisms between the elements are well understood so that the relationships can be displayed in the form of an asymmetric DSM, similar to the cause-effect matrix shown in Table 5.2. Furthermore, it is advantageous if the relationships can be represented in a binary form and relationships are, at least in parts, uni-directional. When using the correlation coefficients of Table B.1 to Table B.4 in Appendix B as a basis for the DSM, none of these premises is given. In fact, from the correlation analysis it remains unclear which of the two components that are correlated serves as a prerequisite for which. In case of Lean PD the use of almost every component is highly correlated with the use of the other components. DSM can theoretically handle complex and gradual relationships for which no direction can be identified. However, the results obtained in this case very much depend on the choice of parameters for the heuristics.

Another problem with using correlation data as a basis for DSM is that, due to the lack of cause-effect relationships between the components, no detailed conclusions on the sequence of implementation can be drawn. Using the DSM algorithm, one is able to cluster components which are highly interconnected and should be implemented at the same time. The order in which the identified clusters should be implemented, however, remains unclear. While for some cases, this weakness might be negligible, it is grave in case of the Lean Innovation Roadmap. As can be seen from Table B.1 to Table B.4, the characteristics show particularly strong correlations with the other characteristics of the same component (grey colored fields). Since the strength of the correlations is the measure based on which the characteristics are clustered, the DSM algorithm tends to assign the four characteristics of the same component to one cluster. Hence by trend, the results of DSM suggest implementing all four characteristics of one component at the same time while not giving any recommendations on the order in which the clusters should be implemented. The main question for the sequence of the Lean PD components even after conducting DSM therefore remains largely unanswered. Finally, the implicit outcome that the components can be implemented subsequently and independently is not in line with requirement no. 2.

Adjusted Past Implementation (API)

Because of the apparent weaknesses of the before mentioned approach, it was decided to not use the results generated through DSM for the Lean Innovation Roadmap. Instead a new, alternative methodology labeled Adjusted Past Implementation (API) was developed which will be described in the following paragraphs.

API follows a fundamentally different approach than DSM. While DSM tries to define the ideal order of implementing system elements by looking at their mutual dependencies, API takes an outside perspective and looks at a large number of past implementation processes to come up with a generalizable roadmap for implementation. In a two-step procedure, first a current state map is developed which displays how, on average, a system has been implemented in the past. In a second step, then the current state map is adjusted to account for difficulties which have been reported during the implementation processes. The result is a roadmap which shows the suggested path of implementation on a broad empirical basis but can be flexibly adapted to the conditions in a particular company.

In order to derive the current state map for the implementation of Lean PD, the data gathered in the survey is used. At the first glance, the data describing the rank of implementation for each of the eleven Lean PD components seemed to lend itself for the derivation of the current state map. However, firstly, this data was only available for the components and not for the 44 characteristics. Secondly, since coded in ranks, i.e. ordinal data, the time of implementation could not be displayed accurately on a metric scale. As an approximate for the time of implementation, therefore, the average use of the 44 characteristics, listed again in Table 10.1, was used. This was considered appropriate since an early implementation of a component goes along with a higher use (see correlation analysis B of Section 8.2.1). The original scale employed to describe the use of the characteristics (1 to 5) was converted into an inverse scale (4 to 0) by subtracting all ratings for the use of the characteristics from 5. As an example, the rating of 4.09 for characteristic no. 1 (standard milestones define a sequence in which the development tasks are conducted) was transformed into a rating of 5 – 4.09 = 0.91 on the inverse scale. The original rating of characteristic no. 2, 3.81, is equivalent to an inverse rating of 1.19.

Table 10.1: Numbered Lean PD characteristics

Component		Characteristic	
11.	Process Standardization	1.	Standard milestones define a sequence in which the development tasks are conducted
		2.	Standardized tools are used for project planning and control
		3.	Standardized tools and procedures are used for design tasks
		4.	Standardized documents are used for capturing knowledge and lessons learned
10.	Simultaneous Engineering	5.	Representatives from manufacturing, quality assurance and purchasing are integrated in the concept definition phase
		6.	There are frequent review meetings with development, manufacturing, quality assurance and purchasing
		7.	There is a formalized process for evaluating design proposals regarding manufacturing and assembly compatibility
		8.	Development and testing of production facilities is done in parallel to product development
9.	Strong Project Manager	9.	Project manager leads the product development project from concept to market
		10.	Project manager defines the product concept and advocates the customer value
		11.	Project manager sets the project timeframe and controls the adherence to it
		12.	Project manager chooses the technology and makes major component choices
8.	Workload Leveling	13.	Product development resources are planned on a cross-project basis
		14.	Development activities are scheduled and prioritized
		15.	Actual and planned capacity utilization are compared frequently
		16.	Resources are flexibly adapted in case of occurring bottlenecks
7.	Specialist Career Path	17.	There is a designated career path for technical specialists in their functional areas
		18.	Promotion is based on functional experience and knowledge
		19.	More experienced employees are responsible for mentoring and supporting junior engineers
		20.	Performance of individuals is regularly evaluated and discussed in feedback meetings
6.	Product Variety Management	21.	There are clear goals for the use of off-the-shelf components within a product
		22.	There are clear goals for the reuse of product parts among different modules, products and product families
		23.	There are modular components with standardized interfaces
		24.	There are common product platforms encompassing several product lines
5.	Supplier Integration	25.	Parts are evaluated according to their criticality before making outsourcing decisions
		26.	A small number of high-capability suppliers are used for critical parts
		27.	Critical suppliers are integrated in the concept definition phase
		28.	Suppliers are mentored to improve their performance
4.	Rapid Prototyping, Simulation and Testing	29.	Designs are quickly modeled and tested using physical models
		30.	Computer-aided modeling and simulation are used
		31.	Rapid prototyping technology is used
		32.	Methods of Lean Production are used in prototype build and tool manufacturing

Component		Characteristic	
3.	Responsibility-based Planning and Control	33.	Developers are given the opportunity to set their own goals and negotiate deadlines for their tasks
		34.	Developers are given the opportunity to check their own performance based on a formalized feedback process
		35.	Developers are evaluated based on their performance
		36.	Developers are given the opportunity to experiment with new approaches to improve efficiency
2.	Set-based Engineering	37.	A large number of possible solutions for a product module are considered early in the process
		38.	Alternative solutions for a product module are designed and tested simultaneously
		39.	Decisions are delayed in favor of a particular solution until objective data are available
		40.	A concept for a product module is not revised once it has been selected
1.	Cross-project Knowledge Transfer	41.	There are methods and devices to collect information on successful procedures, tools and designs across projects
		42.	Best practices and lessons learned from previous projects are reviewed
		43.	Documented knowledge is continuously updated by the engineers
		44.	The collected knowledge is frequently simplified and generalized

Using the inverse ratings for the use and the affiliation with the eleven Lean PD components as variables, the characteristics were plotted in a two-dimensional space as shown in Figure 10.1. The numbers on the y-axis code the eleven Lean PD components as numbered in Table 10.1. The numbers shown in the arrows correspond to the 44 characteristics listed in Table 10.1. Assumed that the inverse use of the characteristics is a reasonable approximate for their time of implementation, the graph shows the current state map as derived from the survey data. Each of the arrows represents an implementation stream of one of the eleven Lean PD components.

It is noteworthy that, even though Figure 10.1 does not yet show the final Lean Innovation Roadmap, it already fulfils most of the requirements defined in Section 10.1.1. The current state map details the order of implementation for all of the 44 Lean PD characteristics, showing an implementation process with overlapping and concurrent phases. In addition, the components of Process Standardization (component no.11), Set-based Engineering (no.2) and Cross-project Knowledge Transfer (no.1) which have been identified as lower-level and higher-level components are positioned as expected. The only requirement which is not fully met is requirement no.4. Cross-project Knowledge Transfer, for example, as discussed in Section 9.3, was found to facilitate the implementation of several other components. Therefore, its very late implementation as suggested by the current state map seems not ideal. To account for this, in the second step of API the position of the implementation streams for the components is adjusted to generate the final Lean Innovation Roadmap.

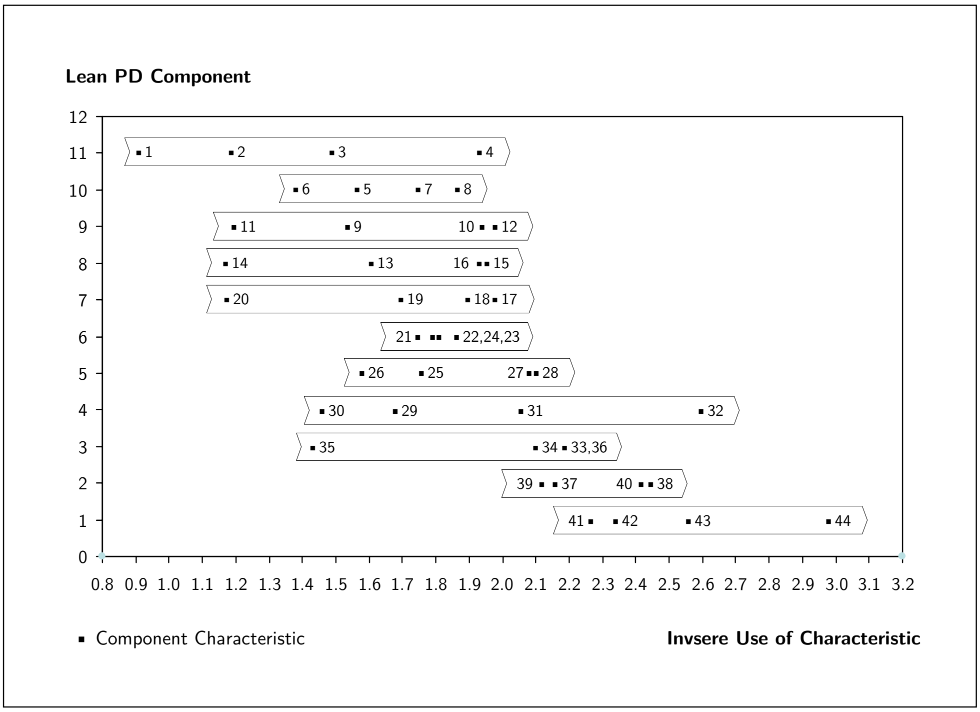


Figure 10.1: Current state map of the Lean PD Characteristics

The second step of API is based on the notion that, while the current state map shows the average implementation path taken by a large number companies in the past, this does not necessarily imply that this path is the ideal way of implementing Lean PD. In fact, it can be assumed that decisions to implement the components in practice are often taken independently without considering the impact on the system as a whole. The full range of interdependencies between the components, in many cases, is likely to be unknown.

To derive a roadmap which fully reflects the fact that some components serve as prerequisite for others, the findings shown in Table 8.4 are taken as a basis. For each of the eleven Lean PD components, the table displays how its use is correlated with the perceived ease of implementing other components. It seems reasonable to assume that, generally speaking, components which have a positive impact on the perceived ease of implementing others should be introduced rather early whereas those which do not facilitate the introduction of other components should be implemented rather late. To get an idea of the role each of the component plays with regard to the implementation of others, the average correlation coefficient can be calculated for every of the rows in Table 8.4. These average values are listed in Table 10.2. A positive value indicates that on average the component facilitates the implementation of other components, i.e. serves as a prerequisite. A negative value, in contrast, shows that the component, by trend, should be implemented rather late.

Table 10.2: Correction factors for the Lean PD implementation streams

Component		Correction Factor (CF)
11.	Process Standardization	0.053
10.	Simultaneous Engineering	0.018
9.	Strong Project Manager	-0.086
8.	Workload Leveling	0.051
7.	Specialist Career Path	-0.034
6.	Product Variety Management	0.027
5.	Supplier Integration	0.035
4.	Rapid Prototyping, Simulation and Testing	-0.009
3.	Responsibility-based Planning and Control	0.088
2.	Set-based Engineering	-0.017
1.	Cross-project Knowledge Transfer	0.088

The so-called correction factors (CF) listed in Table 10.2 can be used to adapt the current state map so that the map not only shows the average past process of implementation but reflects the most efficient way of introducing the components. For this purpose, the implementation streams shown in Figure 10.1 can simply be shifted relative to each other as suggested by the factors. The positive factor of Process Standardization (component no.11), for example, indicates that its implementation stream should be shifted further to the left. The implementation stream of the Strong Project Manager, in contrast, should be moved to the right.

The correction factors give an idea about the direction to which the single streams should be shifted. Since the factors are average correlation coefficients, which, by definition, are dimensionless, the absolute amount by which the implementation streams should be shifted, however, remains unclear. Mathematically, this can be stated as

$$POS_{new,i} = POS_{old,i} - x \cdot CF_i \qquad (10.1)$$

where $POS_{new,i}$ is the adjusted position of the implementation stream of component i, $POS_{old,i}$ is the position of the implementation stream of component i as shown in the current state map, CF_i is the correction factor of component i (see Table 10.2) and x is an unknown correction coefficient. The positions $POS_{new,i}$ and $POS_{old,i}$ are expressed as the average inverse use of the characteristics of a component.

In order to determine the optimal correlation coefficient x, one can make use of the same logic that has already been discussed in the context of DSM. The main assumption of DSM was that components which are highly dependent should not be implemented subsequently but at the same time. The choice of x directly influences the position of the implementation streams for the components relative to each other. For very large values of x components which are highly correlated in their use are shifted apart from each other, thereby negatively influencing the efficiency of implementation. The goal when trying to identify the ideal roadmap of implementation therefore is to minimize the difference in time of implementation between highly interdependent components. When using the correlation of use between the components (see Table 8.3) as the measure for the interdependency, for two components i and j this implies that the relation

$$\frac{\left|POS_{new,i} - POS_{new,j}\right|}{COR_{i,j}} \tag{10.2}$$

needs to be minimized. In this formula, $COR_{i,j}$ is the correlation coefficient between the use of component i and j. To achieve the ideal roadmap for the system as a whole, one can formulate the goal as

$$\min\ \Delta = \sum_{i=1}^{11}\sum_{j=1}^{11}\frac{\left|POS_{new,i} - POS_{new,j}\right|}{COR_{i,j}} \tag{10.3}$$

or, substituting POS_{new} with equation (10.1), as

$$\min\ \Delta = \sum_{i=1}^{11}\sum_{j=1}^{11}\frac{\left|POS_{old,i} - POS_{old,j} - x\cdot\left(CF_i - CF_j\right)\right|}{COR_{i,j}} \tag{10.4}$$

In this formula all variables except for x are known so that the optimization criterion Δ can be plotted against different values for x as shown in Figure 10.2. It shows that up to a value of $x = 1.3$ shifting the implementation streams leads to a decrease in Δ. This implies that in fact, when moving the implementation streams in the direction indicated by the sign of the correction factors, a positive effect on the optimization criterion Δ can be achieved. When choosing a correction factor x larger than 1.3, however, Δ rises again. Hence, a value of $x = 1.3$ for the correction factor was found to be the optimal choice to derive the Lean Innovation Roadmap. All of the correction factors shown in Table 10.2 were therefore multiplied by 1.3. Then, each of the eleven implementation streams of Figure 10.1 was shifted by the component-specific factor. The final result, the Lean Innovation Roadmap, will be shown and described in detail in the next section.

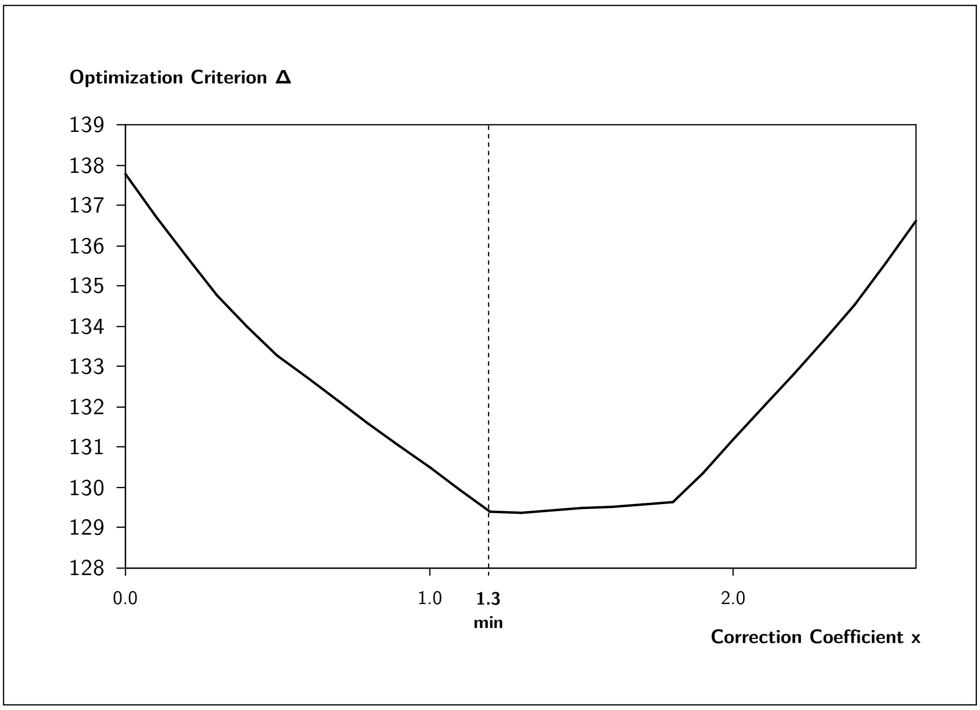


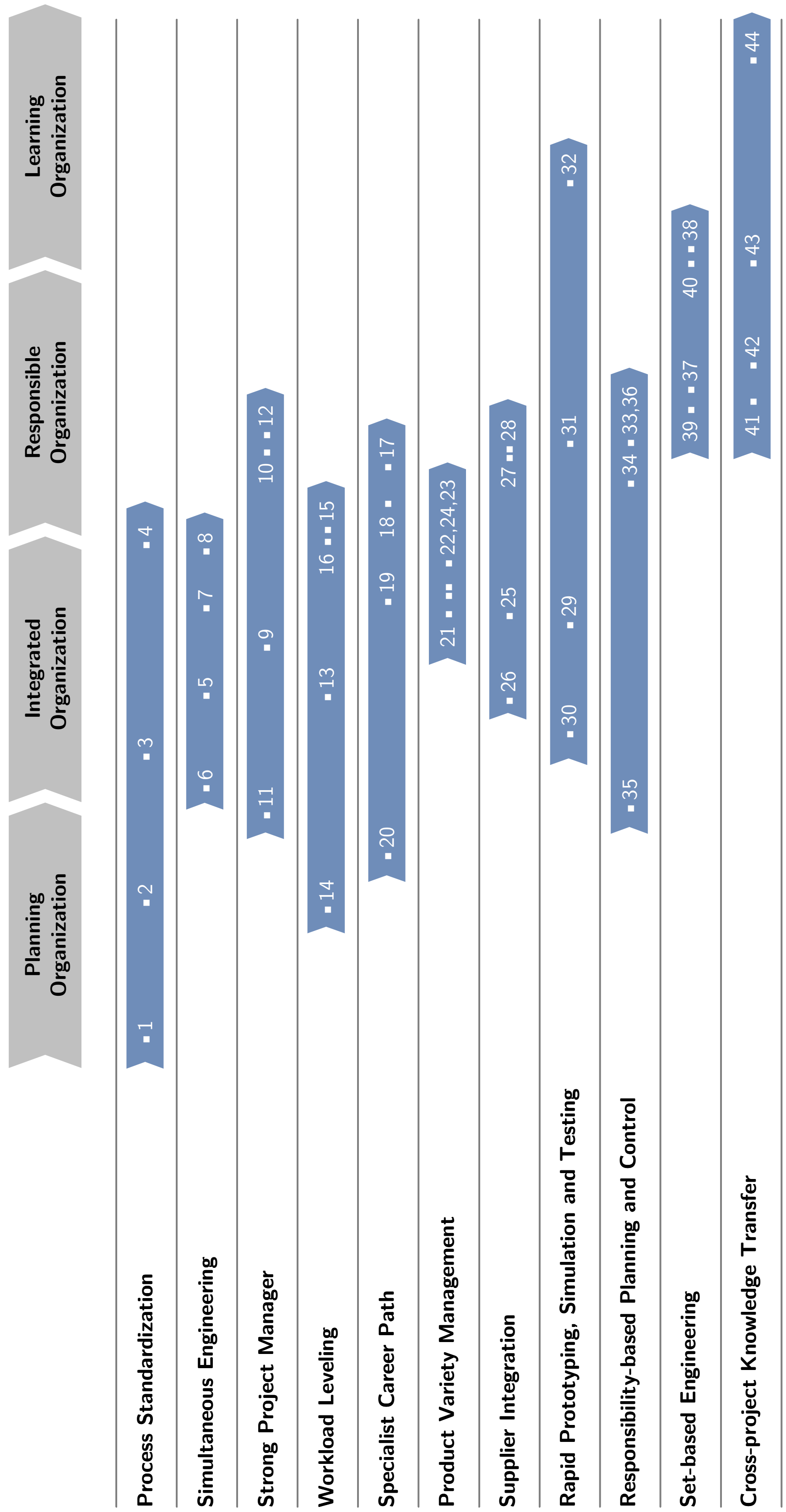
Figure 10.2: Plot of optimization criterion Δ against correction coefficient x

10.2 Description of the Lean Innovation Roadmap

Figure 10.3 shows the final outcome of the Adjusted Past Implementation (API) procedure described in the previous section: the Lean Innovation Roadmap. Like the current state map of Figure 10.1, the roadmap shows eleven implementation streams for the eleven Lean PD components which, as numbers, contain the 44 characteristics as listed in Table 10.1. Compared to the current state map, the implementation streams of the components have been shifted. For the sake of readability, the y-axis has been replaced by the names of the eleven Lean PD components. Furthermore, the process of implementation has been divided into four major phases which are shown at the top of the roadmap.

Before describing in detail which parts of a Lean PD system ought to be implemented in each of the four phases, some general observations on the Lean Innovation Roadmap shall be made. First, it is important to note again that according to the roadmap and in line with the requirements stated in Section 10.1.1, the eleven Lean PD components are implemented in concurrent and overlapping implementation streams. Interestingly, these streams differ quite considerably with regard to their length. While the implementation of Process Standardization and Rapid Prototyping, Simulation and Testing, for example, spans several of the four major implementation phases, all four characteristics of Product Variety Management are introduced within a comparatively short time.

Figure 10.3: Lean Innovation Roadmap



The fact that for some of the components there are relatively large gaps between the implementation of their single characteristics displays that even for a common domain it cannot be assumed that parts of Lean PD are equally easy to implement and should be implemented at once. Instead, the Lean Innovation Roadmap as presented in Figure 10.3 reflects the finding of this thesis that most parts of a Lean PD system only make sense in an environment that supports their use. It is therefore not surprising that the implementation of certain Lean PD characteristics is delayed until parts of other components have been introduced.

To avoid misinterpretations, finally, one remark shall be made on how to read the Lean Innovation Roadmap. Although for reasons of illustration, the arrows showing the implementation streams for the Lean PD components have a clear beginning and end, this should not imply that at the end of the arrow, the implementation of the component has to be completed. Rather, the numbered points represent the starting points for implementing the respective characteristic. The speed of implementation highly depends on the resources dedicated to the process, the size of the organization and the number of components already in place. In contrast to common practice in literature, it was therefore decided to intentionally forego on attaching a time scale to the roadmap. Furthermore, the roadmap focuses on describing the implementation of the actual Lean PD components. Supporting measures and general change management practices, which have been discussed in Sections 7.2.2, 8.2.4 and 9.5, are not included in the Lean Innovation Roadmap. In this sense, the roadmap is no substitute for a more detailed implementation plan to be developed on a company basis. It can just serve as a guideline regarding which components to implement in which order and help to better understand the complex interdependencies to be considered.

In the following sections, the four major phases of the Lean Innovation Roadmap – planning organization, integrated organization, responsible organization and learning organization – are described in more detail. It shall be pointed out which parts of a Lean PD system are introduced in each of the phases and how the phases contribute to the overall goal of achieving a Lean PD system. The focus of the following sections is on explaining the order of implementing the pieces of a Lean PD system. For a comprehensive description of the components and their background, the interested reader is referred to Chapter 4.

10.2.1 Planning Organization

Although the activities of the first phase of the Lean Innovation Roadmap belong to implementation streams of different Lean PD components, they follow a common purpose: to create the infrastructure for a planning PD organization. Several authors in the literature have argued that before starting to implement more sophisticated pieces of a Lean PD system, it is necessary to establish measures that ensure the stability of the system. In line with this notion, the Lean Innovation Roadmap, as derived from the empirical survey data, suggests to first build the necessary capabilities for planning and scheduling product development projects.

According to the roadmap, in a first step, standard milestones should be defined which define a sequence in which the development tasks of a company are conducted (no.1). Development activities should be clearly scheduled and prioritized (no.14). For this purpose, tools should be implemented which allow to plan and control PD projects in a standardized way (no.2).

While at first, the planning of PD projects may be done by designated planers, it is important that this task be delegated to the project managers at the end of phase one. The project manager should set the project timeframe and control the adherence to it (no.11). Furthermore, the performance of the development engineers should be regularly evaluated and discussed in feedback meetings (no.20 and 35).

10.2.2 Integrated Organization

With the development of a planning organization, the foundation for a structured and well-coordinated execution of PD projects has been laid. As soon as the organization has built the according infrastructure, the next stage of implementing Lean PD can be tackled: the integrated organization.

While the first phase was concerned with providing an outer framework for the PD system, the second phase turns inwards and aims to implement measures which support the actual design process. On the one hand, this includes fostering internal design capabilities by the use of information technology and product optimization. On the other hand, important internal stakeholders, such as manufacturing and quality assurance, are integrated into the design process to ensure that the goals within the organization are well aligned.

In order to achieve the first goal of enhancing internal design capabilities, first of all standardized tools and procedures for design tasks should be developed (no.3). As an important part of this, a company should implement infrastructure for computer-aided modeling and simulation (no.30) as well as standardized routines for quick physical modeling (no.29). Furthermore, products should be optimized to reduce variety in both engineering, manufacturing and service processes. For this purpose, clear goals for the use of off-the-shelf components within a product (no.21) and the reuse of product parts among different modules, products and product families need to be defined (no.22). It should be investigated whether components can be broken down into modular components with standardized interfaces (no.24). In addition, it should be considered to introduce common product platforms which encompass several product lines and may contribute to cost savings in the longer term (no.23).

The second focus of phase two of the Lean Innovation Roadmap is to integrate the internal stakeholders. Towards this end, first of all, frequent review meetings with development, manufacturing, quality assurance and purchasing should be established (no.6). Representatives from these functions should be integrated into the concept definition phase (no.5) and play an important role in evaluating the design proposals regarding manufacturing and assembly compatibility (no.7). The coordination of the different functions should be done by the strong project manager who leads the product development project from concept to market (no.9). The product development resources ought to be planned on a cross-project basis (no.13) and flexibly adapted in case of occurring bottlenecks (no.16). Eventually, development and testing of production facilities should be done in parallel with product development (no.8).

Besides its focus on design capabilities and the integration of internal stakeholders, the second phase of the Lean Innovation Roadmap contains some activities which serve as a preparation for the third stage of the roadmap, the responsible organization. For critical parts of a product, a small number of high-capability suppliers should be used (no.26). In general, parts should be evaluated according to their criticality before making outsourcing decisions (no.25). Also, a mentoring system should be established to ensure that junior engineers are supported by more experienced employees (no.19). As a first step towards an organization-wide knowledge management, standardized documents should be developed which are suited to support the capturing of best practices and lessons learned (no.4).

10.2.3 Responsible Organization

The activities of the stage "integrated organization" ensure that a company possesses the necessary capabilities for the design process and the claims of all relevant internal stakeholders are recognized. The third phase of the Lean Innovation Roadmap goes beyond a mere integration of stakeholders and intends to establish a particular sense of ownership among all participants and extend the focus of Lean PD by bringing suppliers into the PD process.

As a basis for a PD system which rewards responsibility and personal commitment, promotions of engineers should be based on functional experience and knowledge (no.18). Designated career paths should be introduced which allow specialists to climb the career ladder in their particular functional areas without losing their technical focus (no.17). At the same time, the project manager, besides only being responsible for administrative tasks, should be directly involved in defining the product concept and advocating the customer value (no.10). As the one who, ultimately, is the one responsible for the product, he chooses the technology and makes major component choices (no.12). Developers are given the opportunity to check their own performance based on a formalized feedback process (no.34). They set their own goals, negotiate deadlines for their tasks (no.33) and are given the opportunity to experiment with new approaches to improve efficiency (no.36). In line with the increased sense of accountability within the organization, critical suppliers are integrated early in the product development process and involved when deriving the product concept (no.27). As important contributors to the value generated by the company, they are mentored in the same way as junior engineers by their superiors (no.28).

The augmented accountability of all participants in the product development project, which is the focus of the phase "responsible organization", leads to a situation where individual performance and suggestions for improvements are recognized and rewarded. The resulting innovative potential enables the organization to explore a larger number of ideas and conserve the generated knowledge for reuse. Product solutions should be intensively tested using rapid prototyping technology (no.31). Decisions ought to be delayed in favor of a particular solution until objective data are available (no.39). Instead of deciding for a particular solution at an early stage, a large number of possible solutions should be considered (no.37). This, in turn, drastically increases the amount of knowledge created. Therefore, it is important to implement designated methods and devices which serve to collect the information on successful procedures, tools and designs across projects (no.41). The best practices and lessons learned should be reviewed and reused in subsequent projects (no.42).

10.2.4 Learning Organization

After successfully implementing all pieces of a Lean PD system described in the previous sections, the organization can finally tackle the last of the four phases of the Lean Innovation Roadmap to become a truly learning organization.

In Sections 9.1 and 9.2 it was already pointed out that Cross-project Knowledge Transfer, i.e. the continuous improvement of a company's knowledge base by capturing, reusing and updating knowledge is likely to be one of the key components of a Lean PD system. In fact, while the previous phases laid important foundations for a successful execution of PD projects, the fourth phase of the Lean Innovation Roadmap is concerned with instruments aiming to maximize organizational learning. Making strong use of Set-based Engineering, alternative solutions for a product module are designed and tested simultaneously (no.38), subsequently narrowed in and not revised once a particular concept has been selected (no.40). To quickly generate and test products, methods of Lean Production are used in prototype build and tool manufacturing (no.32). Most importantly, the large amount of information generated is used to continuously update the existing knowledge base (no.43). This knowledge is then frequently abstracted and simplified to yield generalizable conclusions on how to improve the company's products and processes (no.44).

A company which manages to implement the parts of the last stage, the learning organization, will find itself in the position to continuously boost the value it creates with its products. Only when critically pondering past performance, drawing on previous experience and deriving general implications from phenomena observed during the projects, an organization can improve its products on a long-term basis. It is very likely, that with the right instruments in place, learning and innovation can become systematic and steady elements of a company's processes instead of incidental, unpredictable events. However, it should be noted again that the way to a truly learning organization is long and cannot be cut short easily. Stable processes, the integration of all relevant stakeholders and a distinct responsibility of all participants for their work are prerequisites to long-term organizational learning. In this sense, the stages of a planning organization, an integrated organization and a responsible organization are more than phases that describe the implementation of disconnected tools. They are important interstations on the roadmap towards a lean and continuously learning product development organization.

The discussion of the fourth stage, learning organization, concludes the description of the Lean Innovation Roadmap. In the following section, differences between the roadmap derived in this thesis and existing roadmaps in literature shall be pointed out.

10.3 Differences to Existing Roadmaps on Lean PD

The previous sections described the derivation of the Lean Innovation Roadmap and provided a detailed explanation of its four major phases. In the following paragraphs it shall be detailed how the Lean Innovation Roadmap differs from roadmaps for Lean PD suggested in literature. Towards this end, the existing approaches to roadmaps discussed in Section 1.2 shall be taken on and compared with the Lean Innovation Roadmap as shown in Figure 10.3.

First, major differences between the Lean Innovation Roadmap and existing approaches can be observed with regard to the methodology used to derive the recommendations for implementation. As pointed out in Section 4.1, several authors have conducted empirical studies to identify the key components of a Lean PD system. So far, however, no study has been available which specifically aimed at examining the question of how to implement Lean PD in an organizational setting. Section 1.2 stated that existing approaches are all based on intuition or simply treated as additional information to a previous detailed description of the Lean PD elements. None of the existing roadmaps for Lean PD draws on broad empirical data to support the order of implementation it suggests.

In contrast to this, the Lean Innovation Roadmap has been systematically derived. It builds on a coherent theoretical framework of eleven Lean PD components and an in-depth investigation of their interdependencies. The structure of the roadmap is based on a comprehensive survey among 113 companies the data of which was used to test explicit hypotheses on the implementation process. The results from these analyses, in turn, served as a basis to formulate clear requirements to a roadmap for Lean PD which were translated into the final roadmap using two alternative methods: DSM and API (see Section 10.1).

Apart from the methodology used, the roadmap derived in this thesis strongly differs from alternative approaches with regard to its level of detail. It has already been pointed out that most of the roadmaps covered in literature remain rather superficial and do not cover the full range of Lean PD components described in literature. The roadmap suggested by Kennedy is largely limited to general aspects of change management such as the definition of goals and the set up of change teams [Kenne 03] p.235. Recommendations on the order of implementing the actual four components of a Lean PD system he covers remain very vague. Even Morgan and Liker's roadmap which is based on an exhaustive explanation of Lean PD practices at Toyota considers only few components of a Lean PD system. Surprisingly, although Morgan and Liker have been highly involved in investigating and advocating the principle of Set-based Engineering, this component is not mentioned in their roadmap [Morga 06] p.349. Compared to this, the Lean

Innovation Roadmap, showing the implementation path for eleven Lean PD components with their 44 characteristics, provides very detailed information on the single pieces which need to be implemented. Based on a comprehensive literature review, it covers a broad range of practices previously identified by researchers. At the same time, it forgoes on describing general change management methods which are not specific to Lean PD.

In general, none of the approaches in literature so far sufficiently takes into account the nature of the different parts of a Lean PD system and their interdependencies. Almost all of the existing roadmaps show the implementation process as a sequence of distinct, subsequent phases. Whereas Kennedy, Schuh et al. as well as Morgan and Liker propose structures with five phases, Ward suggests a roadmap consisting of 10 sequential steps. By doing so, the authors neglect one of the most important findings of this thesis, namely that all parts of a Lean PD system are highly interwoven and therefore require an overlapping and concurrent implementation. Furthermore, none of the authors explicitly investigates to what extent particular Lean PD components serve as prerequisites to others. Probably due to the lack of clear empirical data, it is not argued why certain components should be implemented earlier than others.

Morgan and Liker's roadmap is one of the few which has a level of detail allowing a direct comparison with the order of implementation suggested by the Lean Innovation Roadmap derived in this thesis. The path of implementation they suggest differs considerably from the one displayed in Figure 10.3. After an initial preparation phase, they propose to conduct value stream mapping, something which in this thesis has been shown to not measurably support the implementation of a Lean PD system (see Section 9.5). As a starting point for changing the organizational structure, they suggest introducing the role of a chief engineer. Measures aiming to stabilize the PD system such as tools for project planning or workload leveling, which are implemented in phase one of the Lean Innovation Roadmap, are not considered by Morgan and Liker. In addition, Morgan and Liker clearly separate between the implementation of a Lean organization and the introduction of supporting Lean tools and technology [Morga 06] p.349. In the Lean Innovation Roadmap, the tools and methods are introduced in parallel to organizational changes whenever they are needed to support a particular infrastructure. Similarly, unlike in Morgan and Liker's approach, integration of suppliers is not treated as a last, separate phase which requires all other components to be in place. Rather, in the Lean Innovation Roadmap, even though it is implemented rather late, Supplier Integration is seen as a process which is pursued in parallel to other efforts of implementing a Lean PD system.

10.4 Limitations of the Lean Innovation Roadmap

Although when deriving the Lean Innovation Roadmap great care was taken to follow a systematic approach and back decisions with empirical data, there are inherent limitations which should not remain unmentioned.

To begin with, it is important to note that the roadmap as displayed in Figure 10.3 is based on the current understanding of a Lean PD system as derived from literature. As has been pointed out in Section 6.2.1, it was explicitly not the goal of this thesis to identify formerly unknown best practices of Lean PD. Instead, the definition of Lean PD as used in this research draws on previous studies which identified success factors of Lean PD systems. While the definition of a Lean PD system consisting of eleven Lean PD components is supposed to represent a coherent summary of all previous approaches to Lean PD, it is not claimed that this definition is eternally valid. In fact, as can be seen from Table 4.1, the number of practices considered to be important parts of Lean PD has continuously risen in the past. Hence, it is likely – and desirable – that in the future continuous improvement of industry practices will lead to the emergence of new best practices which will have to be integrated into the definition of a Lean PD system.

Further limitations of the Lean Innovation Roadmap may be due to the empirical data which was used to derive its structure. The use of Lean PD components, as shown in Section 9.4, was found to differ according to both company size and industry sector. Hence, it cannot be fully excluded that the particular sample chosen led to a bias towards particular parts of a Lean PD system. Furthermore, bias in the answers due to individual perception, e.g. when asking for the difficulty of implementing a particular component, cannot be avoided.

Finally, it is noteworthy that, of course, the Lean Innovation Roadmap represents an average and ideal way of implementing a Lean PD system. To be generally applicable, the Lean Innovation Roadmap was built on a broad empirical basis. However, it should be recognized that it is impossible to consider all contingency factors influencing the process of implementation in a real-world setting. Different companies will show fundamentally differing starting points for their journey towards Lean PD. Moreover, the culture, organization and available resources for implementation of a company will have a major influence on how difficult particular components are perceived to implement. As a result, the Lean Innovation Roadmap should not be regarded as a ready implementation plan which has to be strictly followed by every company. Instead, it should serve as a guideline which helps a company to develop its own, detailed plan for implementing Lean PD and establishing a learning organization.

11 Conclusion and Future Work

After in the previous chapter, the Lean Innovation Roadmap was derived and described, this last chapter shall recapitulate the major findings of this thesis and point to possible areas of future work. Section 11.1 provides a brief summary of the research. Building on this, Section 11.2 explains how this work contributes to existing literature on Lean PD. Finally, in Section 11.3 ideas for future research projects resulting from this investigation are presented.

11.1 Summary of Research

This thesis aimed at examining the question how Lean principles can be successfully implemented in product development systems. Towards this end, building on a sound theoretical framework, explicit hypotheses on the introduction of Lean PD were derived, tested and ultimately translated into a comprehensive Lean Innovation Roadmap.

Following a systematic approach, at the beginning of this research the shortcomings of existing roadmaps dealing with the implementation of Lean PD were identified. Then, drawing on literature, the basics of Lean Thinking, product development as well as existing approaches to Lean PD were reviewed. Existing definitions of Lean PD were found to strongly vary. Therefore, a novel, coherent definition of a Lean PD system, consisting of eleven distinct Lean PD components, was derived. The components of this definition of Lean PD were elaborated on and investigated with regard to their interdependencies. The findings of this theoretical analysis served to derive five major hypotheses on the introduction of a Lean PD system.

To test the hypotheses, a comprehensive, international survey was conducted. The data from 113 product development departments gathered through the survey was analyzed using descriptive statistics to give an overview of the use of different Lean PD practices and measures supporting the process of implementation. Moreover, an exploratory analysis including correlation analyses, a content analysis and t-tests were conducted to better understand the nature of a Lean PD system. After explicitly corroborating or refuting the five hypotheses in the light of the results from the analyses, finally, the Lean Innovation Roadmap was derived. For this purpose, based on the hypothesis tests, four explicit requirements to be met by the roadmap were phrased. To derive the roadmap two alternative approaches were used. Since the use of Design Structure Matrix, an approach recommended in literature, did not yield satisfactory results, a new approach called Adjusted Past Implementation was introduced and applied to generate the Lean Innovation Roadmap.

11.2 Contributions

This thesis makes several important contributions to the research stream of Lean Product Development. The major findings and contributions of this work shall be discussed in the following paragraphs.

As a first important contribution this research proposes a novel, coherent definition of a Lean PD system. As was discussed in 4.1, existing approaches to Lean PD were found to differ considerably regarding their focus and were not composed of clearly distinguishable, tangible components. The definition of a Lean PD system consisting of eleven Lean PD components derived in this thesis is an attempt to combine all existing approaches in a single, exhaustive and clearly structured framework. Considering that the domain of Lean PD is still in its infancy, the definition of eleven Lean PD components may contribute to the discussion on what practices differentiate a Lean PD system from a traditional one.

As a second contribution, this thesis provides an overview of the current use of Lean PD in industry practice. While authors such as Schuh et al. and Brown have conducted surveys on the use of particular PD practices before, the empirical data gathered in this research is particularly interesting because it allows for a direct comparison of the different components of Lean PD. The fact that for each component use, rank of implementation, perceived difficulty of implementation and perceived usefulness were inquired, helps to draw a very detailed picture of Lean PD as currently applied in companies (see Section 7.2).

Beyond describing the status quo of Lean PD, this research strongly adds to a better understanding of Lean PD as a system. The interdependencies of the Lean PD components were analyzed both on a theoretical and empirical level. It was found that Lean PD can be regarded as a system of highly interwoven components which should not be implemented independently. Rather, implementing Lean PD requires a process of overlapping and concurrent phases which take into account this particular nature of a Lean PD system. Moreover, findings of this research point to a certain path dependency among the components. The eleven Lean PD components differ according to number of other components they presume. Some of the components, such as Process Standardization, have been found to serve as enablers for other components. They have been labeled as lower-level components and should be implemented rather early. Other components, such as Set-based Engineering, build on several of the other Lean PD components. As so-called higher-level components, they should be implemented rather late (see Sections 9.2 and 9.3).

Two observations made during the in-depth investigation of the Lean PD system are of particular interest as they stand in stark contrast to findings of previous studies on Lean PD. The first observation concerns the role of the Strong Project Manager. In the literature, the Strong Project Manager is frequently mentioned as a pivotal component of a Lean PD system which has strong ties to all system components. The findings of this research do not support this view. In fact, as the research described in this thesis shows, the Strong Project Manager is the only component of a Lean PD system the use of which is largely unrelated to that of almost all other components (see Sections 8.2.1 and 9.1). This finding is striking and may be taken on in future research.

Another finding which runs contrary to prevailing opinion uttered in literature is that, compared to the domain of Lean Production, value stream mapping can be assumed to play a very limited role in implementing Lean in a PD system. While it is not doubted that value stream mapping may be of help to identify wastes in processes, value stream mapping, as discussed in Sections 8.2.4 and 9.5, was not found to significantly contribute to the implementation of the eleven value-enhancing Lean PD components. This finding is of great importance because in the past a lot of effort has been put into adapting the method of value stream mapping to the field of product development. Several authors such as Oppenheim or Morgan and Liker recommend using value stream mapping as a starting point for the implementation process and even build their definition of Lean PD around it. The prominent role value stream mapping has been assigned by previous researchers is at least partly questioned by the findings of this research.

The main contribution and intended outcome of this thesis is the Lean Innovation Roadmap described in the previous Chapter 10. As pointed out in Sections 1.2 and 10.3, previous roadmaps for Lean PD system have been very vague, have not been based on broad empirical data and are often presented without a solid reasoning why a particular order of implementation was suggested to be the best. So far, the question of how to implement the components of a Lean PD system has mainly been treated as a supplementary note to a previous description of Lean PD practices. The research presented in this thesis represents the first scientific approach which explicitly investigates the implementation of a Lean PD system. The roadmap derived is based on both a comprehensive theoretical investigation of the Lean PD system and broad empirical data from international companies. Its structure has been derived taking into account the findings from in-depth analyses of system interdependencies. Since DSM as a method proved to be not helpful for deriving the roadmap, a new method called Adjusted Past Implementation (API) was developed. In the case of the Lean Innovation Roadmap, API as a methodology yielded results which were well in line with the requirements. Therefore, this new method might be of help when trying to solve similar problems in the future.

Although the goal of this research was not to evaluate the importance of particular Lean PD components, many of the findings of this research point to a role of Cross-project Knowledge Transfer as a key differentiating factor between a lean and a traditional PD system. In the past, much attention has been paid to the components of Simultaneous and Set-based Engineering. Both of these components are important parts of a Lean PD system. However, the research described in this thesis showed that, in fact, for Cross-project Knowledge Transfer there is the largest gap between the current and ideal degree to which it is used. On the one hand, this component strongly supports a number of other Lean PD components and thus appears to play a crucial role on the way to a learning organization. On the other hand, companies use this component the least, perceive its implementation as the most difficult and point to a lack of supporting tools. One of the core areas of future research might therefore lie in further exploring the process of information exchange between PD projects and developing ways to aid the necessary knowledge transfer.

11.3 Future Work

Concluding this thesis, some starting points for potential future work shall be pointed out. Two diametrically opposed directions for future research are identified which may further contribute to a better understanding of a Lean PD system and support companies in their efforts of implementation.

The first possible direction of future research lies in an extension of the research methodology presented in this thesis. As explained in Section 6.1, for this research it was decided to use a macro perspective and investigate the use of Lean PD based on a comprehensive, international survey. While the sample size of 113 allowed to draw generalizable conclusions on the process of implementing Lean PD, an even larger sample would naturally broaden the number of possible analyses which can be conducted. For example, it would be interesting to compare the use of Lean PD across countries and determine how cultural and local contingency factors influence the use of particular practices. Furthermore, a larger sample could help to extend the list of problems experienced by companies (see Section 8.2.2) and ultimately generate a ranked catalogue of inhibitors. Such a catalogue may be of great value when trying to develop supporting tools and measures for implementing Lean PD. As the answers given by the survey participants show, currently there is still a lack of supporting tools for several of the Lean PD components. The development of such tools can therefore be identified as an important goal for future research efforts.

A second way of extending the research described in this thesis is to shift the methodological approach from a macro investigation towards a procedure based on detailed case study investigations. Using case studies, it can be tested whether the findings of this research can be verified and examined in more depth for single companies. In addition, assuming a contingency perspective, it can be analyzed which particular factors induce companies to implement certain Lean PD components at a certain point in time. The higher level of detail that can be reached through case studies can serve as a basis to increase the depth of the Lean Innovation Roadmap. By adding more insights, the roadmap can be transformed into a Lean Innovation Manual. An important part of such a manual could be specific performance measures which enable a company to exactly measure its maturity level for a particular component. Furthermore, checklists could be developed which serve as clear guidelines during the implementation process and may be used to derive implementation goals.

When extending the Lean Innovation Roadmap it should be considered to complement the recommendations on the introduction of the actual Lean PD components by general advices on the use of change management practices. Some supporting measures described in literature have already been discussed with regard to their impact on the implementation of Lean PD in Sections 8.2.4 and 9.5. Nevertheless, many questions on how to structure the process of organizational change remain open: What is the most promising way of rolling out the implementation effort across the organization? Should a company make use of pilot projects? According to which criteria should the participants in such projects be selected? How can wide-spread buy-in of employees and management be reached? What is the right balance between top-down implementation and a bottom-up change initiative? All of these questions represent interesting research themes which might be addressed by future investigations.

As a final remark, it shall be emphasized that the interest of companies in a further exploration of Lean PD and its implementation is quite large. Of the 113 persons survey during this research, 54 explicitly stated that they were willing to take part in more detailed interviews on the implementation of Lean PD. Several of the survey participants unsolicitedly contacted the author of this thesis to express that the focus of this research was of particular relevance for their company. Many of them had already spent first thoughts on how to implement Lean in a product development setting and were glad to be given a possibility to exchange their ideas. This strong interest on the side of practitioners offers large potential for further investigations and may open up interesting opportunities for collaboration between research and industry in the future.

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Appendix A: Survey on the Introduction of Lean PD

[6%]

Lean Product Development and Lean Innovation are approaches to leverage the successful concept of Lean Thinking in the field of product development. The question of how development processes in corporate enterprises can be designed in a lean and efficient way is attracting increased attention in research. A number of components have been identified that are characteristic of a lean product development system.

This survey is part of a collaboration between the Lean Advancement Initiative (LAI) of the Massachusetts Institute of Technology, Cambridge, Massachusetts, and the Institute for Manufacturing and Operations Research (IFU) of the Technical University of Braunschweig, Germany.

The goal of this study is to investigate how lean principles can be implemented in product development systems to maximize the probability of implementation success and develop a lean product innovation process.

Your benefit: Every participant will receive a written report by July 2009. The report will outline the results of the survey and give insights on how to implement lean product development most efficiently.

Your effort: Completing the survey will require about 20 to 30 minutes.

Time frame: We kindly ask you to complete the survey by 15 March, 2009.

Confidentiality: All the information collected is treated as highly confidential and handled to preserve the anonymity of the respondents. Results will be presented in aggregate and individual respones will not be singled out.

For questions regarding the content of the survey or its background, please contact Joern Hoppmann (Lean Advancement Initiative, Massachusetts Institute of Technology, Cambridge, Massachusetts, jhoppman@mit.edu), Dr. Eric Rebentisch (Lean Advancement Initiative, Massachusetts Institute of Technology, Cambridge, Massachusetts, erebenti@mit.edu) or Thimo Zahn (Institute for Manufacturing and Operations Research, Technical University of Braunschweig, tzahn@ifu.tu-bs.de).

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Figure A.1: Introductory page of the survey

Unit of Analysis

Our unit of analysis is an individual division within an organization. Please answer the following questions considering the division of your organization in which you are currently placed.

Information on the Introduction Process

First, please answer some general questions on the introduction of Lean Principles in your product development organization.

Has your organization defined goals for implementing Lean principles in product development?

- ○ We do not have any goals and we are not planning to develop any.
- ○ We do not have any goals but we are planning to develop some.
- ○ We have developed an overall strategy but we have not defined lower-level goals and performance measures to achieve it yet.
- ○ We have developed an overall strategy and measurable lower-level goals but we do not have suitable performance measures.
- ○ We have developed an overall strategy, measurable lower-level goals and the according performance measures.

Has your organization declared a person responsible for implementing Lean principles in product development?

○ Yes ○ No

Is your organization planning to use or already using external help (e.g. consultants, sensei, etc.) to implement Lean principles in product development?

○ Yes ○ No

Has your organization conducted value stream mapping on product development processes?

- ○ We have not conducted value stream mapping and we are not planning to use this method.
- ○ We have not conducted value stream mapping but we are planning to use it.
- ○ We have done value stream mapping for a small number of our processes.
- ○ We have done value stream mapping for the majority of our processes.
- ○ We have done value stream mapping for all of our processes.

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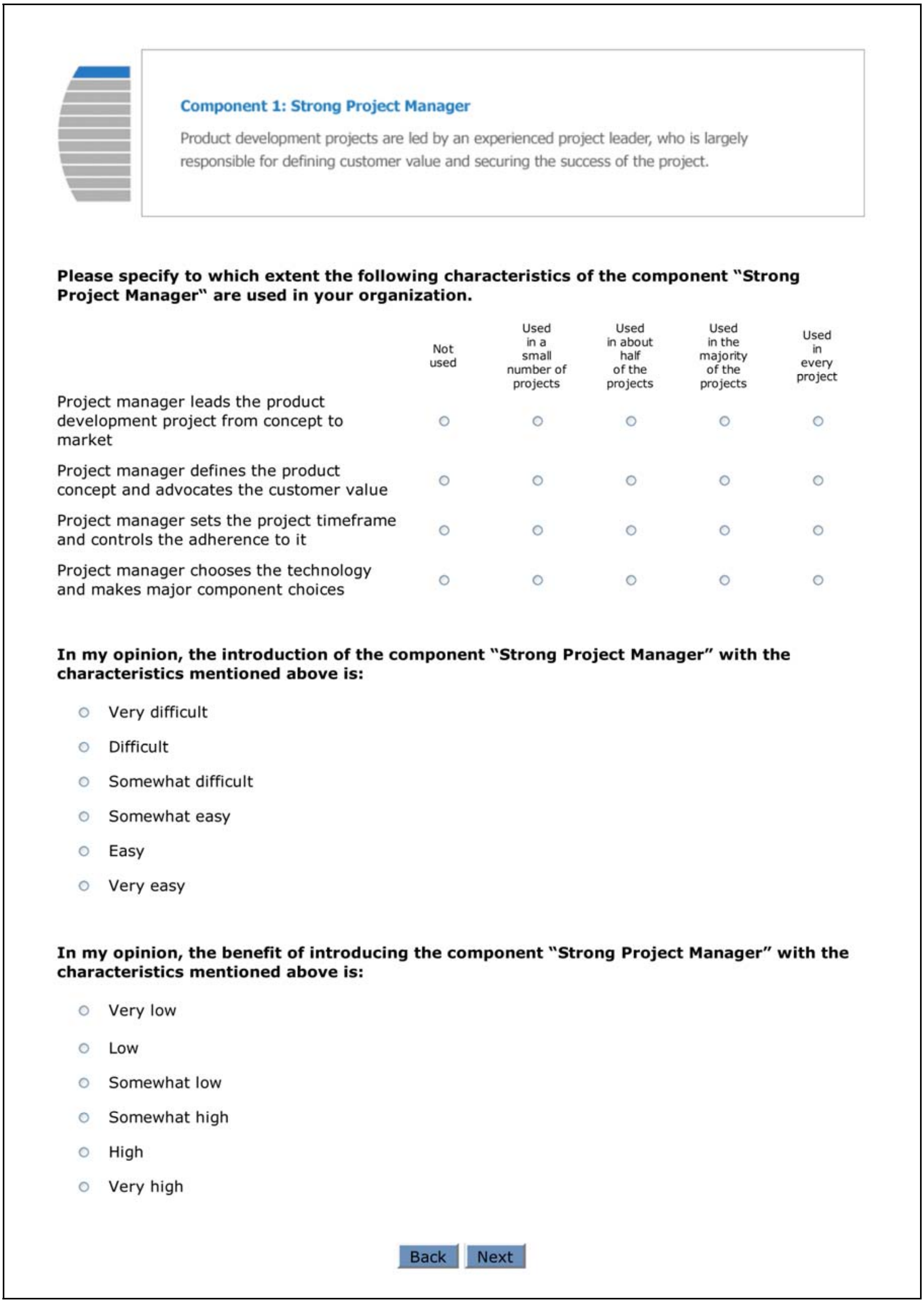
Figure A.2: General questions on the process of implementing Lean PD



Component 1: Strong Project Manager

Product development projects are led by an experienced project leader, who is largely responsible for defining customer value and securing the success of the project.

Please specify to which extent the following characteristics of the component "Strong Project Manager" are used in your organization.

	Not used	Used in a small number of projects	Used in about half of the projects	Used in the majority of the projects	Used in every project
Project manager leads the product development project from concept to market	○	○	○	○	○
Project manager defines the product concept and advocates the customer value	○	○	○	○	○
Project manager sets the project timeframe and controls the adherence to it	○	○	○	○	○
Project manager chooses the technology and makes major component choices	○	○	○	○	○

In my opinion, the introduction of the component "Strong Project Manager" with the characteristics mentioned above is:

- ○ Very difficult
- ○ Difficult
- ○ Somewhat difficult
- ○ Somewhat easy
- ○ Easy
- ○ Very easy

In my opinion, the benefit of introducing the component "Strong Project Manager" with the characteristics mentioned above is:

- ○ Very low
- ○ Low
- ○ Somewhat low
- ○ Somewhat high
- ○ High
- ○ Very high

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Figure A.3: Questions on the component of the Strong Project Manager

Component 2: Set-based Engineering

When developing a product module, a large number of alternative solutions are considered early in the process. The set of solutions is subsequently narrowed based on simultaneous development and testing of the alternatives.

Please specify to what extent the following characteristics of the component "Set-based Engineering" are used in your organization.

	Not used	Used in a small number of projects	Used in about half of the projects	Used in the majority of the projects	Used in every project
A large number of possible solutions for a product module are considered early in the process	○	○	○	○	○
Alternative solutions for a product module are designed and tested simultaneously	○	○	○	○	○
Decisions are delayed in favour of a particular solution until objective data are available	○	○	○	○	○
A concept for a product module is not revised once it has been selected	○	○	○	○	○

In my opinion, the introduction of the component "Set-based Engineering" with the characteristics mentioned above is:

- ○ Very difficult
- ○ Difficult
- ○ Somewhat difficult
- ○ Somewhat easy
- ○ Easy
- ○ Very easy

In my opinion, the benefit of introducing the component "Set-based Engineering" with the characteristics mentioned above is:

- ○ Very low
- ○ Low
- ○ Somewhat low
- ○ Somewhat high
- ○ High
- ○ Very high

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Figure A.4: Questions on the component of Set-based Engineering

Component 3: Process Standardization

When planning, executing and documenting projects, standardized processes, tools and methods are used.

Please specify to what extent the following characteristics of the component "Process Standardization" are used in your organization.

	Not used	Used in a small number of projects	Used in about half of the projects	Used in the majority of the projects	Used in every project
Standard milestones define a sequence in which the development tasks are conducted	○	○	○	○	○
Standardized tools are used for project planning and control	○	○	○	○	○
Standardized tools and procedures are used for design tasks	○	○	○	○	○
Standardized documents are used for capturing knowledge and lessons learned	○	○	○	○	○

In my opinion, the introduction of the component "Process Standardization" with the characteristics mentioned above is:

- ○ Very difficult
- ○ Difficult
- ○ Somewhat difficult
- ○ Somewhat easy
- ○ Easy
- ○ Very easy

In my opinion, the benefit of introducing the component "Process Standardization" with the characteristics mentioned above is:

- ○ Very low
- ○ Low
- ○ Somewhat low
- ○ Somewhat high
- ○ High
- ○ Very high

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Figure A.5: Questions on the component of Process Standardization

Component 4: Specialist Career Path

Engineers are given the opportunity to advance in their technical domain, based on personal coaching and frequent feedback by their superiors.

Please specify to what extent the following characteristics of the component "Specialist Career Path" are used in your organization.

	Not used	Used in a small number of functions	Used in about half of the functions	Used in the majority of the functions	Used in every function
There is a designated career path for technical specialists in their functional areas	○	○	○	○	○
Promotion is based on functional experience and knowledge	○	○	○	○	○
More experienced employees are responsible for mentoring and supporting junior engineers	○	○	○	○	○
Performance of individuals is regularly evaluated and discussed in feedback meetings	○	○	○	○	○

In my opinion, the introduction of the component "Specialist Career Path" with the characteristics mentioned above is:

- ○ Very difficult
- ○ Difficult
- ○ Somewhat difficult
- ○ Somewhat easy
- ○ Easy
- ○ Very easy

In my opinion, the benefit of introducing the component "Specialist Career Path" with the characteristics mentioned above is:

- ○ Very low
- ○ Low
- ○ Somewhat low
- ○ Somewhat high
- ○ High
- ○ Very high

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Figure A.6: Questions on the component of the Specialist Career Path

Component 5: Product Variety Management

Achievement of scale effects through designated use of commodities, reuse of parts, definition of modular components with standardized interfaces and development of product platforms.

Please specify to what extent the following characteristics of the component "Product Variety Management" are used in your organization.

	Not used	Used in a small number of projects	Used in about half of the projects	Used in the majority of the projects	Used in every project
There are clear goals for the use of off-the-shelf components within a product	○	○	○	○	○
There are clear goals for the reuse of product parts among different modules, products and product families	○	○	○	○	○
There are modular components with standardized interfaces	○	○	○	○	○
There are common product platforms encompassing several product lines	○	○	○	○	○

In my opinion, the introduction of the component "Product Variety Management" with the characteristics mentioned above is:

- ○ Very difficult
- ○ Difficult
- ○ Somewhat difficult
- ○ Somewhat easy
- ○ Easy
- ○ Very easy

In my opinion, the benefit of introducing the component "Product Variety Management" with the characteristics mentioned above is:

- ○ Very low
- ○ Low
- ○ Somewhat low
- ○ Somewhat high
- ○ High
- ○ Very high

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Figure A.7: Questions on the component of Product Variety Management

Component 6: Workload Leveling

Required and available resources are planned on a cross-project basis. Workload allocations and capacities are flexibly adapted during the project based on frequent comparisons of planned versus actual capacity requirements.

Please specify to what extent the following characteristics of the component "Workload Leveling" are used in your organization.

	Not used	Used in a small number of projects	Used in about half of the projects	Used in the majority of the projects	Used in every project
Product development resources are planned on a cross-project basis	○	○	○	○	○
Development activities are scheduled and prioritized	○	○	○	○	○
Actual and planned capacity utilization are compared frequently	○	○	○	○	○
Resources are flexibly adapted in case of occurring bottlenecks	○	○	○	○	○

In my opinion, the introduction of the component "Workload Leveling" with the characteristics mentioned above is:

- ○ Very difficult
- ○ Difficult
- ○ Somewhat difficult
- ○ Somewhat easy
- ○ Easy
- ○ Very easy

In my opinion, the benefit of introducing the component "Workload Leveling" with the characteristics mentioned above is:

- ○ Very low
- ○ Low
- ○ Somewhat low
- ○ Somewhat high
- ○ High
- ○ Very high

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Figure A.8: Questions on the component of Workload Leveling

Component 7: Supplier integration

Suppliers of critical parts are identified early in the project, integrated into the development process and actively supported to improve their performance.

Please specify to what extent the following characteristics of the component "Supplier Integration" are used in your organization.

	Not used	Used in a small number of projects	Used in about half of the projects	Used in the majority of the projects	Used in every project
Parts are evaluated according to their criticality before making outsourcing decisions	○	○	○	○	○
A small number of high-capability suppliers are used for critical parts	○	○	○	○	○
Critical suppliers are integrated in the concept definition phase	○	○	○	○	○
Suppliers are mentored to improve their performance	○	○	○	○	○

In my opinion, the introduction of the component "Supplier Integration" with the characteristics mentioned above is:

- ○ Very difficult
- ○ Difficult
- ○ Somewhat difficult
- ○ Somewhat easy
- ○ Easy
- ○ Very easy

In my opinion, the benefit of introducing the component "Supplier Integration" with the characteristics mentioned above is:

- ○ Very low
- ○ Low
- ○ Somewhat low
- ○ Somewhat high
- ○ High
- ○ Very high

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Figure A.9: Questions on the component of Supplier Integration

Component 8: Responsibility-based Planning and Control

Development engineers are locally responsible for planning, execution and control of detailed product development activities.

Please specify to what extent the following characteristics of the component "Responsibility-based Planning and Control" are used in your organization.

	Not used	Used in a small number of projects	Used in about half of the projects	Used in the majority of the projects	Used in every project
Developers are given the opportunity to set their own goals and negotiate deadlines for their tasks	○	○	○	○	○
Developers are given the opportunity to check their own performance based on a formalized feedback process	○	○	○	○	○
Developers are evaluated based on their performance	○	○	○	○	○
Developers are given the opportunity to experiment with new approaches to improve efficiency	○	○	○	○	○

In my opinion, the introduction of the component "Responsibility-based Planning and Control" with the characteristics mentioned above is:

- ○ Very difficult
- ○ Difficult
- ○ Somewhat difficult
- ○ Somewhat easy
- ○ Easy
- ○ Very easy

In my opinion, the benefit of introducing the component "Responsibility-based Planning and Control" with the characteristics mentioned above is:

- ○ Very low
- ○ Low
- ○ Somewhat low
- ○ Somewhat high
- ○ High
- ○ Very high

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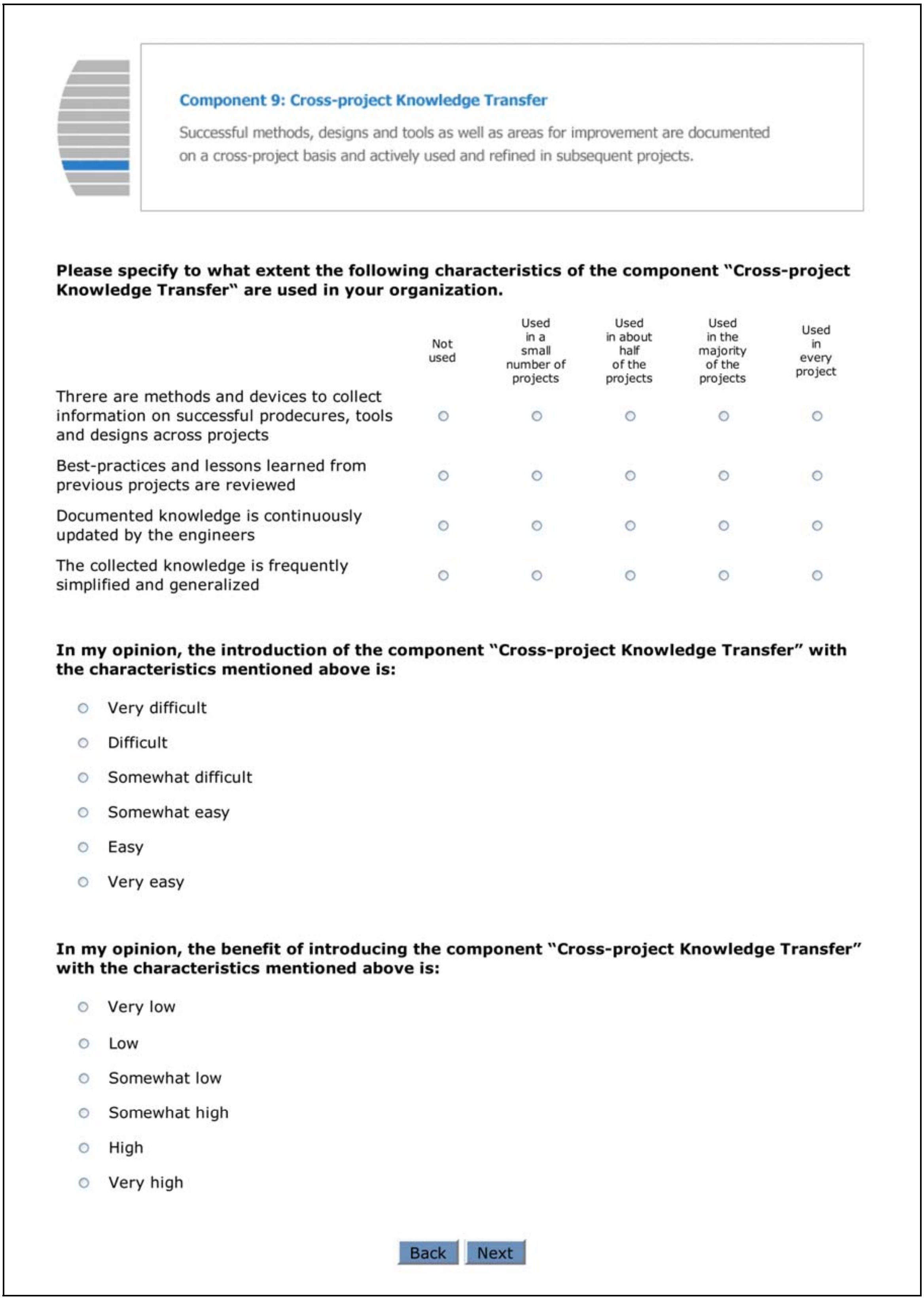
Figure A.10: Questions on the component of Responsibility-based Planning and Control



Component 9: Cross-project Knowledge Transfer

Successful methods, designs and tools as well as areas for improvement are documented on a cross-project basis and actively used and refined in subsequent projects.

Please specify to what extent the following characteristics of the component "Cross-project Knowledge Transfer" are used in your organization.

	Not used	Used in a small number of projects	Used in about half of the projects	Used in the majority of the projects	Used in every project
Threre are methods and devices to collect information on successful prodecures, tools and designs across projects	○	○	○	○	○
Best-practices and lessons learned from previous projects are reviewed	○	○	○	○	○
Documented knowledge is continuously updated by the engineers	○	○	○	○	○
The collected knowledge is frequently simplified and generalized	○	○	○	○	○

In my opinion, the introduction of the component "Cross-project Knowledge Transfer" with the characteristics mentioned above is:

- ○ Very difficult
- ○ Difficult
- ○ Somewhat difficult
- ○ Somewhat easy
- ○ Easy
- ○ Very easy

In my opinion, the benefit of introducing the component "Cross-project Knowledge Transfer" with the characteristics mentioned above is:

- ○ Very low
- ○ Low
- ○ Somewhat low
- ○ Somewhat high
- ○ High
- ○ Very high

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Figure A.11: Questions on the component of Cross-project Knowledge Transfer

Component 10: Rapid Prototyping, Simulation and Testing

For a fast and reliable evaluation of concepts and drafts, rapid prototyping technologies, computer aided simulation and methods for fast physical modelling are used.

Please specify to what extent the following characteristics of the component "Rapid Prototyping, Simulation and Testing" are used in your organization.

	Not used	Used in a small number of projects	Used in about half of the projects	Used in the majority of the projects	Used in every project
Designs are quickly modeled and tested using physical models	○	○	○	○	○
Computer-aided modelling and simulation are used	○	○	○	○	○
Rapid prototyping technology is used	○	○	○	○	○
Methods of Lean Production are used in prototype build and tool manufacturing	○	○	○	○	○

In my opinion, the introduction of the component "Rapid Prototyping, Simulation and Testing" with the characteristics mentioned above is:

○ Very difficult

○ Difficult

○ Somewhat difficult

○ Somewhat easy

○ Easy

○ Very easy

In my opinion, the benefit of introducing the component "Rapid Prototyping, Simulation and Testing" with the characteristics mentioned above is:

○ Very low

○ Low

○ Somewhat low

○ Somewhat high

○ High

○ Very high

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Figure A.12: Questions on the component of Rapid Prototyping, Simulation and Testing

Component 11: Simultaneous Engineering

Representatives from production, quality assurance and purchasing departments are integrated into development activities at an early stage. The design of production processes and facilities is conducted in parallel to the development of the product.

Please specify to what extent the following characteristics of the component "Simultaneous Engineering" are used in your organization.

	Not used	Used in a small number of projects	Used in about half of the projects	Used in the majority of the projects	Used in every project
Representatives from manufacturing, quality assurance and purchasing are integrated in the concept definition phase	○	○	○	○	○
There are frequent review meetings with development, manufacturing, quality assurance and purchasing	○	○	○	○	○
There is a formalized process for evaluating design proposals regarding manufacturing and assembly compatibility	○	○	○	○	○
Development and testing of production facilities is done in parallel to product development	○	○	○	○	○

In my opinion, the introduction of the component "Simultaneous Engineering" with the characteristics mentioned above is:

- ○ Very difficult
- ○ Difficult
- ○ Somewhat difficult
- ○ Somewhat easy
- ○ Easy
- ○ Very easy

In my opinion, the benefit of introducing the component "Simultaneous Engineering" with

- ○ Very low
- ○ Low
- ○ Somewhat low
- ○ Somewhat high
- ○ High
- ○ Very high

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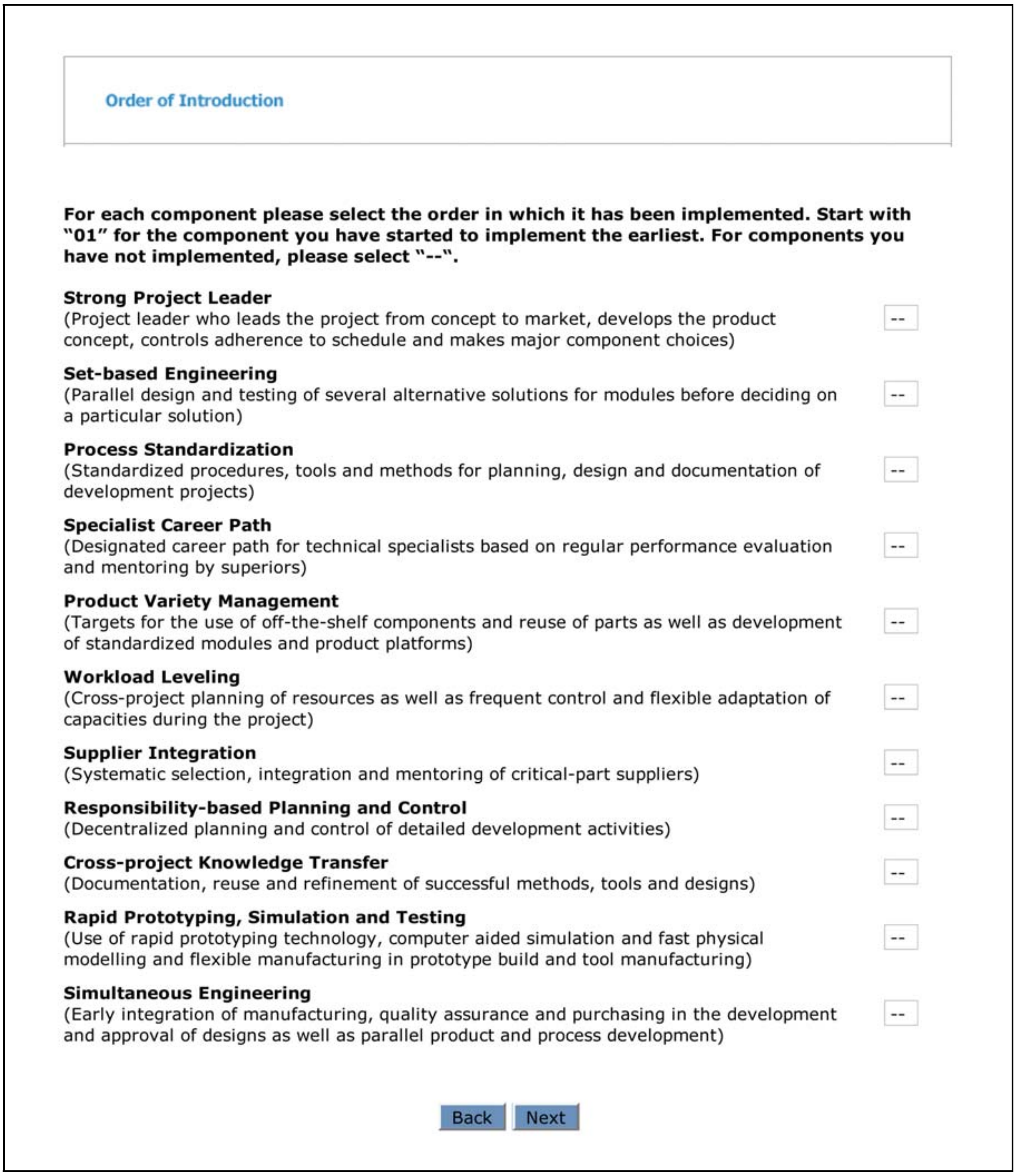
Figure A.13: Questions on the component of Simultaneous Engineering



Order of Introduction

For each component please select the order in which it has been implemented. Start with "01" for the component you have started to implement the earliest. For components you have not implemented, please select "--".

Strong Project Leader (Project leader who leads the project from concept to market, develops the product concept, controls adherence to schedule and makes major component choices)	--
Set-based Engineering (Parallel design and testing of several alternative solutions for modules before deciding on a particular solution)	--
Process Standardization (Standardized procedures, tools and methods for planning, design and documentation of development projects)	--
Specialist Career Path (Designated career path for technical specialists based on regular performance evaluation and mentoring by superiors)	--
Product Variety Management (Targets for the use of off-the-shelf components and reuse of parts as well as development of standardized modules and product platforms)	--
Workload Leveling (Cross-project planning of resources as well as frequent control and flexible adaptation of capacities during the project)	--
Supplier Integration (Systematic selection, integration and mentoring of critical-part suppliers)	--
Responsibility-based Planning and Control (Decentralized planning and control of detailed development activities)	--
Cross-project Knowledge Transfer (Documentation, reuse and refinement of successful methods, tools and designs)	--
Rapid Prototyping, Simulation and Testing (Use of rapid prototyping technology, computer aided simulation and fast physical modelling and flexible manufacturing in prototype build and tool manufacturing)	--
Simultaneous Engineering (Early integration of manufacturing, quality assurance and purchasing in the development and approval of designs as well as parallel product and process development)	--

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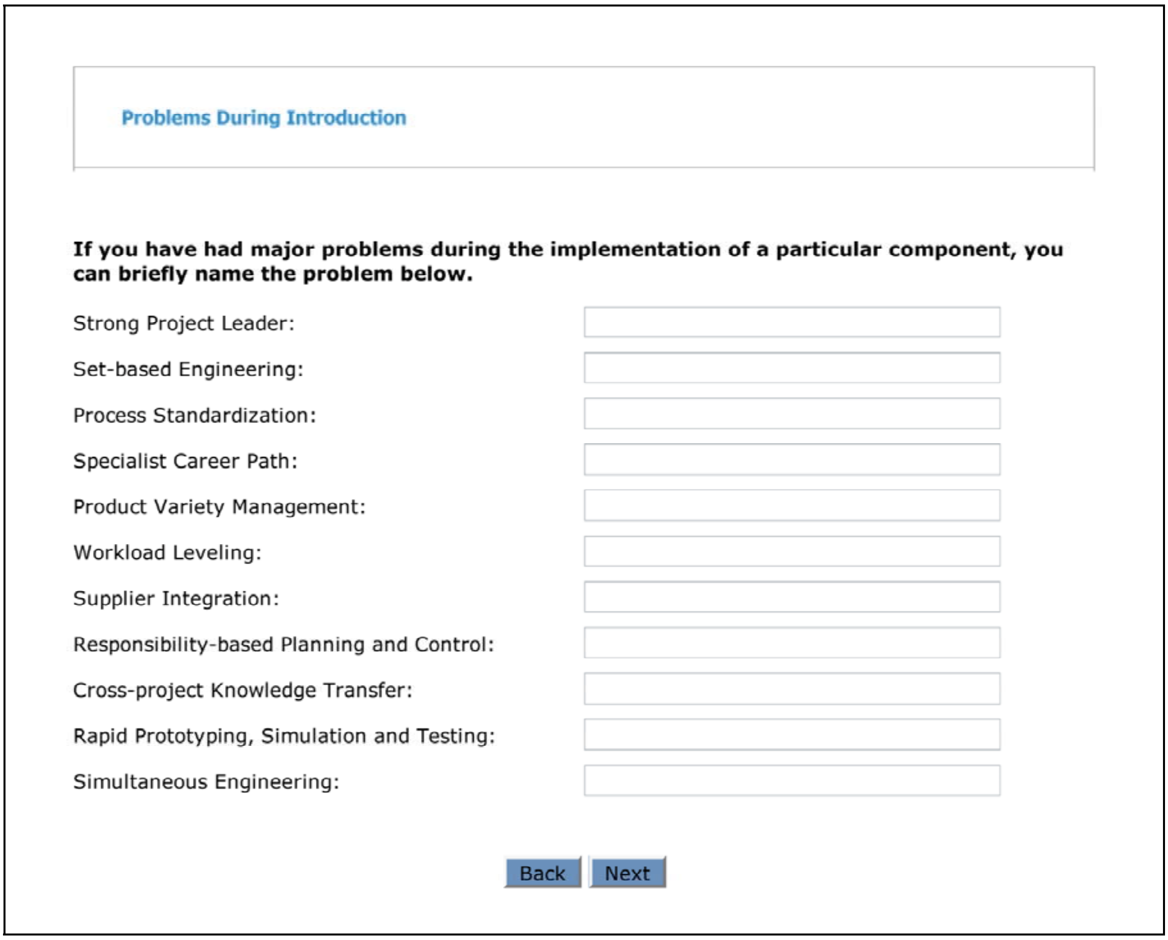
Figure A.14: Questions on the order of introduction


Problems During Introduction

If you have had major problems during the implementation of a particular component, you can briefly name the problem below.

Strong Project Leader:
Set-based Engineering:
Process Standardization:
Specialist Career Path:
Product Variety Management:
Workload Leveling:
Supplier Integration:
Responsibility-based Planning and Control:
Cross-project Knowledge Transfer:
Rapid Prototyping, Simulation and Testing:
Simultaneous Engineering:

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Figure A.15: Questions on problems experienced during introduction

Company Information

Please provide some general information on your company. All the information is kept strictly confidential and used for statistical purposes only.

What is the industrial sector of your company?

- ○ Automotive
- ○ Industrial equipment
- ○ Aerospace manufacturing
- ○ Consumer electronics
- ○ Others: ________

What was the revenue of your company in 2007 in Million Dollars?

____

How many employees does your company have?

____

Please provide the country where your product development organization is located.

____

What is your position in your company?

- ○ Chief product development officer
- ○ Chief engineer (company level)
- ○ Chief engineer (department level)
- ○ Product development engineer
- ○ Others: ________

I would be willing to participate in a short interview supplementary to the questions of this survey.

○ Yes ○ No

If you provide your e-mail address, you will receive the written report of this study by July 2009. The report will outline the results of the survey and give insights on how to implement lean product development most efficiently.

____

Figure A.16: Questions on company characteristics

Appendix B: Correlation Analyses on the Interdependencies between the Lean PD Components

Table B.1: Correlations of the use of the Lean PD characteristics (Analysis A) – part 1

No.	Characteristic	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	Project manager leads the product development project from concept to market	1	.344**	.391**	.282**	.160	.109	.032	.206*	.049	.145	.161	.187*	.092	.007	.130	.042	.144	.062	.084	.134	.331**	.238*
2	Project manager defines the product concept and advocates the customer value	.344**	1	.368**	.497**	.111	.096	-.035	.139	-.087	.027	-.067	-.014	.010	-.041	-.063	.032	.063	.077	-.048	.085	.040	.042
3	Project manager sets the project timeframe and controls the adherence to it	.391**	.368**	1	.362**	.078	.124	.279**	.091	.176	.185*	.095	.065	.137	.071	.123	.231*	.010	-.022	-.047	.098	.199*	.257**
4	Project manager chooses the technology and makes major component choices	.282**	.497**	.362**	1	.207*	.145	.101	.142	.047	.119	.141	.164	.010	.027	-.001	.141	.089	.040	-.088	.064	.042	.056
5	A large number of possible solutions for a product module are considered early in the process	.160	.111	.078	.207*	1	.544**	.399**	.068	.004	.012	.174	.140	.263**	.324**	.336**	.179	.246**	.203*	.176	.212*	.018	.188*
6	Alternative solutions for a product module are designed and tested simultaneously	.109	.096	.124	.145	.544**	1	.401**	.254**	.067	.079	.151	.124	.140	.126	.323**	.188*	.270**	.193*	.117	.165	.135	.247**
7	Decisions are delayed in favour of a particular solution until objective data are available	.032	-.035	.279**	.101	.399**	.401**	1	.244**	.136	.161	.114	.167	.134	.311**	.376**	.247**	.217*	.186*	.153	.189*	.045	.283**
8	A concept for a product module is not revised once it has been selected	.206*	.139	.091	.142	.068	.254**	.244**	1	.154	.136	-.010	.131	.108	.149	.298**	.208*	.287**	.205*	.186*	.083	.203*	.266**
9	Standard milestones define a sequence in which the development tasks are conducted	.049	-.087	.176	.047	.004	.067	.136	.154	1	.646**	.497**	.308**	.302**	.302**	.274**	.414**	.305**	.242**	.175	.214*	.276**	.364**
10	Standardized tools are used for project planning and control	.145	.027	.185*	.119	.012	.079	.161	.136	.646**	1	.495**	.443**	.170	.225*	.240*	.315**	.354**	.332**	.116	.331**	.344**	.304**
11	Standardized tools and procedures are used for design tasks	.161	-.067	.095	.141	.174	.151	.114	-.010	.497**	.495**	1	.413**	.247**	.195*	.218*	.298**	.371**	.317**	.128	.252**	.292**	.285**
12	Standardized documents are used for capturing knowledge and lessons learned	.187*	-.014	.065	.164	.140	.124	.167	.131	.308**	.443**	.413**	1	.020	.191*	.188*	.237*	.328**	.366**	.248**	.410**	.207*	.252**
13	There is a designated career path for technical specialists in their functional areas	.092	.010	.137	.010	.263**	.140	.134	.108	.302**	.170	.247**	.020	1	.691**	.407**	.463**	.154	.121	.090	.044	.236*	.295**
14	Promotion is based on functional experience and knowledge	.007	-.041	.071	.027	.324**	.126	.311**	.149	.302**	.225*	.195*	.191*	.691**	1	.445**	.501**	.237*	.190*	.094	.117	.237*	.421**
15	More experienced employees are responsible for mentoring and supporting junior engineers	.130	-.063	.123	-.001	.336**	.323**	.376**	.298**	.274**	.240*	.218*	.188*	.407**	.445**	1	.405**	.468**	.440**	.405**	.336**	.283**	.405**
16	Performance of individuals is regularly evaluated and discussed in feedback meetings	.042	.032	.231*	.141	.179	.188*	.247**	.208*	.414**	.315**	.298**	.237*	.463**	.501**	.405**	1	.229*	.190*	.191*	.126	.295**	.455**
17	There are clear goals for the use of off-the-shelf components within a product	.144	.063	.010	.089	.246**	.270**	.217*	.287**	.305**	.354**	.371**	.328**	.154	.237*	.468**	.229*	1	.793**	.546**	.534**	.147	.287**
18	There are clear goals for the reuse of product parts among different modules. products and product families	.062	.077	-.022	.040	.203*	.193*	.186*	.205*	.242**	.332**	.317**	.366**	.121	.190*	.440**	.190*	.793**	1	.665**	.686**	.156	.313**
19	There are modular components with standardized interfaces	.084	-.048	-.047	-.088	.176	.117	.153	.186*	.175	.116	.128	.248**	.090	.094	.405**	.191*	.546**	.665**	1	.644**	.220*	.402**
20	There are common product platforms encompassing several product lines	.134	.085	.098	.064	.212*	.165	.189*	.083	.214*	.331**	.252**	.410**	.044	.117	.336**	.126	.534**	.686**	.644**	1	.142	.325**
21	Product development resources are planned on a cross-project basis	.331**	.040	.199*	.042	.018	.135	.045	.203*	.276**	.344**	.292**	.207*	.236*	.237*	.283**	.295**	.147	.156	.220*	.142	1	.595**
22	Development activities are scheduled and prioritized	.238*	.042	.257**	.056	.188*	.247**	.283**	.266**	.364**	.304**	.285**	.252**	.295**	.421**	.405**	.455**	.287**	.313**	.402**	.325**	.595**	1

* p<0.05 ** p<0.01

Table B.2: Correlations of the use of the Lean PD characteristics (Analysis A) – part 2

No.	Characteristic	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
23	Actual and planned capacity utilization are compared frequently	.296**	.100	.267**	.222*	.065	.081	.117	.303**	.287**	.321**	.266**	.371**	.170	.228*	.253**	.311**	.284**	.305**	.325**	.252**	.601**	.616**
24	Resources are flexibly adapted in case of occurring bottlenecks	.278**	.139	.134	.226*	.204*	.171	.066	.191*	.202*	.282**	.159	.247**	.109	.205*	.266**	.163	.119	.184	.159	.183	.457**	.489**
25	Parts are evaluated according to their criticality before making outsourcing decisions	.257**	.061	.052	.133	.421**	.224*	.179	.072	.401**	.313**	.405**	.195*	.329**	.288**	.468**	.337**	.483**	.462**	.457**	.362**	.189*	.375**
26	A small number of high-capability suppliers are used for critical parts	.309**	.078	.086	.103	.365**	.286**	.173	.147	.272**	.160	.256**	.253**	.373**	.330**	.402**	.242**	.470**	.347**	.368**	.354**	.277**	.279**
27	Critical suppliers are integrated in the concept definition phase	.134	.044	.151	.078	.269**	.123	.254**	.199*	.449**	.355**	.321**	.255**	.343**	.339**	.321**	.448**	.410**	.290**	.376**	.215*	.283**	.378**
28	Suppliers are mentored to improve their performance	.147	-.095	.087	.121	.326**	.279**	.314**	.136	.164	.077	.185	.120	.241*	.299**	.249**	.281**	.252**	.245**	.390**	.199*	.206*	.362**
29	Developers are given the opportunity to set their own goals and negotiate deadlines for their tasks	.108	-.015	.069	.234*	.197*	.137	.134	.046	.128	.086	.107	-.063	.211*	.190*	.173	.196*	.074	.017	.093	.048	.280**	.235*
30	Developers are given the opportunity to check their own performance based on a formalized feedback process	.029	-.021	.085	.244**	.222*	.255**	.362**	.142	.201*	.270**	.234*	.261**	.135	.268**	.226*	.268**	.165	.138	.168	.167	.238*	.261**
31	Developers are evaluated based on their performance	.194*	.077	.216*	.135	.319**	.240*	.172	.163	.074	.040	.144	.100	.275**	.285**	.414**	.321**	.202*	.179	.166	.124	.232*	.300**
32	Developers are given the opportunity to experiment with new approaches to improve efficiency	.144	-.078	-.016	.109	.291**	.203*	.275**	.185*	.125	.112	.089	.156	.239*	.315**	.324**	.212*	.151	.176	.233*	.250**	.205*	.294**
33	There are methods and devices to collect information on successful prodecures, tools and designs across projects	-.048	.077	.029	.232*	.268**	.274**	.193*	.135	.271**	.195*	.177	.325**	.261**	.294**	.226*	.336**	.171	.192*	.207*	.268**	.167	.293**
34	Best-practices and lessons learned from previous projects are reviewed	.185*	-.054	.071	-.029	.249**	.260**	.263**	.116	.205*	.282**	.462**	.499**	.167	.269**	.403**	.281**	.363**	.384**	.454**	.409**	.290**	.424**
35	Documented knowledge is continuously updated by the engineers	-.011	.023	.013	.060	.277**	.307**	.225*	.094	.225*	.209*	.259**	.428**	.263**	.292**	.201*	.349**	.317**	.232*	.334**	.251**	.168	.401**
36	The collected knowledge is frequently simplified and generalized	.090	.087	.071	.140	.166	.224*	.276**	.132	.203*	.299**	.313**	.438**	.199*	.209*	.149	.228*	.405**	.369**	.345**	.402**	.194*	.335**
37	Designs are quickly modeled and tested using physical models	.186*	-.076	.132	.064	.231*	.344**	.288**	.221*	.175	.010	.125	.028	.189*	.193*	.180	.166	.165	.185	.185*	.062	.098	.269**
38	Computer-aided modelling and simulation are used	.162	.043	.147	.032	.340**	.293**	.197*	.000	.176	.072	.252**	.047	.263**	.219*	.206*	.163	.202*	.189*	.124	.118	.062	.153
39	Rapid prototyping technology is used	.222*	-.083	.134	.094	.250**	.343**	.275**	-.030	.197*	.127	.273**	.071	.146	.128	.202*	.309**	.100	.116	.231*	.072	.135	.288**
40	Methods of Lean Production are used in prototype build and tool manufacturing	.109	.021	.088	.211*	.327**	.274**	.389**	.152	.175	.160	.230*	.294**	.141	.212*	.255**	.351**	.327**	.385**	.405**	.315**	.076	.310**
41	Representatives from manufacturing, quality assurance and purchasing are integrated in the concept definition phase	.238*	.121	.270**	.172	.263**	.307**	.204*	.032	.246**	.253**	.209*	.207*	.030	.106	.185*	.372**	.180	.192*	.173	.241*	.245**	.437**
42	There are frequent review meetings with development, manufacturing, quality assurance and purchasing	.175	-.042	.270**	.038	.314**	.301**	.326**	.115	.288**	.179	.290**	.227*	.228*	.283**	.402**	.446**	.196*	.194*	.197*	.193*	.272**	.407**
43	There is a formalized process for evaluating design proposals regarding manufacturing and assembly compatibility	.127	-.029	.250**	.071	.300**	.270**	.263**	.138	.304**	.305**	.261**	.322**	.235*	.320**	.289**	.309**	.257**	.368**	.337**	.389**	.244**	.465**
44	Development and testing of production facilities is done in parallel to product development	.098	-.045	.149	.088	.259**	.200*	.215*	.087	.305**	.292**	.288**	.278**	.264**	.355**	.327**	.430**	.211*	.342**	.283**	.254**	.253**	.405**

* p<0.05 ** p<0.01

Table B.3: Correlations of the use of the Lean PD characteristics (Analysis A) – part 3

No.	Characteristic	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44
1	Project manager leads the product development project from concept to market	.296**	.278**	.257**	.309**	.134	.147	.108	.029	.194*	.144	-.048	.185*	-.011	.090	.186*	.162	.222*	.109	.238*	.175	.127	.098
2	Project manager defines the product concept and advocates the customer value	.100	.139	.061	.078	.044	-.095	-.015	-.021	.077	-.078	.077	-.054	.023	.087	-.076	.043	-.083	.021	.121	-.042	-.029	-.045
3	Project manager sets the project timeframe and controls the adherence to it	.267**	.134	.052	.086	.151	.087	.069	.085	.216*	-.016	.029	.071	.013	.071	.132	.147	.134	.088	.270**	.270**	.250**	.149
4	Project manager chooses the technology and makes major component choices	.222*	.226*	.133	.103	.078	.121	.234*	.244**	.135	.109	.232*	-.029	.060	.140	.064	.032	.094	.211*	.172	.038	.071	.088
5	A large number of possible solutions for a product module are considered early in the process	.065	.204*	.421**	.365**	.269**	.326**	.197*	.222*	.319**	.291**	.268**	.249**	.277**	.166	.231*	.340**	.250**	.327**	.263**	.314**	.300**	.259**
6	Alternative solutions for a product module are designed and tested simultaneously	.081	.171	.224*	.286**	.123	.279**	.137	.255**	.240*	.203*	.274**	.260**	.307**	.224*	.344**	.293**	.343**	.274**	.307**	.301**	.270**	.200*
7	Decisions are delayed in favour of a particular solution until objective data are available	.117	.066	.179	.173	.254**	.314**	.134	.362**	.172	.275**	.193*	.263**	.225*	.276**	.288**	.197*	.275**	.389**	.204*	.326**	.263**	.215*
8	A concept for a product module is not revised once it has been selected	.303**	.191*	.072	.147	.199*	.136	.046	.142	.163	.185*	.135	.116	.094	.132	.221*	.000	-.030	.152	.032	.115	.138	.087
9	Standard milestones define a sequence in which the development tasks are conducted	.287**	.202*	.401**	.272**	.449**	.164	.128	.201*	.074	.125	.271**	.205*	.225*	.203*	.175	.176	.197*	.175	.246**	.288**	.304**	.305**
10	Standardized tools are used for project planning and control	.321**	.282**	.313**	.160	.355**	.077	.086	.270**	.040	.112	.195*	.282**	.209*	.299**	.010	.072	.127	.160	.253**	.179	.305**	.292**
11	Standardized tools and procedures are used for design tasks	.266**	.159	.405**	.256**	.321**	.185	.107	.234*	.144	.089	.177	.462**	.259**	.313**	.125	.252**	.273**	.230*	.209*	.290**	.261**	.288**
12	Standardized documents are used for capturing knowledge and lessons learned	.371**	.247**	.195*	.253**	.255**	.120	-.063	.261**	.100	.156	.325**	.499**	.428**	.438**	.028	.047	.071	.294**	.207*	.227*	.322**	.278**
13	There is a designated career path for technical specialists in their functional areas	.170	.109	.329**	.373**	.343**	.241*	.211*	.135	.275**	.239*	.261**	.167	.263**	.199*	.189*	.263**	.146	.141	.030	.228*	.235*	.264**
14	Promotion is based on functional experience and knowledge	.228*	.205*	.288**	.330**	.339**	.299**	.190*	.268**	.285**	.315**	.294**	.269**	.292**	.209*	.193*	.219*	.128	.212*	.106	.283**	.320**	.355**
15	More experienced employees are responsible for mentoring and supporting junior engineers	.253**	.266**	.468**	.402**	.321**	.249**	.173	.226*	.414**	.324**	.226*	.403**	.201*	.149	.180	.206*	.202*	.255**	.185*	.402**	.289**	.327**
16	Performance of individuals is regularly evaluated and discussed in feedback meetings	.311**	.163	.337**	.242**	.448**	.281**	.196*	.268**	.321**	.212*	.336**	.281**	.349**	.228*	.166	.163	.309**	.351**	.372**	.446**	.309**	.430**
17	There are clear goals for the use of off-the-shelf components within a product	.284**	.119	.483**	.470**	.410**	.252**	.074	.165	.202*	.151	.171	.363**	.317**	.405**	.165	.202*	.100	.327**	.180	.196*	.257**	.211*
18	There are clear goals for the reuse of product parts among different modules, products and product families	.305**	.184	.462**	.347**	.290**	.245**	.017	.138	.179	.176	.192*	.384**	.232*	.369**	.185	.189*	.116	.385**	.192*	.194*	.368**	.342**
19	There are modular components with standardized interfaces	.325**	.159	.457**	.368**	.376**	.390**	.093	.168	.166	.233*	.207*	.454**	.334**	.345**	.185*	.124	.231*	.405**	.173	.197*	.337**	.283**
20	There are common product platforms encompassing several product lines	.252**	.183	.362**	.354**	.215*	.199*	.048	.167	.124	.250**	.268**	.409**	.251**	.402**	.062	.118	.072	.315**	.241*	.193*	.389**	.254**
21	Product development resources are planned on a cross-project basis	.601**	.457**	.189*	.277**	.283**	.206*	.280**	.238*	.232*	.205*	.167	.290**	.168	.194*	.098	.062	.135	.076	.245**	.272**	.244**	.253**
22	Development activities are scheduled and prioritized	.616**	.489**	.375**	.279**	.378**	.362**	.235*	.261**	.300**	.294**	.293**	.424**	.401**	.335**	.269**	.153	.288**	.310**	.437**	.407**	.465**	.405**

* p<0.05 ** p<0.01

Table B.4: Correlations of the use of the Lean PD characteristics (Analysis A) – part 4

No.	Characteristic	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44
23	Actual and planned capacity utilization are compared frequently	1	.538**	.232*	.204*	.344**	.265**	.228*	.355**	.212*	.168	.251**	.325**	.243**	.363**	.083	.078	.118	.247**	.306**	.307**	.307**	.213*
24	Resources are flexibly adapted in case of occurring bottlenecks	.538**	1	.245**	.185*	.263**	.318**	.336**	.358**	.338**	.290**	.303**	.201*	.245**	.277**	.099	.052	.119	.216*	.286**	.316**	.244**	.275**
25	Parts are evaluated according to their criticality before making outsourcing decisions	.232*	.245**	1	.570**	.494**	.483**	.261**	.306**	.327**	.218*	.264**	.358**	.306**	.291**	.133	.216*	.235*	.303**	.348**	.362**	.306**	.378**
26	A small number of high-capability suppliers are used for critical parts	.204*	.185*	.570**	1	.412**	.329**	.209*	.238*	.330**	.319**	.206*	.378**	.314**	.299**	.248**	.344**	.193*	.297**	.178	.301**	.261**	.212*
27	Critical suppliers are integrated in the concept definition phase	.344**	.263**	.494**	.412**	1	.459**	.230*	.293**	.242**	.290**	.318**	.286**	.417**	.298**	.267**	.151	.158	.335**	.366**	.481**	.409**	.415**
28	Suppliers are mentored to improve their performance	.265**	.318**	.483**	.329**	.459**	1	.197*	.319**	.386**	.240*	.252**	.294**	.253**	.277**	.334**	.202*	.359**	.475**	.273**	.384**	.356**	.404**
29	Developers are given the opportunity to set their own goals and negotiate deadlines for their tasks	.228*	.336**	.261**	.209*	.230*	.197*	1	.475**	.376**	.394**	.298**	.033	.293**	.102	.000	-.117	-.020	.036	.269**	.154	-.014	.055
30	Developers are given the opportunity to check their own performance based on a formalized feedback process	.355**	.358**	.306**	.238*	.293**	.319**	.475**	1	.430**	.459**	.297**	.130	.286**	.279**	.045	-.023	.084	.318**	.304**	.257**	.175	.168
31	Developers are evaluated based on their performance	.212*	.338**	.327**	.330**	.242**	.386**	.376**	.430**	1	.374**	.232*	.222*	.218*	.189*	.186*	.164	.175	.204*	.316**	.386**	.172	.216*
32	Developers are given the opportunity to experiment with new approaches to improve efficiency	.168	.290**	.218*	.319**	.290**	.240*	.394**	.459**	.374**	1	.269**	.167	.262**	.158	.186*	-.004	.157	.230*	.265**	.278**	.310**	.251**
33	There are methods and devices to collect information on successful prodecures. tools and designs across projects	.251**	.303**	.264**	.206*	.318**	.252**	.298**	.297**	.232*	.269**	1	.370**	.662**	.471**	.048	.010	.056	.144	.298**	.289**	.213*	.219*
34	Best-practices and lessons learned from previous projects are reviewed	.325**	.201*	.358**	.378**	.286**	.294**	.033	.130	.222*	.167	.370**	1	.493**	.525**	.272**	.347**	.390**	.309**	.311**	.326**	.348**	.323**
35	Documented knowledge is continuously updated by the engineers	.243**	.245**	.306**	.314**	.417**	.253**	.293**	.286**	.218*	.262**	.662**	.493**	1	.580**	.110	.140	.126	.255**	.346**	.337**	.330**	.316**
36	The collected knowledge is frequently simplified and generalized	.363**	.277**	.291**	.299**	.298**	.277**	.102	.279**	.189*	.158	.471**	.525**	.580**	1	.072	.079	.123	.255**	.255**	.274**	.291**	.211*
37	Designs are quickly modeled and tested using physical models	.083	.099	.133	.248**	.267**	.334**	.000	.045	.186*	.186*	.048	.272**	.110	.072	1	.536**	.676**	.423**	.189*	.357**	.308**	.262**
38	Computer-aided modelling and simulation are used	.078	.052	.216*	.344**	.151	.202*	-.117	-.023	.164	-.004	.010	.347**	.140	.079	.536**	1	.599**	.380**	.212*	.303**	.357**	.197*
39	Rapid prototyping technology is used	.118	.119	.235*	.193*	.158	.359**	-.020	.084	.175	.157	.056	.390**	.126	.123	.676**	.599**	1	.516**	.250**	.317**	.291**	.287**
40	Methods of Lean Production are used in prototype build and tool manufacturing	.247**	.216*	.303**	.297**	.335**	.475**	.036	.318**	.204*	.230*	.144	.309**	.255**	.255**	.423**	.380**	.516**	1	.172	.303**	.396**	.394**
41	Representatives from manufacturing, quality assurance and purchasing are integrated in the concept definition phase	.306**	.286**	.348**	.178	.366**	.273**	.269**	.304**	.316**	.265**	.298**	.311**	.346**	.255**	.189*	.212*	.250**	.172	1	.701**	.555**	.520**
42	There are frequent review meetings with development. manufacturing. quality assurance and purchasing	.307**	.316**	.362**	.301**	.481**	.384**	.154	.257**	.386**	.278**	.289**	.326**	.337**	.274**	.357**	.303**	.317**	.303**	.701**	1	.616**	.677**
43	There is a formalized process for evaluating design proposals regarding manufacturing and assembly compatibility	.307**	.244**	.306**	.261**	.409**	.356**	-.014	.175	.172	.310**	.213*	.348**	.330**	.291**	.308**	.357**	.291**	.396**	.555**	.616**	1	.730**
44	Development and testing of production facilities is done in parallel to product development	.213*	.275**	.378**	.212*	.415**	.404**	.055	.168	.216*	.251**	.219*	.323**	.316**	.211*	.262**	.197*	.287**	.394**	.520**	.677**	.730**	1

* p<0.05 ** p<0.01

Table B.5: Correlations between use and ranks of implementation for Lean PD components (Analysis B)

	Rank Strong Project Manager	Rank Set-based Engineering	Rank Process Standardization	Rank Specialist Career Path	Rank Product Variety Management	Rank Workload Leveling	Rank Supplier Integration	Rank Responsibility-based Planning and Control	Rank Cross-project Knowledge Transfer	Rank Rapid Prototyping, Simulation and Testing	Rank Simultaneous Engineering
Use of Strong Project Manager	-.253*	.187	-.067	.075	-.035	.015	-.004	.030	.214*	.043	.175
Use of Set-based Engineering	.138	-.299**	.014	.006	.054	.015	.100	.058	.177	-.117	.002
Use of Process Standardization	.159	.086	-.215*	.152	-.006	.008	-.048	.095	.027	.099	-.014
Use of Specialist Career Path	.042	-.060	.014	-.279*	.062	.009	-.078	.066	.357**	.148	-.104
Use of Product Variety Management	.061	.128	-.139	.162	-.186	-.035	-.091	.043	.015	.126	.032
Use of Workload Leveling	.024	.048	.019	.028	-.061	-.300**	-.044	-.070	.204	.072	.175
Use of Supplier Integration	.092	.050	.151	.040	.046	-.064	-.218*	.021	.279**	.034	.007
Use of Responsibility-based Planning and Control	.126	-.277*	.185	-.012	.149	-.124	.070	-.402**	.208	.088	.034
Use of Cross-project Knowledge Transfer	.162	-.034	-.011	.127	-.093	.119	-.051	.053	-.198	-.007	-.024
Use of Rapid Prototyping, Simulation and Testing	.194	-.086	.113	.182	-.033	.042	.074	.064	.293**	-.407**	-.042
Use of Simultaneous Engineering	.306**	.075	.187	.233*	.061	.078	-.200	-.019	.106	-.035	-.212*

* $p<0.05$ ** $p<0.01$

Table B.6: Correlations between use of characteristics and the perceived ease of implementing the Lean PD components (Analysis C) – part 1

	Ease of Implementation Strong Project Manager	Ease of Implementation Set-based Engineering	Ease of Implementation Process Standardization	Ease of Implementation Specialist Career Path	Ease of Implementation Product Variety Management	Ease of Implementation Workload Leveling	Ease of Implementation Supplier Integration	Ease of Implementation Responsibility-based Planning and Control	Ease of Implementation Cross-project Knowledge Transfer	Ease of Implementation Rapid Prototyping, Simulation and Testing	Ease of Implementation Simultaneous Engineering
Project manager leads the product development project from concept to market	.192*	-.089	.004	-.028	-.083	-.065	-.123	-.020	-.090	.007	-.078
Project manager defines the product concept and advocates the customer value	.225*	-.140	.010	.007	-.133	.028	-.067	-.067	-.236*	-.122	.045
Project manager sets the project timeframe and controls the adherence to it	.127	-.269**	-.004	-.040	-.139	-.079	-.116	-.066	-.187*	-.030	-.110
Project manager chooses the technology and makes major component choices	.347**	-.225*	-.104	-.207*	-.199*	-.117	-.105	-.081	-.236*	-.075	-.142
A large number of possible solutions for a product module are considered early in the process	-.063	.306**	-.061	.138	-.079	-.187*	.051	.098	-.089	.019	.032
Alternative solutions for a product module are designed and tested simultaneously	.133	.313**	.032	.092	-.109	-.045	.000	.044	-.028	.025	-.087
Decisions are delayed in favour of a particular solution until objective data are available	.059	.286**	.087	.294**	-.088	-.078	.116	.231*	-.047	.058	.083
A concept for a product module is not revised once it has been selected	.131	.191*	-.101	.050	-.123	-.002	-.176	.029	-.067	-.035	-.136
Standard milestones define a sequence in which the development tasks are conducted	.106	.069	.132	.097	.008	.009	-.046	.001	-.073	.069	.062
Standardized tools are used for project planning and control	.146	.101	.182	.173	.178	.097	-.060	.017	-.034	-.017	.058
Standardized tools and procedures are used for design tasks	.156	.143	.175	.041	.027	-.095	-.037	-.010	-.051	.061	.050
Standardized documents are used for capturing knowledge and lessons learned	.167	.161	.249**	.132	.158	.040	.015	.061	.012	-.075	.075
There is a designated career path for technical specialists in their functional areas	-.009	.156	-.009	.431**	-.019	.004	-.059	.011	.020	-.035	-.121
Promotion is based on functional experience and knowledge	-.103	.154	-.047	.488**	-.085	.003	-.091	.125	-.100	-.118	-.048
More experienced employees are responsible for mentoring and supporting junior engineers	-.078	.179	-.045	.306**	.001	-.070	-.070	.033	-.009	-.015	-.077
Performance of individuals is regularly evaluated and discussed in feedback meetings	.090	.079	-.075	.308**	-.266**	-.075	-.073	.104	-.182	-.053	-.072

* p<0.05 ** p<0.01

Table B.7: Correlations between use of characteristics and the perceived ease of implementing the Lean PD components (Analysis C) – part 2

	Ease of Implementation Strong Project Manager	Ease of Implementation Set-based Engineering	Ease of Implementation Process Standardization	Ease of Implementation Specialist Career Path	Ease of Implementation Product Variety Management	Ease of Implementation Workload Leveling	Ease of Implementation Supplier Integration	Ease of Implementation Responsibility-based Planning and Control	Ease of Implementation Cross-project Knowledge Transfer	Ease of Implementation Rapid Prototyping, Simulation and Testing	Ease of Implementation Simultaneous Engineering
There are clear goals for the use of off-the-shelf components within a product	.058	.161	.143	.251**	.219*	-.072	-.007	.013	-.026	.045	-.019
There are clear goals for the reuse of product parts among different modules, products and product families	-.054	.123	.082	.245**	.185*	-.055	-.059	-.005	-.097	.013	-.057
There are modular components with standardized interfaces	-.118	.227*	.015	.118	.181	-.026	.115	.092	-.015	.144	-.127
There are common product platforms encompassing several product lines	-.045	.120	.164	.223*	.298**	.000	.130	-.005	-.011	.015	-.033
Product development resources are planned on a cross-project basis	.130	.147	.129	.042	-.005	.291**	-.055	.034	.095	.075	-.116
Development activities are scheduled and prioritized	.076	.269**	.069	.226*	-.054	.273**	-.011	.150	.011	.049	-.018
Actual and planned capacity utilization are compared frequently	.126	.194*	.046	.024	.059	.260**	-.014	.099	.000	.019	-.096
Resources are flexibly adapted in case of occurring bottlenecks	.049	.121	-.054	-.054	-.014	.387**	.092	-.012	.096	.240*	.076
Parts are evaluated according to their criticality before making outsourcing decisions	-.003	.125	-.083	.205*	-.009	-.102	.094	.058	-.144	.067	.009
A small number of high-capability suppliers are used for critical parts	.125	.164	.089	.226*	.005	-.014	.124	.066	-.074	.049	-.040
Critical suppliers are integrated in the concept definition phase	.106	.247**	.000	.111	.041	.044	.206*	.099	-.047	.122	.141
Suppliers are mentored to improve their performance	-.011	.086	-.114	.009	-.098	.037	.109	.036	-.060	.171	-.041
Developers are given the opportunity to set their own goals and negotiate deadlines for their tasks	.186*	.165	.016	-.089	.104	.173	.206*	.339**	.140	.010	-.044
Developers are given the opportunity to check their own performance based on a formalized feedback process	.109	.253**	.135	.019	.093	.132	.195*	.375**	.048	.081	.079
Developers are evaluated based on their performance	.097	.085	.036	-.004	.002	-.018	-.033	.118	-.021	.037	-.019
Developers are given the opportunity to experiment with new approaches to improve efficiency	.157	.242**	-.006	.228*	.045	.110	.018	.243**	-.038	.017	.120

* p<0.05   ** p<0.01

Table B.8: Correlations between use of characteristics and the perceived ease of implementing the Lean PD components (Analysis C) – part 3

	Ease of Implementation Strong Project Manager	Ease of Implementation Set-based Engineering	Ease of Implementation Process Standardization	Ease of Implementation Specialist Career Path	Ease of Implementation Product Variety Management	Ease of Implementation Workload Leveling	Ease of Implementation Supplier Integration	Ease of Implementation Responsibility-based Planning and Control	Ease of Implementation Cross-project Knowledge Transfer	Ease of Implementation Rapid Prototyping, Simulation and Testing	Ease of Implementation Simultaneous Engineering
There are methods and devices to collect information on successful prodecures, tools and designs across projects	.289**	.270**	.124	.248**	.065	.223*	.121	.005	.229*	-.040	.080
Best-practices and lessons learned from previous projects are reviewed	.089	.268**	.134	.196*	.086	-.067	.084	.038	.081	.048	-.049
Documented knowledge is continuously updated by the engineers	.170	.301**	.164	.267**	.101	.214*	.124	.184	.193*	.007	.103
The collected knowledge is frequently simplified and generalized	.191*	.214*	.210*	.179	.125	.130	.105	.090	.198*	-.079	-.014
Designs are quickly modeled and tested using physical models	.089	.086	.076	.071	-.056	-.151	.008	.029	-.110	.324**	.008
Computer-aided modelling and simulation are used	-.147	.014	-.026	.131	-.110	-.238*	-.104	-.094	-.240*	.213*	-.123
Rapid prototyping technology is used	.053	.007	-.017	.052	-.115	-.153	-.026	.049	-.164	.365**	-.040
Methods of Lean Production are used in prototype build and tool manufacturing	-.054	.070	.090	.145	-.022	-.023	.103	.197*	-.223*	.232*	.020
Representatives from manufacturing, quality assurance and purchasing are integrated in the concept definition phase	.087	.094	-.021	-.030	-.104	-.036	.059	.045	-.063	-.030	.196*
There are frequent review meetings with development, manufacturing, quality assurance and purchasing	-.044	.108	.030	.194*	-.139	.085	.129	.104	-.016	.088	.232*
There is a formalized process for evaluating design proposals regarding manufacturing and assembly compatibility	-.050	.200*	.004	.162	-.017	.105	-.068	.077	-.113	.013	.181
Development and testing of production facilities is done in parallel to product development	-.102	.113	-.105	.120	-.203*	-.007	-.019	.129	-.132	.014	.199*

* $p<0.05$ ** $p<0.01$

Table B.9: Correlations between use and perceived usefulness of implementation for Lean PD components (Analysis D)

	Usefulness of Implementation Strong Project Manager	Usefulness of Implementation Set-based Engineering	Usefulness of Implementation Process Standardization	Usefulness of Implementation Specialist Career Path	Usefulness of Implementation Product Variety Management	Usefulness of Implementation Workload Leveling	Usefulness of Implementation Supplier Integration	Usefulness of Implementation Responsibility-based Planning and Control	Usefulness of Implementation Cross-project Knowledge Transfer	Usefulness of Implementation Rapid Prototyping, Simulation and Testing	Usefulness of Implementation Simultaneous Engineering
Use of Strong Project Manager	.248**	-.020	-.015	.124	.072	.007	-.091	.017	-.046	-.016	.055
Use of Set-based Engineering	-.125	-.059	-.137	.045	-.147	-.143	.024	-.032	-.100	.132	-.073
Use of Process Standardization	.021	-.287**	.201*	-.057	.009	.128	.068	.028	-.138	.115	.029
Use of Specialist Career Path	-.153	.051	.048	.232*	.196*	.108	.158	.036	-.075	.072	.123
Use of Product Variety Management	-.156	-.366**	-.080	-.013	.163	-.014	.099	-.067	-.069	.089	.008
Use of Workload Leveling	-.064	-.206*	.036	.059	.040	.008	.087	.011	-.307**	-.039	-.030
Use of Supplier Integration	-.088	-.080	-.008	.088	.077	-.031	.278**	-.084	-.022	.132	.097
Use of Responsibility-based Planning and Control	.041	-.022	.018	.039	.028	-.066	-.081	.233*	-.047	-.034	-.116
Use of Cross-project Knowledge Transfer	-.188*	-.216*	-.032	.032	-.134	-.046	.056	-.044	-.024	.054	-.149
Use of Rapid Prototyping, Simulation and Testing	-.075	.076	-.033	.101	.069	.076	.234*	.066	.052	.515**	.215*
Use of Simultaneous Engineering	-.154	-.097	.067	.220*	.029	.132	.175	.069	-.008	.114	.262**

* $p<0.05$ ** $p<0.01$

Table B.10: Correlations between rank and perceived ease of implementation for Lean PD components (Analysis F)

	Ease of Implementation Strong Project Manager	Ease of Implementation Set-based Engineering	Ease of Implementation Process Standardization	Ease of Implementation Specialist Career Path	Ease of Implementation Product Variety Management	Ease of Implementation Workload Leveling	Ease of Implementation Supplier Integration	Ease of Implementation Responsibility-based Planning and Control	Ease of Implementation Cross-project Knowledge Transfer	Ease of Implementation Rapid Prototyping, Simulation and Testing	Ease of Implementation Simultaneous Engineering
Rank Strong Project Leader	-.116	.311**	-.026	-.022	.065	-.041	.134	.075	.101	.008	.196
Rank Set-based Engineering	-.067	-.262*	-.078	-.123	-.099	-.150	.027	-.156	-.164	-.132	-.135
Rank Process Standardization	.038	.036	-.097	-.044	-.058	.054	.188	.151	.003	.153	.056
Rank Specialist Career Path	.136	.065	.073	-.190	.178	-.078	.139	.201	-.072	.016	.033
Rank Product Variety Management	-.204	.003	-.025	-.052	-.075	-.072	.037	.119	-.129	-.175	-.069
Rank Workload Leveling	.019	.005	.022	.154	-.034	-.092	-.015	.052	.045	-.122	.049
Rank Supplier Integration	-.057	-.028	.033	-.028	-.005	-.074	-.163	.140	-.060	-.098	-.301**
Rank Responsibility-based Planning and Control	-.124	-.043	-.076	.108	-.148	-.233*	-.162	-.166	-.114	-.243*	-.189
Rank Cross-project Knowledge Transfer	-.019	-.020	-.063	-.011	-.020	-.138	-.069	.038	-.277**	.057	-.250*
Rank Rapid Prototyping, Simulation and Testing	-.115	.008	.056	.206	.268*	.196	.103	.068	.106	-.256*	-.064
Rank Simultaneous Engineering	.098	-.100	.102	-.095	-.032	.180	-.085	.042	-.097	.042	-.119

* $p<0.05$ ** $p<0.01$

Table B.11: Correlations between ranks and perceived usefulness of implementing the Lean PD components (Analysis G)

	Usefulness of Implementation Strong Project Manager	Usefulness of Implementation Set-based Engineering	Usefulness of Implementation Process Standardization	Usefulness of Implementation Specialist Career Path	Usefulness of Implementation Product Variety Management	Usefulness of Implementation Workload Leveling	Usefulness of Implementation Supplier Integration	Usefulness of Implementation Responsibility-based Planning and Control	Usefulness of Implementation Cross-project Knowledge Transfer	Usefulness of Implementation Rapid Prototyping, Simulation and Testing	Usefulness of Implementation Simultaneous Engineering
Rank Strong Project Leader	-.286**	-.037	.184	.247*	-.236*	.109	-.047	.002	.152	.172	.233*
Rank Set-based Engineering	.019	-.116	.038	.115	.241*	.225*	.110	.105	-.143	.012	.279*
Rank Process Standardization	-.078	.098	.006	.096	.036	.149	.066	.150	.065	.065	.165
Rank Specialist Career Path	.077	-.202	.187	-.091	-.084	-.124	-.128	.104	.058	.031	-.081
Rank Product Variety Management	-.036	.179	.049	.102	-.077	-.050	.088	.084	.016	-.126	.065
Rank Workload Leveling	-.095	.069	.006	.141	-.015	.071	-.095	-.019	.127	.074	.080
Rank Supplier Integration	.014	.200	.026	-.104	.010	-.148	-.160	.006	-.123	-.095	-.104
Rank Responsibility-based Planning and Control	-.068	.065	.134	.012	-.006	-.081	.179	-.228*	-.050	-.064	-.067
Rank Cross-project Knowledge Transfer	.136	.218*	.124	.213*	.356**	.099	.310**	.015	-.036	.136	.128
Rank Rapid Prototyping, Simulation and Testing	-.163	-.068	.003	.057	.063	-.072	-.124	-.107	-.026	-.451**	-.040
Rank Simultaneous Engineering	.094	-.003	-.042	-.161	.088	-.035	-.116	-.243*	-.062	-.034	-.205*

* p<0.05 ** p<0.01

Table B.12: Correlations of the perceived ease of implementing the Lean PD components (Analysis H)

	Ease of Implementation Strong Project Manager	Ease of Implementation Set-based Engineering	Ease of Implementation Process Standardization	Ease of Implementation Specialist Career Path	Ease of Implementation Product Variety Management	Ease of Implementation Workload Leveling	Ease of Implementation Supplier Integration	Ease of Implementation Responsibility-based Planning and Control	Ease of Implementation Cross-project Knowledge Transfer	Ease of Implementation Rapid Prototyping, Simulation and Testing	Ease of Implementation Simultaneous Engineering
Ease of Implementation Strong Project Manager	1	.139	.289**	.034	.100	.215*	.101	.182	.121	.114	.269**
Ease of Implementation Set-based Engineering	.139	1	.187*	.168	.200*	.176	.177	.355**	.213*	-.044	.183
Ease of Implementation Process Standardization	.289**	.187*	1	.208*	.462**	.360**	.280**	.295**	.264**	.116	.337**
Ease of Implementation Specialist Career Path	.034	.168	.208*	1	.134	.195*	.099	.140	.096	-.103	.145
Ease of Implementation Product Variety Management	.100	.200*	.462**	.134	1	.294**	.348**	.093	.430**	.175	.163
Ease of Implementation Workload Leveling	.215*	.176	.360**	.195*	.294**	1	.320**	.297**	.404**	.193*	.312**
Ease of Implementation Supplier Integration	.101	.177	.280**	.099	.348**	.320**	1	.370**	.338**	.246**	.387**
Ease of Implementation Responsibility-based Planning and Control	.182	.355**	.295**	.140	.093	.297**	.370**	1	.055	.001	.358**
Ease of Implementation Cross-project Knowledge Transfer	.121	.213*	.264**	.096	.430**	.404**	.338**	.055	1	.180	.238*
Ease of Implementation Rapid Prototyping, Simulation and Testing	.114	-.044	.116	-.103	.175	.193*	.246**	.001	.180	1	.274**
Ease of Implementation Simultaneous Engineering	.269**	.183	.337**	.145	.163	.312**	.387**	.358**	.238*	.274**	1

* $p<0.05$ ** $p<0.01$

Table B.13: Correlations between the perceived ease and perceived usefulness of implementing the Lean PD components (Analysis I)

	Usefulness of Implementation Strong Project Manager	Usefulness of Implementation Set-based Engineering	Usefulness of Implementation Process Standardization	Usefulness of Implementation Specialist Career Path	Usefulness of Implementation Product Variety Management	Usefulness of Implementation Workload Leveling	Usefulness of Implementation Supplier Integration	Usefulness of Implementation Responsibility-based Planning and Control	Usefulness of Implementation Cross-project Knowledge Transfer	Usefulness of Implementation Rapid Prototyping, Simulation and Testing	Usefulness of Implementation Simultaneous Engineering
Ease of Implementation Strong Project Manager	.050	-.175	-.003	-.212*	-.199*	.038	-.114	.009	.087	-.005	-.060
Ease of Implementation Set-based Engineering	-.448**	-.166	.003	.015	-.337**	.010	-.030	.110	-.009	-.006	-.060
Ease of Implementation Process Standardization	-.221*	-.233*	-.024	-.248**	-.249**	-.127	-.121	-.008	.072	-.045	-.153
Ease of Implementation Specialist Career Path	-.285**	-.054	-.236*	.157	-.028	.062	.043	.094	.158	-.035	.105
Ease of Implementation Product Variety Management	-.187*	-.253**	-.029	-.132	-.126	-.172	-.126	.079	.053	-.052	-.117
Ease of Implementation Workload Leveling	-.206*	-.226*	-.303**	-.145	-.270**	-.120	-.103	.079	-.022	-.275**	-.162
Ease of Implementation Supplier Integration	-.101	-.190*	-.115	.020	-.273**	-.126	-.091	.086	.058	-.139	-.177
Ease of Implementation Responsibility-based Planning and Control	-.180	-.121	-.064	-.079	-.218*	.006	-.134	.249**	.127	-.128	-.065
Ease of Implementation Cross-project Knowledge Transfer	-.249**	-.115	-.122	-.106	-.248**	-.287**	-.161	-.094	-.168	-.177	-.300**
Ease of Implementation Rapid Prototyping, Simulation and Testing	.023	-.075	-.060	-.200*	.024	-.095	.166	-.033	-.078	.343**	.112
Ease of Implementation Simultaneous Engineering	-.150	-.239*	-.023	-.086	-.271**	.041	-.123	.026	.114	.008	.095

* $p<0.05$ ** $p<0.01$

Table B.14: Correlations of perceived usefulness of implementing the Lean PD components (Analysis J)

	Usefulness of Implementation Strong Project Manager	Usefulness of Implementation Set-based Engineering	Usefulness of Implementation Process Standardization	Usefulness of Implementation Specialist Career Path	Usefulness of Implementation Product Variety Management	Usefulness of Implementation Workload Leveling	Usefulness of Implementation Supplier Integration	Usefulness of Implementation Responsibility-based Planning and Control	Usefulness of Implementation Cross-project Knowledge Transfer	Usefulness of Implementation Rapid Prototyping, Simulation and Testing	Usefulness of Implementation Simultaneous Engineering
Usefulness of Implementation Strong Project Manager	1	.213*	.258**	.007	.244**	.102	.041	.150	.088	.099	.007
Usefulness of Implementation Set-based Engineering	.213*	1	.055	.274**	.222*	-.064	.238*	.061	.164	.179	.198*
Usefulness of Implementation Process Standardization	.258**	.055	1	.137	.171	.327**	.185	.201*	.180	.139	.234*
Usefulness of Implementation Specialist Career Path	.007	.274**	.137	1	.236*	.121	.271**	.218*	.251**	.171	.280**
Usefulness of Implementation Product Variety Management	.244**	.222*	.171	.236*	1	.258**	.311**	.048	-.055	.199*	.139
Usefulness of Implementation Workload Leveling	.102	-.064	.327**	.121	.258**	1	.217*	.326**	.132	.367**	.482**
Usefulness of Implementation Supplier Integration	.041	.238*	.185	.271**	.311**	.217*	1	.073	.160	.458**	.360**
Usefulness of Implementation Responsibility-based Planning and Control	.150	.061	.201*	.218*	.048	.326**	.073	1	.222*	.138	.199*
Usefulness of Implementation Cross-project Knowledge Transfer	.088	.164	.180	.251**	-.055	.132	.160	.222*	1	.111	.241*
Usefulness of Implementation Rapid Prototyping, Simulation and Testing	.099	.179	.139	.171	.199*	.367**	.458**	.138	.111	1	.391**
Usefulness of Implementation Simultaneous Engineering	.007	.198*	.234*	.280**	.139	.482**	.360**	.199*	.241*	.391**	1

* p<0.05 ** p<0.01