Applying Product Configuration Systems in Engineering Companies
Motivations and Barriers for Configuration Projects

Ladeby, Klaes Rohde

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Applying Product Configuration Systems in Engineering Companies

– Motivations and Barriers for Configuration Projects

Klaes Rohde Ladeby

July 2010
Thesis for the degree of Doctor of Philosophy

Applying Product Configuration Systems in Engineering Companies
Motivations and Barriers for Configuration Projects
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2009

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PART 0: INTRODUCTION .................................................................................................................. 1

PREFACE ........................................................................................................................................ 2

ASSUMPTIONS I’VE MADE ABOUT YOU IN WRITING THIS THESIS ........................................... 3

THANK YOU ................................................................................................................................. 4

ABSTRACT ...................................................................................................................................... 5

RESUMÉ ........................................................................................................................................ 6

1 INTRODUCTION ............................................................................................................................ 7

1.1 PRODUCT CONFIGURATION IN ENGINEERING COMPANIES ................................................ 8

1.1.1 Configuration at FLSmidth A/S .......................................................................................... 8

1.1.2 A Closer Look at the Example ......................................................................................... 10

1.2 PRODUCT CONFIGURATION SYSTEMS AS A FIELD OF RESEARCH .................................... 13

1.2.1 The Technical University of Denmark ........................................................................... 14

1.2.2 The Helsinki University of Technology .......................................................................... 15

1.2.3 Forza and Salvador .......................................................................................................... 16

1.2.4 The University of Klagenfurt ......................................................................................... 17

1.3 THE AIM OF THE THESIS ..................................................................................................... 18

1.4 STRUCTURE OF THE THESIS ............................................................................................... 18

1.5 SUMMARY .............................................................................................................................. 19

PART I: EXISTING KNOWLEDGE AND RESEARCH QUESTIONS ......................................................... 21

2 THE LITERATURE OF PRODUCT CONFIGURATION SYSTEMS .................................................. 22

2.1 THE RISE AND FALL OF R1 .................................................................................................... 22

2.1.1 McDermott’s (1982) ‘R1: A Rule-Based Configurer of Computer Systems’ ................... 23

2.1.2 Barker et al. (1989) ‘Expert Systems for Configuration at Digital - Xcon and Beyond’ .... 24

2.1.3 Reflections on ‘The Rise and Fall of R1’ .......................................................................... 26

2.2 DEFINITION OF CONFIGURATION AND THE CONFIGURATION TASK ................................ 27

2.2.1 Mittal and Frayman (1989) ‘Towards a generic model of configuration tasks’ .............. 27

2.2.2 Cunis et al. (1989) ‘PLAKON - an approach to domain-independent construction’ .......... 29

2.2.3 Heimrich & Jüngst (1991) ‘A resource-based paradigm for the configuring of technical systems from modular components’ ........................................................................... 30

2.2.4 Najmann & Stein (1992) ‘A theoretical framework for configuration’ ............................ 34

2.2.5 Soininen et al. (1998) ‘Towards a general ontology of configuration’ ........................... 34

2.2.6 Reflections on ‘Definition of Configuration and the Configuration Task’ ..................... 36

2.3 PRODUCT CONFIGURATION SYSTEMS – A NEW KIND OF EXPERT SYSTEMS ................ 37

2.3.1 Krause et al. (1993) ‘Product Modelling’ ......................................................................... 38

2.3.2 Schwarze (1996) ‘Configuration of Multiple-variant products’ ................................ 39

2.3.3 Hvam (1999) ‘A procedure for building product models’ ............................................. 41

2.3.4 Franke & Piller (2004) ‘Value creation by toolkits for user innovation and design’ ....... 43

2.3.5 Forza & Salvador (2007) ‘Product Information Management for Mass Customization’ ... 45

2.3.6 Hvam, Mortensen & Riis (2008) ‘Product Customization’ ............................................ 47

2.3.7 Reflections on ‘Product Configuration Systems – a new Kind of Expert Systems’ ........ 50

2.4 SUMMARY .............................................................................................................................. 52

3 RESEARCH QUESTIONS AND METHODOLOGY ...................................................................... 53

3.1 DEVELOPING RESEARCH QUESTIONS .................................................................................. 54

3.1.1 What We Know ................................................................................................................. 56

3.1.2 What Should be Researched ............................................................................................. 56

3.1.3 Research Questions ........................................................................................................... 57

3.2 METHODOLOGY ..................................................................................................................... 57

3.3 SUMMARY .............................................................................................................................. 59

PART II: UNDERSTANDING CONFIGURATION .............................................................................. 61
4 DEVELOPING A FRAME OF REFERENCE .................................................62
  4.1 TECHNICAL SYSTEMS (THE PRODUCT) .....................................62
    4.1.1 Function structure of TS ............................................65
    4.1.2 Organ structure of TS .............................................66
    4.1.3 Component structure of TS .........................................66
  4.2 CONFIGURATION TASK .........................................................67
  4.3 PRODUCT MODEL ..............................................................70
  4.4 CONFIGURATORS OR CONFIGURATION SYSTEMS ..........................73
  4.5 UNDERSTANDING THE TOTAL CONFIGURATION SYSTEM .............75
    4.5.1 Understanding the Operand of the TCS ...........................76
    4.5.2 Understanding the Operators of the TCS ..........................78
    4.5.3 Understanding the User as an Operator ...........................78
    4.5.4 Understanding the Product Configuration System as Operator ..79
    4.5.5 Understanding the Organisation as Operator .....................79
    4.5.6 Understanding the Configuration Process of the TCS ...........82
  4.6 SUMMARY ........................................................................83

5 DEVELOPING A TYPOLOGY OF PRODUCT CONFIGURATION SYSTEM ....84
  5.1 TYPOLOGY OF PRODUCT CONFIGURATION SYSTEMS BASED ON PRODUCT KNOWLEDGE ....85
    5.1.1 Component Structure ................................................87
    5.1.2 Function Structure ....................................................87
    5.1.3 Mapping Between Function Structure and Component Structure ....87
    5.1.4 Purpose ...............................................................88
    5.1.5 Mapping Between Function Structure and Purpose ..............88
  5.2 SUMMARY ........................................................................90

6 PREREQUISITES FOR CONFIGURATION ..........................................92
  6.1 KNOWLEDGE FOR CONFIGURATION SYSTEMS ............................92
  6.2 ESTIMATING CONFIGURATION READINESS ................................95
  6.3 DEFINITION OF CONFIGURATION SCOPE ..................................95
  6.4 ESTIMATING KNOWLEDGE ....................................................96
    6.4.1 Assessing Process Knowledge ......................................96
    6.4.2 Assessing Product Knowledge ......................................97
  6.5 ESTIMATING READINESS .....................................................98
  6.6 SUMMARY .........................................................................99

PART III: CONFIGURATION IN ENGINEERING COMPANIES ..................101

7 CONFIGURATION IN ENGINEERING COMPANIES ...........................102
  7.1 MOTIVATION FOR CONFIGURATION PROJECTS IN ENGINEERING COMPANIES ........102
    7.1.1 Standardisation of Process Knowledge .............................105
    7.1.2 Standardisation of Product Knowledge .............................110
  7.2 UNDERSTANDING KNOWLEDGE ELICITATION IN ENGINEERING COMPANIES ..........113
  7.3 UNDERSTANDING CONFIGURATION PROJECTS ............................115
    7.3.1 Issues with the Professional Bureaucracy .........................120
    7.3.2 Issues with the Operating Adhocracy ...............................120
  7.4 DATA COLLECTION ................................................................121
    7.4.1 Structure of Interviews ...............................................122
    7.4.2 Structure of Case Chapters .........................................123
  7.5 SUMMARY .........................................................................124

8 CASE: GEA NIRO .........................................................................125
  8.1 DESCRIPTION OF CASE: GEA NIRO .......................................125
    8.1.1 Configuration at GEA NiRo ...........................................126
    8.1.2 Development and Implementation ....................................129
    8.1.3 Operation ...............................................................130
  8.2 ANALYSIS OF CASE: GEA NIRO ...........................................131
    8.2.1 The Motivation for the Configuration Project ....................131
## List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>AEnv</td>
<td>Active environment</td>
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<tr>
<td>API</td>
<td>Active pharmaceutical ingredient</td>
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<td>B2B</td>
<td>Business to Business</td>
</tr>
<tr>
<td>B2C</td>
<td>Business to Consumer</td>
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<tr>
<td>BPMN</td>
<td>Business process modelling notation</td>
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<tr>
<td>CRL</td>
<td>Configuration rule language</td>
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<tr>
<td>CTO</td>
<td>Configure-to-order</td>
</tr>
<tr>
<td>CVM</td>
<td>Contingent valuation method</td>
</tr>
<tr>
<td>ETO</td>
<td>Engineer-to-order</td>
</tr>
<tr>
<td>GERAM</td>
<td>Generalised enterprise reference architecture and methodology</td>
</tr>
<tr>
<td>HuS</td>
<td>Human system</td>
</tr>
<tr>
<td>MTO</td>
<td>Make-to-order</td>
</tr>
<tr>
<td>MTS</td>
<td>Make-to-stock</td>
</tr>
<tr>
<td>OOA</td>
<td>Object-Oriented Analysis</td>
</tr>
<tr>
<td>OOD</td>
<td>Object-Oriented Design</td>
</tr>
<tr>
<td>OSDL</td>
<td>Order specification decoupling line</td>
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<tr>
<td>PAM</td>
<td>Project activity model</td>
</tr>
<tr>
<td>PETO</td>
<td>Research project at Technical University of Denmark: Product Configuration – Economical Technical and Organisational Issues</td>
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<tr>
<td>PFMP</td>
<td>Product family master plan</td>
</tr>
<tr>
<td>PVM</td>
<td>Product variant master</td>
</tr>
<tr>
<td>STO</td>
<td>Select-to-order</td>
</tr>
<tr>
<td>TCS</td>
<td>Total configuration system</td>
</tr>
<tr>
<td>TP</td>
<td>Technical process</td>
</tr>
<tr>
<td>TS</td>
<td>Technical System</td>
</tr>
<tr>
<td>TTS</td>
<td>Theory of Technical Systems</td>
</tr>
<tr>
<td>UML</td>
<td>Unified Modelling Language</td>
</tr>
<tr>
<td>VA</td>
<td>Vickrey auction</td>
</tr>
<tr>
<td>VisCon</td>
<td>The visual configuration project at NNE Pharmaplan</td>
</tr>
<tr>
<td>WTP</td>
<td>Willingness to pay</td>
</tr>
</tbody>
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Part Ø: Introduction

“Human beings, who are almost unique [among animals] in having the ability to learn from the experience of others, are also remarkable for their apparent disinclination to do so.”

Douglas Adams
Preface

I generally don’t trust prefaces much, and I suggest that you don’t either. Prefaces are rarely written in the same style and voice as the rest of the book. Your best opportunity in seeing if this book is for you implicate flipping back to the Table of Contents, picking a chapter you think sounds interesting, and skimming through what I have to say about it. Present thesis was written in a period over almost three years, consequently the voice of the book is different across chapters.

In April 2004 this project was begun in cooperation with NNE Pharmaplan. The intention was to study the modelling of product knowledge when it is used as a basis for visual configuration in engineering companies. In four months we created financial room for testing visual configuration at NNE Pharmaplan by developing a prototype on a visual configuration system - the Visual Configuration Project (VisCon) was born. During this period I gained much knowledge of NNE Pharmaplan’s way of management, project execution, and product portfolio.

The development of the prototype progressed quickly through the help of two master thesis students, and by December 2004 we could make a rough estimate of the investment needed and show how the software fulfilled NNE Pharmaplan’s needs. It turned out that the initial software chosen could not fulfil our demands to the graphical user interface, but the management of NNE Pharmaplan still agreed to fund the VisCon project for a full scale project if the right software was found.

In February 2005 the right software turned up or rather the company to develop the right software turned up. A one month pilot project was initiated to test the software with the goal of developing a full functioning prototype. The prototype would be used to provide a virtual mock-up of Novo Nordisk’s FVII\(^1\) on the InterPhex\(^2\) conference in New York in 2005. The purpose was to illustrate and market how NNE Pharmaplan conceptualised pharmaceutical plants through the intelligent application of modular engineering and visual configuration.

The project proceeded and in April 2005 I was given the unique possibility of taking a key position in the development of a visual configuration system for conceptualising pharmaceutical plants in the conceptual design phase. I quickly decided to pursue this possibility and took a year of absence from my Ph.D. study. That year I worked full time on the VisCon project as a knowledge engineer. Version 1 was released to the users in September 2005; Version 2 in January 2006. Version 2 marked an important step in the VisCon project – the transition from development project to operation. The VisCon project is described in more conference proceedings, see (Larsen, Ladeby, & Gjøl, 2006; Ladeby, Larsen, & Gjøl, 2007).

In April 2006 it was time for me to hand over the operation of the VisCon system to a new group of employees, and start focusing on my Ph.D. project again.

After I returned to my Ph.D., I changed the theme for my Ph.D. The VisCon project has made it clear to me that the modelling of knowledge was not the biggest issue in a project such as the VisCon project. In fact, since the modular philosophy from modular engineering was implemented in NNE Pharmaplan, all process modules in a facility were completely decoupled and had no other relation to other modules than a few pipes. Furthermore, because there was such a high abstraction

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\(^1\) Designed and constructed by NNE Pharmaplan. Nominated and won the Facility of the year price 2005 at Interphex

\(^2\) The largest annual event for the pharmaceutical industry – www.interphex.com
level in the VisCon project, the techniques used to model knowledge were not groundbreaking. Thus, it would be hard to make a scientific contribution on the basis of the work carried out in NNE Pharmaplan.

However, during my leave of absence, I participated in the 3rd Mass Customization and Personalization Conference in Hong Kong in 2005, and the following year, during the Production and Operation Management Society conference in Boston 2006, it became clear to me that there was an interesting research area on how product configuration systems were applied in engineering companies. The understanding of how configuration projects were carried out in engineering companies was undocumented (at best it was case described in a narrative style).

Although there are a lot of recent case studies concerning product configuration systems in engineering companies, until today, the case stories have been anecdotal descriptions of IT-projects. This makes it hard to compare configuration projects in engineering companies versus configuration projects in manufacturing companies. Furthermore, it makes it hard to analyse what characterises the different approaches, what advantages can be expected when choosing one instead of the other, and at what costs. So we needed a frame to describe configuration projects in engineering companies.

Such a frame would be used both to explain the difficulties that configuration projects encounter in engineering companies and to compare configuration projects across different types of organisations.

All told I decided to write about why and how product configuration systems can be applied in engineering companies. To do this I needed a frame which made it possible to describe configuration systems consistently so that they could be compared across different companies thus gaining a better understanding of how configuration project are carried out in engineering companies. I also needed to subdivide configuration systems into groups and find the prerequisites for configuring.

**Assumptions I’ve Made about You in Writing This Thesis**

You are intelligent - not stupid. So if I structured the thesis in the right chapters, and write these well, I assume that you won’t have to use time on slowly construction of elaborate frameworks. Instead, I hope that I’ll quickly can lead you to the point and spend time there. You are probably either something of a peer with more, less, or different experience or either you are related to me as friend or family in which case you fell obligated to read this thesis. In the latter case I hope, that I included a suiting amount of background material, so you’ll understand the points that I’m trying to make.

I assume that you are curious and pragmatic. I assume that you want to learn, and are open to different ideas, and will appreciate the value of careful and well thought-out contributions to the research field of product configuration systems even if you don’t agree with them.

I assume that you do not like jargon, or buzzwords. I do not think that buzzwords and jargon helps in researching and applying new information (although it definitely helps in selling lots of books to managers). I will try to avoid the use of buzzword and jargon in this thesis.

Finally, I hope you will not take your self and research in general too seriously. However I hope and assume that I have managed to write a thesis which is both rigorous and relevant for the community.
Thank you

Many persons have assisted me through this project, and my deepest apologies to those who I have forgotten to mention in the following.

A special thank you goes to my supervisor Jørgen Lindgaard Pedersen, who motivated me throughout my project, and assisted with his insight and knowledge. Associate professor Kasper Edwards deserves a special mentioning for having lead me clear of pitfalls and dangers in a predominately Tayloristic environment.

I had the luck of becoming part of a great team during my Ph.D. study. My fellow Ph.D. colleagues Anders Haug, Gudmundur Valur Odsson, and Tim Teglgaard Christensen have been a tremendous support in moments of disillusion and despair – thank you guys for all the support and motivation.

My beloved girlfriend has been of great assistance and support to me throughout the process of writing my Ph.D. In times of desolation she always stood by my side. My lovely daughter Vilma gave me the motivation to finalise the project and get on with my (or our) life/lives. I am also thankful to my family as well as my extended family that supported me. This thesis could not have been completed without them.

I would like to thank the following persons, who have helped in various stages of the project. Kasper Bonnevie, Manager, NNE Pharmaplan (2004-2007) for continuous motivation. Gert Mølgaard, Senior Vice President, Consulting, NNE Pharmaplan A/S for making this Industrial Ph.D. project possible and for his support during the project, and last but not least my company supervisor Niels Pedersen, Senior Engineering Manager, NNE Pharmaplan A/S for all his inspiration and support.

Finally, I would like to acknowledge all colleagues in NNE Pharmaplan who supported me and contributed by setting aside time for various discussions in the period of 2004 – 2008.

Klaes R. Ladeby, April 2009, Kgs. Lyngby
Abstract

This Ph.D. thesis looks into the application of configuration systems in engineering companies, and how configuration systems can be used to support business processes in engineering companies. Often the motivation stated by researchers and practitioners is, that a configuration project is a strategic initiative, see (Hvam, 2001; Edwards & Riis, 2004; Hvam et al., 2004; Edwards et al., 2005; Haug, Ladeby, & Edwards, 2007; Hvam, Mortensen, & Riis, 2007; Hvam, Mortensen, & Riis, 2008). The fundamental question in the field of strategic management can be formulated as:

“...how firms achieve and sustain competitive advantage”

(Teece, Pisano, & Shuen, 1997, pp.509)

This question has puzzled academics and preoccupied managers for the last century. Yet, it seems there is still no consensus regarding the meaning of strategy, and how strategy works. Type in the word “strategy” on Amazon.co.uk and 76,133 books apply. Type it in on Google scholar and 8,580,000 homepages apply\(^3\). Obviously, strategy is an important subject. However, the subject also seems to be difficult to perceive. Although this thesis is not about strategy, or strategizing, I would like to pursue the definition of strategy one step further.

“[In order] to be strategic, a capability must be honed to a user need (so that there are customers), unique (so that the products/services produced can be priced without too much regard to competition), and difficult to replicate (so that profits will not be competed away).

(Teece & Pisano, 1994, pp.539)

Are configuration projects in engineering companies established as strategic initiatives? We do not know. This thesis analyse the application of configuration systems in engineering companies by asking and answering the following meta-question: "How are configuration projects carried out in engineering companies?"

Product configuration systems are a fairly young field of research, and the literature used in this project is presented in chapter 2. Chapter 3 begins with a discussion of the scientific point of view, and develops the research questions are by an investigation into shortcomings and strengths of the contributions presented in the previous chapter. Chapter 4 establishes a frame of reference concerning the configuration world. Chapter 5 develops a typology that identifies four different kinds of configuration systems, and chapter 6 elaborates on the prerequisites for configuration. Chapter 7 sets the stage for the two case studies described in chapter 8 and chapter 9. Chapter 10 discusses the results and chapter 11 presents the concluding remarks of this Ph.D.

\(^3\) Results from 2008.10.08
Resumé

I denne phd-afhandling undersøges brugen af konfigureringssystemer i rådgivende ingeniør virksomheder, og hvordan konfigureringssystemer kan benyttes til at understøtte forretningsprocesser heri. Ofte begrundes udviklingen af konfigureringssystemer som et strategisk initiativ, se (Hvam, 2001; Edwards & Riis, 2004; Hvam et al., 2004; Edwards et al., 2005; Haug et al., 2007; Hvam et al., 2007; Hvam et al., 2008). Det fundamentale spørgsmål i strategisk planlægning kan formuleres som:

“...how firms achieve and sustain competitive advantage”

(Teece et al., 1997, pp.509)

Dette spørgsmål har beskæftiget ledere og forskere i det sidste århundrede. Men alligevel er der stadig ingen konsensus omkring hvad en strategi er, og hvad det vil sige at være strategisk. Hvis man søger på ”strategy” på amazone.co.uk får man 76.133 bøger. En tilsvarende søgning på google scholar giver 8.580.000 søgeresultater4. Strategi er tydeligvis et vigtigt emne der optager mange selvom det er et emne der også kan være svært at anvende i praksis. Selvom denne afhandling ikke omhandler strategi eller strategisk planlægning, så vil jeg alligevel gerne komme lidt tættere på definitionen af strategisk med det følgende citat:

“[In order] to be strategic, a capability must be honed to a user need (so that there are customers), unique (so that the products/services produced can be priced without too much regard to competition), and difficult to replicate (so that profits will not be competed away).

(Teece & Pisano, 1994, pp.539)

Igangsættet konfigureringsprojekter i rådgivende ingeniørvirksomheder som strategiske initiativer? Det vides ikke. Denne phd-afhandling vil forsøge at forstå anvendelsen af konfigureringssystemer i rådgivende ingeniørvirksomheder ved at besvare det overordnede spørgsmål: ”Hvordan gennemføres konfigureringsprojekter i rådgivende ingeniørvirksomheder?”


4 Søgeresultater fra 2008.10.08
1 Introduction

Product configuration systems are increasingly seen as an interesting option for firms who wish to pursue a strategy with high degree of product variance while retaining a low cost of specifying the product (Tseng & Piller, 2005). This scenario is often present in mass production companies who wish to pursue a mass customisation strategy (Haug, Ladeby, & Edwards, 2009). Product configuration systems can also be seen as direct productivity drivers in engineering companies and examples of unheard productivity gains are documented. For instance, in 1999 FL.Smidth, a Danish engineering firm, experienced an average drop in engineering hours from 2500 to 190 for producing a quote (Hvam et al., 2004; Hvam, 2006). Product configuration systems may also find use as stand alone product validation systems in parts of the engineering process thus also providing productivity gains (Larsen et al., 2006). Finally, product configuration systems are seen as key enablers in reducing both the cost of eliciting customer wishes and the costs of controlling the high degree of variety in mass customisation companies (Moser, 2007).

While product configuration systems indeed offer significant productivity potential, developing and implementing configuration systems are apparently difficult and prone to delays or failures. The sad observation from the Danish research project ‘Product Configuration – Economical, Technical and Organisational Issues’ (PETO) has been that product configuration projects are systematically delayed. Indeed, all too often at least twice the estimated time is used (Edwards & Riis, 2004; Edwards & Ladeby, 2005). Although product configuration systems have been actively researched (Hvam & Have, 1998; Hvam, 1999; Riis, 2003; Hansen, 2003; Haug & Hvam, 2006a; Haug & Hvam, 2006c) no one offers a explanation of or a reason why there is such a high degree of failure.

Unfortunately, most published work about product configuration systems in general seems to refer only to an intuitive definition of the basic concepts of configuration, and therefore it is difficult to make meaningful comparisons, and not to say impossible to identify why some projects fail while others succeed (a few exceptions are (Stumptner, 1997; Sabin & Weigel, 1998; Fleishanderl et al., 1998; Soininen et al., 1998; Felfernig et al., 2004; Haug, 2007)). Configuration is in some cases considered a part of the design science discussion - a special case of the general field of design activities. In Stumptner (1997) it is assumed that in configuration the design goals and requirements are fully specified, and subcomponents and functions are already known. This assumption is also supported by Sabin and Weigel (1998), who note: “...product configuration is informally a special case of design activity and consists of two key features: a) the artefact being configured is assembled from instances of a fixed set of well-defined component types, and b) components interact with each other in predefined ways.”

However, the core of configuration is selecting and arranging combinations of existing parts that satisfy given specifications. No new component types can be created nor can the interfaces of the existing components be modified. The configured solution must provide a list of selected components, and describe the product structure and topology of the product (Sabin & Weigel, 1998).

The purpose of the present thesis is to explore the following meta-question: "How are configuration projects carried out in engineering companies?". This is complicated by the current state of the research in product configuration systems. In Piller (Piller, 2004) Frank Piller reflects upon research regarding product configuration systems or toolkits as he terms them. He observes that:
“The literature which directly addresses toolkits, mostly supplies only anecdotal studies and describes toolkit cases in a narrative style”

(Piller, 2004, pp.318)

To become more specific in relation to how configuration systems can support the business of engineering companies this thesis will try to create a frame of reference which defines key concepts and definitions related to configuration. Then it will identify different kinds of product configuration systems and describe how they differ, and finally it will identify the prerequisites for configurering. The thesis makes the author’s understanding of configuration explicit to the reader, and it makes it possible to understand: How are configuration projects carried out in engineering companies?

The present thesis is about how product configuration systems primarily known from the manufacturing world can be applied to engineering companies. Before we proceed, let us take a closer look at a well documented case of product configuration from an engineering company: FL.Smidt A/S.

1.1 Product Configuration in Engineering Companies

To get an idea of factors which are important when applying product configuration system in engineering companies, let us take a look at a well-described Danish case. The following mini-case is: 'Configuration at FL.Smidt A/S. FL.Smidt has been working with configuration since the end of the nineties, and has formalised structures in the organisation responsible for the configuration project.

1.1.1 Configuration at FL.Smidt A/S

The case of configuration of quotations at FL.Smidt is described in the literature (see (Hvam et al., 2004; Hvam, Pape, & Nielsen, 2006; Hvam, 2006)). FL.Smidt manufactures large processing plants for cement production. FL.Smidt is an engineering and industrial company with a leading position within the international market of development, engineering and built-up of plants producing cement. FL.Smidt has a market share of more than 50% worldwide based on kiln capacity, and in 2001 the company had a turnover of USD 850 million (Hvam, 2006).

The most important customer requirements and choice options when ordering cement plants can be summarized as follows:

- “Price, including financing terms
- Delivery time
- Operating Costs
- Energy consumption and environmental impact (emissions)”

(Hvam, 2006, pp.447)

The capability to deliver this information in the shape of a binding quotation has become a major competitive factor for FL.Smidt. Given the scale of a turnkey project, even small miscalculations can result in substantial losses for the company. Taken the complexity and uniqueness of each project into consideration, the initial solution was to allocate plenty of resources to the quotation process in order to meet the demands of quotations (Hvam, 2006). This situation

---

5 Cement kilns are the heart of the production process of cement. The kiln capacity usually defines the capacity of the cement plant.
motivated FL.Smidth to develop and implement a product configuration system to support the quotation process. The project contained a radical reengineering of the quotation process as described in Hvam et al. (2004).

**Description of the Quotation Process**

The quotation process was identified to hold a large potential for improvement. Figure 1-1 depicts the sales process before the reengineering of the quotation process, and how it was intended to be after the reengineering process. According to Hvam et al. (2006), the previous quotation process was very large, very complex, and involved several organisational units in the company.

At FL.Smidth they distinguish between two different kinds of quotation:

(i) Budget quotations which provide an overview and a price/weight estimate have a lead-time of 5-20 days, and they require an effort of 5 man weeks.

(ii) Detailed quotations which cover every detail and all equipment is calculated and designed according to customer requirements. These require an effort of 1-2 man-years

(Hvam et al., 2006)

The old procedure was to make a budget quotation for the customer, and if he was interested, a detailed quotation was prepared through a number of iterations. This was time consuming, and as the quotation-to-order ratio was declining, it was decided to redesign the quotation process.

Figure 1-1: Faster and better budget quotes lead to less detailed quotes (Hvam et al., 2004, pp.207).

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**Sales process (As-Is)**

- Budget quote 1
- Detailed quote 1
- Detailed quote 2
- Detailed quote 3

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**Concept (To-Be)**

- Budget quote 1
- Budget quote 2
- Budget quote 3
- Detailed quote 1

The new quotation process is supported by a product configuration system, and budget quotations are used as an active part of the dialogue with the customer. The project at FL.Smidth had a keep-it-simple headline due to the very complex product. For that reason, integrations to other systems were never made. Even though no integration was made to other systems the benefits of the project were still obvious:
1. “reduction in lead time from 15-25 days to 1-2 days for the generation of tenders;
2. better quality of quotes as it is made possible to optimise the cement plants according to the customer’s needs, and as there are less errors in the specifications made in the configuration system relative to the specifications made in the old process; and
3. the direct consumption of engineering resources for making quotations was reduced from five man-weeks to one to two man-days.”

(Hvam et al., 2004, pp.212)

1.1.2 A Closer Look at the Example

A general observation from the case is that product configuration is the use of formalised product knowledge (a product model) embedded in an IT-system (a product configuration system) that supports a business process. So seemingly the knowledge required to develop a configuration system can be divided in two: (i) Knowledge about the product that is configured, and (ii) knowledge about the business process which the system supports.

FL.Smidth changed the business process of producing quotation and formalised knowledge into a configuration system. Could the same rationalisation effects have been obtained by merely changing the quotation process alone? Which role does the configuration system play in this change? If you look at the material presented in the journal papers, it is hard to answer these questions. The case descriptions of FL.Smidth do not describe how many of the benefits obtained by the project were due to the formalisation of product knowledge, and how many were due to changes in the quotation process. A huge rationalisation effect can be obtained if the task to be carried out is changed but this is not necessarily due to the implementation of a configuration system. This task is like comparing apples and oranges as you are no longer comparing the same tasks. For instance, if the scope of the task is reduced, the time it takes to carry out the task is most likely reduced as well.

The answer to the questions is probably that it is a combination of both the formalisation of product knowledge into a configuration system and the change of the business process which enable the dramatic rationalisation effects.

Characteristics of Plants

The world of engineering is both similar and different to the world of manufacturing. Traditionally, the different basic types of manufacturing are described as seen in Figure 1-2. This understanding is adapted by the work of Hayes and Wheelwright (1979) and generally accepted in the operations management society.
The products and services offered by engineering companies are often described as ‘make-to-order’ products (MTO). MTO products are designed, produced, and delivered according to customer specifications through a specific customer order, ending with a customer specific variant of the product (Russell & Taylor III, 2000). MTO products typically have a low degree of standardization. The processes of engineering companies are generally described as projects which take a long time to complete, involve large investment of funds and resources, and produce one item at a time to a specific customer order (Russell & Taylor III, 2000), so typical engineering companies produce a low volume of similar products.

Product configuration systems are generally applied in batch production and mass production companies where the standardization is medium to high and the volume is relatively high as well. Taking into consideration that engineering companies produce non-standardized products according to wishes and desires of the customer, and that the volume of each product is low, how can it be that product configuration systems are interesting in these kinds of companies?

The products of engineering companies are often characterised as made-to-order or one-of-a-kind and give associations to complex systems with very complex functions that serve complex capabilities. According to Hubka & Eder (1995) plants are technical system of the highest level of complexity, and plants have similarities to other major projects and infrastructures such as manufacturing plant, energy generating plant, chemical plant, traffic and utilities infrastructure (Hubka & Eder, 1995). According to Hubka & Eder (1995) a plant displays the following characteristic features:

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6 Often products designed in response to a customer order are referred to as ‘engineered-to-order’, products built and delivered in response to customer requests are referred to as ‘made-to-order’ (Russell & Taylor III, 2000).
• “it is technically complex;
• it is costly to very costly;
• it contains several kinds of technical systems: building, machine, electrical systems, etc.;
• it combines many purchasable elements into a unity (only a small part of any plant is manufactured to order);
• in planning – designing – the emphasis lies clearly in conceptualizing and establishing the processes, and the arrangement (configuration) of the chosen sub-units – machines;
• the technology of the transformation is the dominating element in reference to quality;
• the operator (factor) environment plays an unusually important role, not only technically but also socially and, in large plants, also politically;
• it is realized predominantly (or almost exclusively) in single-item (made-to-order, one-of-a-kind) production, although many of its elements can be manufactured in larger numbers of pieces.” (Hubka & Eder, 1995)

This gives rise to some reflections on configuration in engineering companies. Although a plant is typically one-of-a-kind and technically complex making it ill-suited for configuration, it consists of purchasable elements, and many of these elements are manufactured in larger numbers and these elements could very well be perfectly suited for configuration. So the plant as a whole is probably difficult to configure while the components or parts that the plant consists of should be configurable. Only a small part of the plant is manufactured to order, while most of the plant consists of off-the-shelf components. So how is it possible for companies like FL.Smidth to configure? FL.Smidth configures in early phases of their sales phase of a project. Here the emphasis is on conceptualising and establishing the main processes of the plant. In this process it is possible to use a configuration system to aid with the conceptualisation of a plant and the production of quotation material for the customer.

Configuration – Mass Customization or Design

Several authors have published literature on the means of mass customization. On this subject Piller (2004, pp.317) notes:”...the costs of mass customization include two factors: (i) the cost of providing high flexibility in manufacturing, and (ii) the cost of eliciting customer preferences.” Sabin & Weigel (1998, pp.42) frame it differently: “The impact on mass customization on organizations is twofold; it affects both the product-realization and the order-realization processes”.

Sabin & Weigel (1998) find that the requirement of mass customization at the order-realization level is to understand the customer’s needs and to create a complete description of a product variant that meets those needs. This is basically a configuration step (Sabin & Weigel, 1998). So a natural consequence is that the use of product configuration systems aims at supporting order-realization processes by automating parts of the configuration task, and by minimizing the cost of eliciting customer preferences. In other words, a product configuration system supports the conversion of customer needs to specific customer requirements.

In many recent publications, treating product configuration systems is often only vaguely presented, or as Piller (2004, pp.318) notes: “The literature which directly addresses toolkits, mostly supplies only anecdotal studies and describes toolkits cases in a narrative style.”

Unfortunately, most published work in relation to product configuration systems in general, and especially the configuration task, seems only to refer to an intuitive definition of the configuration
task, and therefore it is difficult to make meaningful comparisons (a few exceptions are (Felfernig et al., 2004; Sabin & Weigel, 1998; Stumptner, 1997; Fleishanderl et al., 1998; Soininen et al., 1998)).

Traditionally, configuration is often considered a part of the design science discussion or even a special case of the general field of design activities. In Stumptner (1997) it is assumed that in configuration the design goals and requirements are fully specified, and subcomponents and functions are already known. This is also supported by Sabin & Weigel (1998), who note: “…product configuration is informally a special case of design activity and consists of two key features: a) the artefact being configured is assembled from instances of a fixed set of well-defined component types, and b) components interact with each other in predefined ways.”

The core of the configuration task is thus to select and arrange combinations of parts that satisfy given specifications. No new component types can be created nor can the interface of the existing components be modified. The configured solution must provide a list of selected components, describe the product structure and topology of the product (Sabin & Weigel, 1998).

A more precise definition of the configuration task is given by Mittal and Frayman (1989). They describe the configuration task as a special kind of design activity in which the artefact is being designed from a set of pre-designed components that can only be connected in certain ways. It is important to notice three aspects related to this definition of configuration. (i) It is not possible to design new components, (ii) the components must be connected to each other in pre-defined and fixed ways (the authors use the term port to describe this, but we suggest “interface”), and (iii) a solution specifies not only the actual components but also how they are connected (Mittal & Frayman, 1989).

Besides the connection-based approach to the conceptualization of configuration knowledge and the configuration task from Mittal and Frayman, Soininen et al. (1998) identify three approaches: a resource-based approach by Heinrich and Jüngst (1991), a structure-based approach by Cunis et al. (1989), and a function-based approach by Najmann and Stein (1992). For the sake of clarity these different approaches will be briefly explained in the sections below.

In the resource-based approach by Heinrich and Jüngst (1991) the interfaces through which technical systems the components and the environment interact are modelled as abstract resources, and each technical entity is characterised by the types and amounts of resources its supplies, consumes and uses (Heinrich & Jüngst, 1991).

The structure-based approach by Cunis et al. (1989) presents product knowledge and the configuration task from a compositional structure of the product point of view. The compositional structure is important because products are commonly described through their structure (Soininen et al., 1998).

Behind the function-based approach lies the assumption that all involved parts of the technical system are solely described by their functionalities. When objects are selected, functionalities are composed in order to specify the functionality of the whole system.

The four different approaches to conceptualisation of the configuration task and the knowledge needed for the configuration task each contribute to the discussion about configuration systems. The four different approaches can be perceived as different perspectives on the configuration task.

1.2 Product Configuration Systems as a Field of Research

Product configuration systems are a fairly young area of research. The development of product configuration systems started with the research carried out on expert systems in the 1980s where the
XCON system at Digital Equipment was the most influential one (see (Barker et al., 1989; McDermott, 1993; McDermott, 1982) for a good description).

In this section, a brief overview of literature from active research groups will be given. However, this should not be seen as the theoretical foundation of the present thesis. The purpose of the section is to give a short overview of the most influential active research groups working with research in product configuration systems. This review is by no means complete, and as the preliminary list of research groups was retrieved by using keywords that deals with product configuration or configuration, relevant and related research groups might have been overlooked.

The relevant literature can be subdivided into, four groups. These are:

(i) Literature from the Technical University of Denmark
(ii) Literature from the Helsinki University of Technology
(iii) Research from Forza and Salvador
(iv) Literature from the University of Klagenfurt

Taken as a whole, these four groups create the context in which this Ph.D. makes a scientific contribution.

Obviously, besides the four groups mentioned above, other communities have carried out research on product configuration. This research has often been presented on conferences but also in journals. For instance at the Department of Production at Aalborg University, research has been carried out on product configuration under the guidance of associate professor K.A. Jørgensen (Jørgensen & Petersen, 2005; Jørgensen, 2007). Research from other communities will be included in the thesis when it is called for.

1.2.1 The Technical University of Denmark

The Department of Manufacturing Engineering and Management has a long tradition of researching within product configuration systems. Most recently, this has been carried out by Jesper Riis (Riis, 2003), Benjamin Loer Hansen (Hansen, 2003), Martin Malis (Malis, 2005), Anders Haug (Haug, 2007), and Gudmundur Valur Oddsson (Oddsson, 2008). This work has taken place with the supervision of Professor Lars Hvam. The projects carried out at Dept. of Manufacturing Engineering and Management have primarily focused on the technical aspects of how product configuration systems and industrial variant specification systems are developed. The research has mainly focused on a procedure for developing configuration systems, and this procedure has been documented in several publications.

Much work from the group at the Technical University of Denmark is related to the Ph.D. of Hvam (1994). The focus of that Ph.D. is the use of IT to support the activities of specifying products and methods. In 1994 only a minor part of the engineering work in these functions in the planning system was supported with information technology. The thesis provides the first version of the procedure for developing systems to support the specification activities in companies using product models - later referred to as configuration systems. The procedure is refined in Hvam (1999). The paper presents a set of simple, easily adaptable concepts and methods for modelling product knowledge. The concepts and methods are based on well-defined concepts and methods from data modelling (object oriented analysis) and domain modelling (product modelling). The concepts are general and can be used for modelling all types of specifications in the different phases in the product life cycle. The procedure consists of seven phases: Analyse specification task, determine content and structure for the modelling task, identify features and prepare OOA-model,
prepare OOD-model, programming, implementation and education of users, and maintenance of the system. The following papers present revised versions of the procedure (Hvam, 2001; Hvam, Riis, & Hansen, 2003; Hvam et al., 2004; Hvam & Ladeby, 2004; Hvam et al., 2006; Hvam & Ladeby, 2007). The purpose of the Ph.D. of Riis (2003) is to further develop the procedure for developing product configuration systems. He does that by extending the description of the phases, and by using the product family master plan as descriptive tool in phase 2.

Hvam and Have (1998) address an increasing need in many companies to perform a radical change in the basic structures of the companies’ specification system. The paper suggests a project guideline for such radical changes. This they accomplish partly by using concepts and methods from the BPR literature for re-engineering of business processes. The specification task is also the theme of (Hansen, Riis, & Hvam, 2003; Hvam et al., 2004; Hvam et al., 2006). The purpose of the Ph.D. of Hansen (2003) is to develop a procedure for developing industrial variant specification systems. The objectives of the thesis are to define variant specification systems, and create a procedure for the development of industrial variant specification systems.

Another theme in the research group at the Technical university of Denmark is to develop a documentation tool. Hvam et al. (2005) deal with identifying requirements for a documentation system that could support the development and maintenance of product configuration systems. The task of handling the documentation of a product model takes up too much time of the process when one develops a product configuration system, as the product models grows and become more complex. The paper identifies requirements and a concept for a documentation tool that could support the development of a product configuration system. The work is based on the procedure for building configurations systems. This work is refined by Anders Haug in several papers on the issue, and his Ph.D. which covers the representation of industrial knowledge (Haug & Hvam, 2005; Haug et al., 2006; Haug & Hvam, 2006a; Haug & Hvam, 2006b; Haug & Hvam, 2006c; Haug, 2007).

Much of the above mentioned research has been summarized in a new book. The book is structured around the procedure for developing product configuration systems (Hvam et al., 2008).

Finally, the Ph.D. study of Gudmundur Oddsson (Oddsson, 2008) deals with the structuring of product knowledge as a basis of embedded configuration, and the Ph.D. study of Malis (2005) deals with the application of product models in extended enterprises.

The Department of Mechanical Engineering at the Technical University of Denmark has also contributed to the research community of product configuration system. This is mainly done by Professor N.H. Mortensen Through his supervision of PhD and his contribution in shape of a formalized notation for product family variant modelling – the PVM or PFMP (Mortensen et al., 2004; Mortensen & Hansen, 2007; Mortensen et al., 2008a; Mortensen et al., 2008b).

1.2.2 The Helsinki University of Technology

A considerable amount of configuration research has materialised from the Helsinki University of Technology in Finland. The research is primarily focused on ontologies, modelling of knowledge, and technical aspects related to configuration.

Tiihonen, Soininen, Männistö, & Sulonen (1996) presents a study of 10 configuration cases from the Finnish industry. The research guides the group’s future research by establishing a framework for understanding the problem area of product configuration, and then testing the framework in 10 case studies. Later, Soininen (1998) proposes a general ontology for configuration to facilitate reuse and share of configuration knowledge. The ontology is a synthesis of earlier
approaches to configuration which is connection based, structure based, resource based, and function based. The ontology defines the following concepts for representation of configuration knowledge: Components, attributes, resources, ports, contexts, functions, constraints, and relations between these concepts. Soininen and Niemela (1999) propose a rule-based language (configuration rule language or CRL) for representing typical forms of configuration knowledge. The language is based on declarative semantics, and the semantics induce formal definitions of the main concepts in product configuration, i.e. configuration models, requirements, configurations, valid configurations, and configurations that satisfy requirements. CRL is finally tested on a car configuration problem. Männistö, Peltonen, Soininen, and Sulonen (2001) discuss the difficult aspects of after-sales management of products which have a large number of variants related to product customisation. They propose modelling product structures at multiple abstraction levels by using a novel mechanism based on generic models of product individuals organised into a specialisation hierarchy. Kojo, Männistö, and Soininen (2003) are concerned with increasing the efficiency of software development by the use of software product families. They propose an approach to modelling the evolution and variability of software product families based on viewing them as configurable products. The approach is based on the ontology for product configuration proposed in Soininen et al. (1998). More recently, Asikainen, Männistö, & Soininen (2007) present a domain ontology called Kumbang for modelling the variability in software product families. Kumbang synthesises previous approaches to modelling variability in software product families. In addition, it includes modelling constructs from the product configuration domain for modelling variability in products. The modelling concepts include components and features with compositional structure and attributes, the interfaces of components, connections between them, and constraints.

1.2.3 Forza and Salvador

Forza and Salvador have produced several papers and one book about product configuration systems. The work of Salvador and Forza is rigorous and relevant.

Forza & Salvador (2002a) report on results from research on product configuration systems to support the order acquisition and fulfilment processes. The research presents a case study of a small company producing voltage transformers. The conclusion of the study is that the implementation of a product configuration system significantly contributes to increasing the effectiveness and efficiency in translating the customer’s needs into product documentation. Moreover, it offers the company a way to incorporate product knowledge otherwise retained by individual employees into organisational memory. However, the introduction of a product configuration system may require significant and potentially painful changes in the way the order acquisition and fulfilment activities are organised, and it may necessitate a high initial investment in terms of man-hours. Forza & Salvador (2002b) describe a case study of the implementation of a product configuration system in a small company manufacturing mould-bases for plastic moulding and punching-bases for metal sheet punching. The research shows that the product configurator is associated with organisational change as part of the firm activities inside the technical office change. Furthermore, the paper suggests that the effects of product configuration software implementation propagate to parts of the company not directly involved in the implementation. Salvador & Forza (2004a) address the need to simultaneously offer their customers tailored products while ensuring short delivery times. This they call the ‘customization-responsiveness squeeze’. By applying a hybrid of quantitative–qualitative research design, the findings indicate that, although the companies rely on product configuration to customize their products, they are presented with a set of related difficulties as well: inadequate product information supply to the sales office, excess of repetitive activities within the technical office and high rate of configuration errors in production. The quantitative part of the research explores the issue under investigation by means of a survey on a sample of 122 companies.
located in Northern Italy and facing the customization-responsiveness squeeze. The qualitative part of the research consists of a set of interviews with key informants performed ex post in selected companies within the sample. In Salvador & Forza (2004b) an analysis of successful sales configurators is used to identify key principles to guide firms in developing sales product configurators capable of presenting efficiently and effectively the firm’s product assortment. Forza et al. (2006) looks at a case study of MarelliMotori, a manufacturer of low- and medium-voltage rotating machines. To cope with the increasing price and time competition, MarelliMotori pursue a mass customisation strategy. A key step when enhancing MarelliMotori’s mass customisation capability is made by grouping components into kits, and the implementation of a product configuration system, which enables postponement of product differentiation along the material flow. Finally, in their 2007 book entitled ‘Product Information Management for Mass Customization’ (Forza & Salvador, 2007), Forza and Salvador synthesise research from a period of four years. The research is comprised of case studies, interviews with configuration system programmers, system engineers, managers, executives, and consultants. The book contains case studies that provide the reader with practical implications of configuration projects.

1.2.4 The University of Klagenfurt

Configuration research carried out at the University of Klagenfurt in Austria is mainly driven by Alexander Felfernig in collaboration with other researchers. The main research theme of the group at the University of Klagenfurt is graphical representation of configuration knowledge, and the group has published their work in several journal papers.

Ferfernig et al. (2000a) illustrate how one employs a standard design language (Unified Modelling Language - UML) for the construction of configuration knowledge bases (component structure and functional architecture) and automatically translate the resulting models into an executable logic representation which is further exploited for calculating distributed configurations. An example of configuring cars shows the whole process from the design of the configuration model to the distributed configuration problem solving. The idea of using UML as domain specific language for the construction of knowledge-based configuration systems is further pursued in (Felfernig, Friedrich, & Jannach, 2000b; Felfernig & Zanker, 2000). In that study, the authors show how classical description concepts for expressing configuration knowledge can be introduced into UML and be translated into logical sentences automatically. The approach proposes the usage of the built-in structuring mechanisms of UML as well as introduced structuring concepts to design graphical depictions of configuration knowledge that are expressive and readable for humans and can be transparently communicated to domain experts. In Felfernig, Friedrich & Jannach (2001) the authors take as their starting point the challenge that the development and implementation of product configuration systems is faced with the challenges of growing complexity of the knowledge base. They propose using UML as standard design language for modelling the configuration knowledge bases. The UML model consists of two constituent parts; a component model, and a set of corresponding functional architectures. The conceptual configuration model can be automatically translated into an executable logic representation. Felfernig et al. (2004) develop a framework suitable for diagnosing configuration knowledge bases, and they also develop a prototype implementation using commercial constraint-based configurator libraries. This shows the feasibility of diagnosis within the tight time bounds of interactive debugging sessions. Felfernig (2007) demonstrates the use of object constraint language and UML as standard representation languages for building platform independent and platform specific configuration models in a mass customisation context.
Another theme at the Klagenfurt group has been the semantic web which provides the conceptual infrastructure to allow new kinds of business application integration. In Felfernig et al. (2002a) the authors outline an approach for integrating web-based configuration systems for highly complex customizable products and services of the semantic web. UML is applied to the acquisition of configuration knowledge, and they provide a set of rules for transforming UML models into configuration knowledge bases. Felfernig et al. (2002b) present an application scenario for configuration web services (under development in the research project CAWICOMS). The paper describes an application scenario for semantic web services in the domain of configuring telecommunication services. Finally, in Felfernig et al. (2003) semantic web ontology languages for configuration knowledge representation are applied. Using UML for configuration knowledge representation supports effective sharing and integration of configuration knowledge on a graphical level.

1.3 The Aim of the Thesis

The aim of this thesis is to answer the meta-question: “How are configuration projects carried out in engineering companies?” Indeed, the aim of this thesis is to understand configuration projects in engineering companies, and the approach is primarily to establish a frame of reference with key concepts and definitions, secondly to propose a typology of configuration systems to differ between different projects, and finally, to propose prerequisites for configuring. This constitutes my set of lenses by which I perceive and try to understand configuration projects in engineering companies.

This thesis also demonstrates the skills that I have obtained during this Ph.D. project. It is required that the Ph.D. student demonstrates knowledge of research field in which he is engaged and contributes to the research in this area. This thesis provides documentation for both.

1.4 Structure of the Thesis

The main binder of the thesis is divided into four parts: (i) Introduction, (ii) Existing Knowledge and Research Questions, (ii) Understanding configuration, (iii) Configuration in Engineering Companies, and (iv) Discussion and Conclusion. Besides the main binder of the thesis, the thesis consists of two separate binders: appendix A and appendix B. These two binders contain the transcriptions from the interviews carried out at two case companies. These two separate binders of the thesis remain confidential, and cannot be obtained freely or at request due to the promise of anonymity to the interviewees. The two separate binders are only presented to the members of the evaluation committee so that they can evaluate the data collection of the thesis.

Figure 1-3 shows the structure of the thesis.
1.5 Summary

The first chapter of this thesis outlines the purpose of the present Ph.D. First, a presentation of a mini-case establishes an initial understanding of configuration in engineering companies, and presents the characteristics of plants, and the configuration process. Secondly, we have a small review of literature structured around four important research communities that focus on configuration. The research communities are: (i) The Technical University of Denmark, (ii) The Helsinki University of Technology, (iii) Forza and Salvador, and (iv) The University of Klagenfurt. Thirdly, the aim of the thesis is presented, and the meta-question that the thesis tries to answer is introduced: How are configuration projects carried out in engineering companies? Finally the structure of the thesis is given to help the reader navigate through the thesis.
Part I: Existing Knowledge and Research Questions

“Nothing can be so amusingly arrogant as a young man who has just discovered an old idea and thinks it is his own.”

Sidney J. Harris
The Literature of Product Configuration Systems

This chapter presents selected readings of product configuration literature in shape of a literature review. The chapter serves two purposes; 1) It is a literature review, and 2) it is an introduction to the field of product configuration. The following sections provide an overview of contributions made to product configuration systems since John McDermott’s ‘R1: A Rule-Based Configurer of Computer Systems’ from 1982.

The literature review is divided into three parts: (i) The Rise and Fall of R1 (section 2.1), (ii) A Definition of Configuration and the Configuration Task (section 2.2), and (iii) Product Configuration Systems – a new Kind of Expert System (section 2.2.5). The logic in this arrangement is as follows.

‘The Rise and Fall of R1’ tells the story of the perhaps most well-known configuration system till today – R1, also known as XCON at Digital Equipment. The configuration system was developed in the beginning of the nineteen eighties, and although the configuration system was difficult to maintain, it started a revolution at DE in which much of the white collars work was automated by different kinds of configuration systems. This section ends by summing up experiences gained during the project by condensing two key papers: Barker et al. (1989) & McDermott (1982).

While the first section focuses on the experiences gained and the lessons learned from the XCON project, the next section ‘Definition of Configuration and the Configuration Task’ focuses on the work made in defining configuration and the configuration task. What does it mean to configure, and what are the core concepts that we are juggling here? These questions will be answered in this section. To answer these questions we see four different perspectives on how you should conceptualize the knowledge needed for the configuration task. The four approaches have little in common but have all gained some acceptance in the research community of product configuration systems. The four different approaches are: (i) A connection-based approach by Mittal and Frayman (1989), (ii) a structure-based approach by Cunis et al. (1989), (iii) a resource-based approach by Heinrich and Jüngst (1991), and (iv) function-based approach by Najman and Stein (1992). The four different approaches present more or less intuitive sets of concepts for representing product knowledge when configuring products. Last but not least the most generalized ontology of product configuration systems is laid out which was published by Soininen, Tiihonen, Männistö, and Sulonen in their paper ‘Towards a general ontology of configuration’ in 1998 (Soininen et al., 1998). Here they synthesize the four approaches mentioned above to a general ontology for configuration. All in all, this section will illumine some general perceptions of configuration and the configuration task.

The final section ‘Product Configuration Systems – a new Kind of Expert Systems’ show research at the start of a new era of product configuration systems (Krause et al., 1993; Schwarze, 1996), knowledge on how to develop product configuration systems (Hvam, 1999), the economical benefits of configuration systems (Franke & Piller, 2004), and two recent books on product configuration (Forza & Salvador, 2007; Hvam et al., 2008). Finally the chapter ends with a summary of the reviewed literature.

2.1 The Rise and Fall of R1

The dawning of product configuration systems as research area is focal point of present selection of papers. Two papers represent this well because they have concern the configuration projects at Digital Equipment Corporation. The configuration systems at Digital are one of the most
successful known examples of applied expert system technology. The project was started at the beginning of the eighties, and the experiences of this starting phase are described in the first paper by McDermott. This is followed by a paper from Barker et al. from 1989 which reviews the experiences gained at Digital in the eighties.

2.1.1 McDermott’s (1982) ‘R1: A Rule-Based Configurer of Computer Systems

John McDermott’s article from 1982 marks the beginning of research into product configuration systems. R1 was a rule-based system that could configure VAX-11/780 computer systems from Digital Equipment Corporation.7 The system was implemented using OPS4, which was a production system language not written for supporting the configuration task as such, but it was applied successfully at Digital.

R1 was used on a regular basis in Digital Equipment Corporation’s manufacturing organisation. Given a customer’s order, R1 could determine what modifications had to be made to that order to fit the system’s functionality and then produce a number of diagrams showing how various components on the order needed to be associated. The system exploited its knowledge of the configuration task to generate a single possible solution to the users needs.

The present summary will focus on the task that R1 solved, and any complications arisen when the task was solved. Domain independent lessons is my primarily goal of the review of this present paper.

A configurer (human or artificial) of VAX systems must basically have two kinds of knowledge to solve the configuration task: (i) Knowledge about the components, and (ii) Knowledge about constraints. Knowledge of the components is the properties that are relevant to the system configuration, e.g., its voltage, its frequency, how many ports it has etc. Knowledge about the constraints is knowledge that enables the configurer to form an acceptable system solution. These rules indicates which components can (or must) be associated, and what constraints must be satisfied in order for the solution to be acceptable.

McDermott measures the difficulty of the VAX configuration task as a function of the amount of component knowledge and the amount of constraint knowledge required to perform the configuration task. On average a configurer has to know 8 properties of each component to perform the configuration task. The VAX product consists of about 420 components which equals 3300 pieces of component information that a VAX configurer must have access to.

Before R1 was developed this insight regarding product structure and which properties are important and which are not, was not available to the employees. Most of the knowledge was not written down, and the only reliable source of knowledge was human experts, and the experts were estranged to the task of quantifying their knowledge and making it explicit. As McDermott extracted knowledge from the experts he made two general observations about this process:

(i) “The experts have a sparse but highly reliable picture of their task domain. When asked to describe the configuration task, they do so in terms of the subtasks involved and the various temporal relationships among these subtasks.

(ii) They also have a considerable amount of very detailed knowledge that indicates the features that particular partial configurations

7 Digital Equipment Corporation was acquired by Compaq in June 1998, which subsequently merged with Hewlett-Packard in May 2002. As of 2006 its product lines were still produced under the Hewlett-Packard name.
and unconfigured components must have in order for the partial configurations to be extended in particular ways.”

(McDermott, 1982, pp.42)

According to McDermott both kinds of extracted knowledge were easily converted into rules. However, he does not provide any methods for making this conversion.

McDermott views the configuration task as a hierarchy of subtasks. The way R1 solves the configuration system is not derived through a rigorous analysis of the demands of the configuration task. Rather, the approach that R1 takes to the configuration task is the same as human configurers, splitting the task into subtasks concerning different contexts, and solving each context before moving on to the next context.

There is, however, one important difference between human configurers and R1. When pieces of error full knowledge are identified it is easily corrected in R1, while it would take a substantial amount of work to correct this with the human configurers. If some aspect of a configuration was criticized by an expert, all that was necessary to do was to find the offending rule, and ask the expert to point out the problem with the condition.

R1 was proven to be a highly competent configurer of VAX 11/780 systems. The configurations that were produced by R1 were consistently adequate, and the information which it made available to the technicians who physically assembled the solution was far more detailed than that produced by human configurers.

McDermott notes that the use of the technology is not warranted for any case. The more structured the task domain is the more suited the technology behind R1 is. A structured task domain allows the task to be split up into subtasks with clear flow control and interfaces between each subtask, with the reduction of complexity as a positive side-effect.

Finally, McDermott notices that a feature that sales personnel and customers requested was that of transforming functional requirements into a structural solution. It was desirable that R1 could provide interactive assistance to a customer or salesperson that would allow him/her to specify functional capabilities of the system he/she wanted and let the R1 select the components that provided such functional capabilities. However, at the time of the present paper, this was not yet implemented. So the ultimate version of R1, where it was the salespeople’s ultimate assistant, a system that could help in best following the customers’ need, was not yet realized.

2.1.2 Barker et al. (1989) ‘Expert Systems for Configuration at Digital - Xcon and Beyond’

In Barker et al. (1989) the authors reflect on almost a decade of lessons learned in designing and building a core of configuration systems at Digital Equipment Corporation. Some of the key lessons that were learned are highlighted in this paper, and two key lessons are:

(i) Building a successful expert system involves more than defining rules in knowledge bases. Rather, one must attend to the needs of the business, and organizational issues as well as to technical issues.

(ii) The technology is still evolving and there is a need to develop new practices specifically to utilize this new technology.

(Barker et al., 1989, pp.298)
The initial purpose of XCON was to support the manufacturing plant personnel in validating the technical correctness of system orders. Up till 1989 the user profile was expanded dramatically, and the configuration system’s user base represented 10 distinct business functions spread out in the world. XCON was used to validate the technical correctness of customer orders, and to guide the assembly of these orders. XSEL was used interactively to assist in the selection of saleable parts which in the end would make up a customer order. For the layout of computer rooms in relation to the configuration(s) under consideration XFL was used. XCLUSTER was used to assist in configuring clusters. XNET was used to configure local area networks. Finally SIZER was used to assist in estimating the sizing of computing resources required for a wide variety of uses in various types of organisations.

The configuration systems at Digital (XCON,XSEL,XFL,XCLUSTER,XNET,SIZER) provided full product coverage for Digital’s current product set which consisted of 42 different families of central processor types and their supporting peripherals and software. The core of Digital’s business was hardware and software configuration. The configuration systems were used worldwide by a broad set of users, ranging from sales through engineering, manufacturing and field service. Thus the configuration systems was involved in the complete order flow and manufacturing cycles at Digital.

The configuration systems benefited Digital in a number of ways. They contributed to customer satisfaction, lower costs, and higher productivity – but perhaps the most important benefit from the configuration systems was, that they contributed to Digital’s ability to maintain its highly successful build-to-order marketing strategy (customized configurations to fit each customer’s specific needs). Although it is difficult to quantify the benefits, the authors estimate the overall net return to Digital to be in excess of $40 million per year. The costs of developing, running, and maintaining the several configuration projects are not mentioned; however the net profit is estimated to be around $40 million per year in Barker et al.’s paper.

At Digital, it was generally believed that the success of applying expert system technologies was due to the careful balancing of three factors: (i) strategy/business, (ii) technical, (iii) human resources/organisation.

Expert systems were a strategic investment for Digital. Digital’s strategy was to sell customized solutions on a build-to-order basis. As products became more complex and varied and gave rise to an almost indefinite number of valid configurations, and as the sales volume increased during the ‘70’s, problems arose with handling this and some kind of support was necessary. Another important reason was the high degree of management commitment at Digital. This helped the technology succeed.

Expert systems were a new and emerging technology at the time, and had not really reached maturity yet. The three biggest challenges facing the expert systems development was according to Barker et al. (1989, pp.304): (i) Volatile subject domains; each year around 40 percent of the rules in the configuration system knowledge base changed, and the scope of the configuration task also changed significantly over the years. (ii) Expanding functional scope; the functional scope of the project was expanded due to new types of users and due to existing users discovering new and different ways to use the configuration systems. XCON was also integrated to other system, and the aim of the configuration projects shifted from accuracy of the knowledge base to things like ease of use, and seamless integration with other software systems. (iii) The configuration systems at Digital
were large and technically complex systems consisting of complex rulebases with 17,500 rules\textsuperscript{8}, five different databases, 350 programs/routines, and over 50,000 lines of code.

In the configuration projects at Digital there were human resource and organisation challenges due to an evolutionary environment. To manage change and adjust norms, it was necessary to pay attention to human resources and organizational issues. The formula for success for the developers and managers at Digital was to put energy into managing these challenges. For the configuration projects at Digital, clarity of roles was an important issue. A model was developed which showed the various roles involved in the development of expert systems. The model reflected a broad perspective on the different players involved in the development of expert systems. It was a model of functions rather than a model of individuals because one individual can play more than one role at any particular point in time, and a given role may be played by more than one individual. As things changed over time, it was estimated on a regular basis which roles were to be filled for the configuration system effort. The roles were: Champion, sponsor, program manager, technical team, expert, and user.

As well as defining roles for the configuration projects at Digital, a general model of expert system development was created. It was based on the experience gained at Digital. The model consists of four major tasks:

(i) Defining and redefining the system, determination of how to exploit expert system technology in relation to the task, and where it is appropriate to use traditional software technology. Defining and designing the system to satisfy a variety of needs.

(ii) Extending and refining the system. This includes the ongoing development of the knowledge base, and knowledge acquisition, integration of systems, etc.

(iii) Delivering the system, in shape of release management, distribution, and support.

(iv) Evaluating the system, measuring system performance, accuracy, maintainability characteristics, and how well the system fulfils the business needs of the company.

It is worth noticing that the authors conclude that the process of developing expert systems is likely to be more iterative than the process of developing traditional software, and that the success of configuration systems at Digital would most likely not have occurred if they had not worked out a development process that allowed for iterative development.

Finally, the value of configuration systems to Digital can be stated as follows (Barker et al., 1989) pp. 310:

• Information that has been distributed ineffectively amongst a variety of organisations was made visible

• The configuration systems allowed Digital to maintain a competitive edge.

• The business fulfilment/build/installation processes of Digital evolved to become more efficient.

2.1.3 Reflections on ‘The Rise and Fall of R1’

XCON has been the most successful expert system which has ever been developed. Nevertheless, the development and maintenance of XCON was stopped at the beginning of the

\textsuperscript{8} The rule-count unaccompanied by other facts is an inadequate characterization of a rule-based expert system. However it provides an overview of the size and the work in maintaining the systems.
nineteen nineties. As the rule-base for the XCON configuration system reached 10,000 rules, it became more and more difficult to maintain. To put it differently: It did the work of 75 people but it took 150 to maintain.

Although the R1 reaped enormous benefits to the technical salespeople at Digital, it required a substantial expertise to use R1 to configure a product that satisfied customer needs. The translation from functional capabilities to structured solutions was not included in the R1 project at Digital. What the R1 could was to derive a valid structural solution from a set of components, and R1 was excellent at doing this. R1 could however not relate the proposed solution to the needs of the customers. This complex task was still done by experts in interaction with the system.

The configuration system experience at Digital gives insights into how much impact expert systems can have on a company, and how one successfully manage ongoing development and implementation of expert systems. Expert systems involve three perspectives, which must be carefully balanced: (i) the strategic/business perspective, (ii) the technical perspective, and (iii) the human resource/organisational perspective. This is supported by Leonard-Barton (1987b), who examines the organisational impact of implementation of a new technology.

When McDermott writes about the harvest of knowledge, he touches upon a common problem in the community of product configuration. Much of the knowledge needed is not explicit, and it is only accessible as tacit knowledge by experienced engineers. It is vital for any configuration project that the domain experts willingly share their tacit knowledge. Lightfoot (1999) concludes that expert knowledge is the source of expert power in the organisation. As soon as this knowledge is made widely accessible in the organisation by formalising it in a configuration system the power of the expert is diminished. For this reason, it is not evident that domain experts willingly give away their knowledge. It is more probable that the domain experts will be unwilling to participate in a configuration project.

The experience from the XCON project does not provide us with any understanding of configuration projects, nor does it answer the meta-question of the present thesis: “How are configuration projects carried out in engineering companies?” However, the project provides us with some hints on important perspectives in configuration projects. Development of expert systems or configuration systems involves careful balancing of: (i) Strategic/business, (ii) technical, and (iii) human resource/organisational.

### 2.2 Definition of Configuration and the Configuration Task

The present section has definition of configuration and configuration task as turning point. Four papers can characterize the work in this field from 1989 to 1992: Mittal & Frayman (1989), Cunis et al. (1989), Heinrich & Jüngst (1991), and Najman & Stein (1992). In 1998 the paper Soininen et al. (1998) tries to summarise the previous mentioned four papers to a general ontology for configuration. This paper is also summarised in this section. All five papers look into the definition of configuration and the configuration task.

#### 2.2.1 Mittal and Frayman (1989) ‘Towards a generic model of configuration tasks’

The most commonly used definition of the configuration task has been provided by Mittal and Frayman (1989). They describe the configuration task as a special kind of design activity in which the key feature is that the artefact being designed is assembled from a set of pre-defined components. A more formal definition is as follows:

“Given: (A) a fixed, pre-defined set of components, where a component is described by a set of properties, ports for connecting it to other
components, constraints at each port that describe the components that can be connected at that port, and other structural constraints (B) some description of the desired configuration; and (C) possibly some criteria for making optimal selections. Build: One or more configurations that satisfy all the requirements, where a configuration is a set of components and a description of the connections between the components in the set, or, detect inconsistencies in the requirements.”

(Mittal & Frayman, 1989, pp.1396)

Mittal and Frayman (1989) then notes that there are three important aspects in this definition:

“[1], the components that can be used to design some artifact are fixed, i.e., one cannot design new components. [2], each component can be connected to certain other components in fixed and pre-defined ways, i.e., the components cannot be modified to get arbitrary connectivity. [3], a solution not only specifies the actual components but also how to connect them together.”

(Mittal & Frayman, 1989, pp.1396)

In other words it is not enough to identify the components regarding a specific solution to given requirements. It is necessary to specify how the components interconnect before the solution can be considered a valid solution of the configuration task.

While this definition of the configuration task sounds reasonable and achievable and general enough to cover a broad array of different domains (from computers to cars), the harsh reality is that this definition impose huge challenges on the configurer (whether human or artificial). Without making further assumptions about the configuration task, imagine the following: Given N components and p ports per component, the solution space of all possible configurations will is then on the order of sqrt[(Np)!] (Mittal & Frayman, 1989, pp.1396). Even for moderate values of N and small values of p, this solution space is quite formidable. 10 Components and 2 ports per component equal sqrt (20!) = 1559776268 possible combinations.

To reduce the complexity of the configuration task the authors introduce two restrictions on the configuration task. These restrictions aid in identifying additional kinds of knowledge that can reduce the complexity. The first restriction is based in the observation that artefacts are typically designed with some purpose in mind. The restriction is that the artefacts are configured according to some known functional architecture, in other words, instead of trying to assemble all possible artefacts that can be assembled from the given components, one restricts the problem to those artefacts that are similar in their architecture(s). This restriction simplifies the task, as the purpose or overall goal of the configuration task is now defined by an overall functional architecture. This architecture allows one to decompose an artefact along defined functional lines. The authors name this restriction “functional architecture”

The second restriction is based on the observation that in many design domains it is often possible to identify some particular component (or a small set of components) which is crucial to implementing a given functionality. The authors define this as the “key components per function” restriction. For example, when configuring a computer, the printing function usually consists of a printing device and some components to connect the printer to the pc and power. Once the printing device has been selected, the other components are often automatically given. Thus, one does not need to consider an arbitrary set of configurations of the printing function - one only needs to select the printing device and build suitable configurations from there. This restriction simplifies and
restricts the configuration task as certain solutions would not be considered in the configuration task.

The two restrictions compliments each other nicely. Together they transform a tightly coupled configuration problem (since the solution can be extended in arbitrary ways) to a more loosely coupled problem because the first restriction defines a functional architecture for the configuration task, and each of the functions can be configured somewhat independently around their key components (the second restriction).

Mittal and Frayman (1989) provide a suggestion for the knowledge needed for the configuration task, and they categorize the knowledge in the following three categories: (i) Knowledge of components, (ii) Knowledge of the functional architecture, and (iii) Knowledge of the mapping from function to components.

The structure of a given product consists of components. Knowledge related to a given component can generally be described independently of other components by a set of physical properties. Typically, components have an interface by which the components connect to other components. (Mittal and Frayman (1989) use the term ‘port’ which corresponds to our understanding of interface). Interfaces can also be described through a set of properties, and one can specify the components that can be attached through a given interface. Often some components consist of sub-components, and these have to be explicitly stated. A common way of describing the product assortment is by using the notation technique called product variant master. This technique is well described in (Hvam, 2001; Haug & Hvam, 2005; Haug & Hvam, 2006b; Riis, 2003)

The functional architecture specifies a functional decomposition of the product and any constraints on their composition. Any given function can be modelled by a set of properties that characterize them.

2.2.2 Cunis et al. (1989) ‘PLAKON - an approach to domain-independent construction’

Cunis et al (1989) have a more structure-based view on the configuration task. In the authors opinion the basic idea of configuring is to compose a construction from a set of components. To solve a configuration problem, the following construction process is proposed. The construction process consists roughly of a central cycle:

- Analysis of the current partial construction
- Selection of an appropriate operation
- Execution of this operation.

The process starts with unrelated components that have been derived from an original task description. These form the initial partial construction that is expanded step-by-step until a complete and consistent configuration is reached. The basic operations in the configuration task are:
• “the decomposition of objects (this corresponds to the decomposition of a task into subtasks, i.e. to a hierarchical or top-down approach; in the example: decomposition of the car into engine, body, and chassis),

• the aggregation of components (bottom-up approach; in the example: construction of a special engine based upon the turbo-charger requirement),

• the specialization of objects (in the example: the object ‘car’ becomes a Jaguar during the process of construction), and

• the specification of parameters and properties (e.g. maximum speed, number and cylinders) a.o. based upon constraints or default information.”

(Cunis et al., 1989, pp.867)

The knowledge needed for carrying out these tasks is conceptual domain knowledge, and conceptual domain knowledge can be modelled in a two-level conceptual hierarchy. In the conceptual hierarchy all objects are described conceptually to support the knowledge acquisition. The two-level conceptual hierarchy consists of a taxonomic hierarchy (for conceptualization and specialization) and a compositional hierarchy (for decomposition and aggregation). Relations and interdependencies between the components are handled as a net of constraints.

A taxonomic hierarchy is a ‘is-a’ hierarchy. This hierarchy defines classes of objects and their specializations (sub-classes). Properties are inherited within this structure. The taxonomic hierarchy allows classes to be specialized forms of more generalized classes (Cunis et al., 1989). For instance, a ‘fruit’ is a generalization of ‘apple’, ‘orange’, ‘mango’ and many others. Apples inherit the properties common to all fruit such as being a fleshy container for the seed of a plant. The compositional hierarchy is placed on top of the taxonomic hierarchy and describes the decomposition of an object into parts, thus the compositional hierarchy defines a ‘has-part’ relationship. The ‘has-part’ relationships are critical to for the configuration of the object.

Taken together, the taxonomic and compositional hierarchies can be viewed as generic representations of the set of acceptable constructions within a given solutions space, and they can be used as a kind of assembly guide to for the configuration task or the construction process.

2.2.3 Heinrich & Jüngst (1991) ‘A resource-based paradigm for the configuring of technical systems from modular components’

Heinrich and Jüngst (1991) advocate the resource-based paradigm for configuring technical systems from modular components. The authors start by defining configuring:

“Configurering is the construction of a technical system according to the requirements of a specification by selecting, parametrizing and positioning instances of suitable existing component types from a given catalogue.”

(Heinrich & Jüngst, 1991, pp.257)

This process does not involve the creation of new components, as the creation of new components is a design task rather than a configuration task (Heinrich & Jüngst, 1991). In the resource-based paradigm:
"...the interfaces through which technical systems, their components and their environment interact are modelled as abstract resources, and each technical entity are modelled as abstract resources, and each technical entity is characterized by the types and amounts of resources it supplies, consumes and uses"

(Heinrich & Jüngst, 1991, pp.257)

Thus, if one uses the resource-based paradigm, the technical system, its environment, and its components can all be modelled by using one single common paradigm. The environment states the resources and amounts of resources demanded by the technical system, and the resources and amounts of resources provided for the technical system by the environment. The components require other resources in order to function which have to be supplied by other components, and at the end of this 'supply chain', some resources must be supplied from the environment to the technical system. So, the concept of resources is an abstraction of the interactions among components in a technical system and its environment.

To configure a technical system the task is to balance the resources so that the resources demanded by the environment are supplied from the technical system, and the resources demanded by the technical system are supplied by the environment. A configuration is not accepted unless the resources which the components and environment demand are balanced to the resources which the environment and the components can maximally supply. So the basic algorithm for solving the configuration task with the resource model would be:

(i) Determine which resources are demanded by the environment according to the requirement specification for the technical system,
(ii) focus on a resource that is not yet balanced,
(iii) determine the list of component types which can supply that given resource,
(iv) incorporate a component from the list into the technical system, and
(v) repeat that process until the resources which the environment and the components demand are balanced by the amount of resources supplied by components or by the environment

According to the resource-based principle, the knowledge needed to find a viable solution to a configuration, if one exists, is merely:

(i) "System knowledge, i.e. knowledge about the resources in the system specification for the modular component system, and
(ii) catalogue knowledge, i.e. the technical specifications of each component typically contained in the manufacturers catalogue."

(Heinrich & Jüngst, 1991, pp.259)

The authors then characterize the heuristic knowledge that only human experts can provide from their experience with the configuration process on three different levels:
(i) “Exception knowledge, e.g. knowledge about idiosyncrasies of components not contained in the catalogue, which is necessary to achieve a correct configuration.

(ii) Evaluation knowledge, e.g. knowledge about a measure of quality of the configuration and about how to predict it on the component level during the configuration process, that will help achieve a good configuration.

(iii) Performance Knowledge, e.g. knowledge about some advantageous sequencing of decisions that will lead to an acceptable configuration quickly.”

(Heinrich & Jüngst, 1991, pp.259)

The five levels of knowledge are depicted in Figure 2-1. With the resource-based model each of these levels of knowledge can be acquired incrementally and quite independently, and according to the authors it is fairly easy to structure the five kinds of knowledge in a knowledge base which will scale-up nicely for the large knowledge bases in practical implications.

Figure 2-1: Levels of knowledge in a resource-based model (Heinrich & Jüngst, 1991)

The following sections contain a more detailed description of the five kinds of knowledge in the resource-based network.

The system knowledge is knowledge about which resources that arises from the design of the system. System knowledge can be modelled as resource taxonomy, and it is typically identified early in the knowledge acquisition process as knowledge about the resources, see Figure 2-2. The example illustrates a programmable logic controller component system. Usually, the system knowledge becomes stable very early in the knowledge acquisition process.
The catalogue knowledge base contains knowledge about the types of components that are available for configuration. This is the largest and most volatile knowledge base. The ideal way of expressing the catalogue knowledge is through a class-tree by using object-oriented techniques. The types of resources that a component supplies or uses are introduced in super-classes thus making it easy to add components by the specialization of the appropriate super-class with the correct default values.

Exception knowledge is knowledge about compatibility and incompatibility of components. Exception knowledge is typically attributed to the components or super-classes which the exception applies to.

Evaluation knowledge is used to evaluate different configurations against each other. Cost is an evaluation criterion which is commonly used. The price or cost of each component can be modelled as a virtual resource for each component. Other evaluation criteria could be: size, lifecycle cost, etc. Evaluation knowledge helps the configurer achieve a good quality of the configuration measured with well-defined parameters.

The performance knowledge is knowledge about how decisions can be sequenced so that an acceptable configuration can be reached quickly.
2.2.4 Najmann & Stein (1992) ‘A theoretical framework for configuration’

According to the authors, manufacturers of complex technical systems must satisfy the demands of their customers at low costs in order to stay competitive. This creates a large number of possible products variants, and for this reason the process of configuring a technical system becomes a complex problem. Many systems have been developed which can assist humans in the process of configuring technical systems. However, the authors note that only a few attempts have been made to formally analyse the nature of typical configuration problems.

Najmann and Stein (1992) develop a general theory of configuration and provide a precise methodology for studying the phenomenon of configuration in their paper from 1992. Rather than specifying a particular method of processing or acquiring configuration knowledge they aim at making a formal description of general configuration problems. Consequently, their methodology is independent of any particular knowledge representation formalism. Finally, they treat different models that can formulate configuration problems, and they conclude that the skeleton-oriented approach is equivalent to the resource-based approach – this discussion is rather technical and will not be treated in the following presentation of their paper.

According to the authors, configuration problems are characterised by a solution\(^9\) that consists of smaller sub objects. The problem is then to select components in such a way that the composition of the components fulfils the demand of the customer. Rather than focusing on how to acquire knowledge about the configuration problem or how to specify models of the processing of the configuration problem, the authors aim at making a formal description of the configuration problem. This description can be used to distinguish between different configuration approaches or to compare different configuration problems. The central concept in this approach is *functionality*. Objects are solely characterised by their functionality. Accordingly, when an object is selected, functionalities arise; indeed the functionality of the whole system is composed in this way. This results in the following definition of a configuration problem:

“A Configuration problem consists basically of three things, (i) a set of objects, (ii) a set of functionalities which are used to describe certain properties of these objects, and (iii) a set of demands which describe the desired properties of the system to be configured.”

(Najmann & Stein, 1992, pp.442)

2.2.5 Soininen et al. (1998) ‘Towards a general ontology of configuration’

The most generalized ontology of product configuration systems has been published by Soininen, Tiihonen, Männistö, and Sulonen in their paper ‘Towards a general ontology of configuration’ in 1998 (Soininen et al., 1998). The ontology presents a set of concepts for representing the knowledge on a configuration and the restrictions on possible configurations.

Following almost two decades of research in artificial intelligence, the intention of the paper is to present a general ontology of configuration that can be used to reuse and share configuration knowledge. At the beginning and the middle of the nineties, configuration systems were a commercial success, and an important area for applying artificial intelligence techniques. Most of the research up till the point of the publication of this paper had focused on problem-solving techniques and modelling of knowledge. Despite the amount of research carried out, a general ontology in the configuration domain had not yet emerged.

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\(^9\) A solution is a completely configured object.
The premise for the ontology was the following two definitions:

“Configuration as a task can be roughly defined as the problem of designing a product using a set of predefined components while taking into account a set of restrictions on how components can be defined.”

“The term product configuration is used to denote the routine engineering activity of this type in the sales-order-delivery process.”

(Soininen et al., 1998, pp.357)

The ontology presented in Soininen et al.’s paper synthesizes and extends the connection-based approach (Mittal & Frayman, 1989), the resource-based approach (Heinrich & Jüngst, 1991), the structure-based approach (Cunis et al., 1989), and the function-based approach (Najmann & Stein, 1992). The ontology contains a detailed conceptualization of the compositional structure of a given product. The importance of the ontology lies in the support it gives to the sharing of knowledge between different configurators that are based on different problem-solving methodologies. A generic ontology for configuration can also be used to document knowledge needed for the configuration task in an easy-to-understand format. By documenting the knowledge according to the ontology proposed, configuration knowledge can easily be modified to fit a given problem-solving methodology.

The earlier methods of configuration knowledge have more or less explicitly presented a set of method specific concepts for representing product knowledge. The conceptualisations have little in common except the central notion of a component. The aim of the authors is primarily to provide an ontology for the required forms of knowledge and their representations for the computer, and only secondarily to provide computer support for configuration tasks. The authors synthesise the four approaches mentioned above as they believe that all four types of modelling concepts are needed to compactly and adequately represent the knowledge on products.

In their ontology the authors define and distinguish between three different kinds of configuration knowledge that exist independently of the problem solving method: (i) Configuration model knowledge, (ii) configuration solution knowledge, and (iii) requirements knowledge.

Configuration model knowledge is knowledge used for specifying the entities that may appear in a configuration, their properties, and the rules on how the entities and their properties can be combined. Configuration solution knowledge specifies a configuration or a partial configuration. A configuration specifies what a real-world product instance must be like. A partial configuration leaves aspects about the real-world product instance open. Requirements knowledge specifies requirements on the configuration to be constructed. Requirements knowledge can be specified with the same concepts as configuration model knowledge and configuration solution knowledge.

The ontology tries to define a set of concepts to represent knowledge, and these different concepts include components, attributes, resources, ports, contexts, functions, constraints, and relations between these. The main contributions of Soininen et al. are the detailed conceptualization of knowledge on product structures and in extending the resource concept with contexts for limiting the availability and use of resources. The presentation of the ontology is structured around the following concepts, which are thoroughly treated in the paper: Taxonomy, attributes, structure, topology, context, resources, functions, and constraints.

Hitherto, the ontology is the most generic ontology, and it extends the previous conceptualisations in several ways. The ontology is built around a larger number of concepts for representing configuration knowledge. Although the authors claim that the clarity of configuration
models should not be compromised by minimizing the number of concepts in a modelling language, the ontology is difficult to apply to configuration knowledge and part of the reason is the many different concepts and a general high academic level of abstraction from the real-world. This makes the configuration models more difficult to understand and, consequently, hard to apply.

2.2.6 Reflections on ‘Definition of Configuration and the Configuration Task’

The above mentioned papers conceptualise configuration in different ways. As Soininen et al. (1998) mentions, they all attempt to define component, and they all contain a thorough discussion of the definition of configuration. However, the papers do not treat the problem of how to carry out configuration projects. They discuss the technology of product configuration: How the system reasons, how the configuration task is solved, and what problems arise when they solve the configuration problem. The papers perceive configuration as a technical issue, and consequently fail to include user related issues and organisational issues related to the implementation. Neither do the papers attempt to subdivide configuration systems thus refining the understanding of such systems. Instead they focus on the task and definition of configuration. Finally, there is no economic evaluation of configuration projects: what are the benefits and what are the costs of developing, and maintaining a configuration system?

Mittal & Frayman (1989) have a connection-based approach to the conceptualisation of configuration. They accept that a configuration task without any restrictions is a mind-throbbing task that seems almost impossible to solve for even moderate numbers of components with few numbers of ports per component. For this reason, they feel it is necessary to make two assumptions before proceeding with the configuration task. These two restrictions define a functional architecture and key components per function. However it is not always the case that the product architecture is designed in such way that it is neither possible to make these assumptions nor describe the functional architecture of the product or key components that can supply these functions. In the real world, it is often necessary with a product sanitation that readies the product for an automated configuration task. In theory, the goal of modularisation is to achieve a one-to-one mapping of function and component, but in reality this is often not achieved. So while mapping functions to components seems a simple task for modular products, in reality it is not. The mapping between functions and components is often one-to-many or many-to-one, indeed in reality many-to-many also exists. This makes the task of mapping functions and components utterly complex (Ulrich, 1995). To sum up, a given function can be implemented by a set of components, but at the same time, actual components are often multi-functional.

Cunis et al. (1989) take a structure-based approach to configuration, where the basic idea of configuring is to compose a construction from a set of components, and the construction process consists roughly of the following central cycle: Analysis of the current partial construction, selection of an appropriate operation, and execution of this operation. The process starts with unrelated components that have been derived from an original task description. These form the initial partial construction that is expanded step-by-step until a complete and consistent configuration is reached.

Heinrich & Jüngst (1991) develop a resource-based conceptualisation of configuration. In the resource-based approach the products (parts, components, interfaces, etc.) are modelled as abstract resources and each technical entity is modelled as resources where the entity is characterized by the types and amounts of resources it supplies, consumes and uses. With the resource-based approach, products, their environment, and their components are modelled using a single common paradigm. The environment states the resources and amounts demanded by the technical system, and those resources and amounts are provided to the technical system by the environment. The components
require other resources for their functioning which have to be supplied by other components, and in the end of this ‘supply chain’ some resources must be supplied by the environment to the technical system. All in all, the concept of resource is an abstraction of the interactions amongst components of a technical system and its environment. To configure a technical system the task is to balance the resources so that the resources demanded by the environment are supplied from the technical system, and the resources demanded by the technical system are supplied by the environment. A configuration is not accepted unless the resources which the components and environment demand are balanced to the resources which the environment and the components can maximally supply.

Najmann & Stein (1992) have a function-based conceptualisation of configuration, where the central notion is functionality. Products, modules, and parts are characterised by their functionality, and the combination of different modules and parts brings different functionalities to the product. Najmann and Stein (1992) develop a general theory of configuration and provide a precise methodology for studying the phenomenon of configuration. Their methodology is independent of any particular knowledge representation formalism.

Finally, Soininen et al. (1998) synthesise and extend the four different conceptualisations of configuration into a general ontology for configuration. The importance of the ontology lies in its capacity of supporting the sharing of knowledge between different configuration systems based on different problem-solving methodologies. By having a general ontology it becomes easier to document knowledge in an easy-to-understand format to a generic model of the product. This can later be modified to fit a given piece of configuration software thus forming a basis for documenting the knowledge needed by the configuration task.

The ontology presented in the paper of Soininen et al. (1998) synthesises and extends the connection-based approach by Mittal & Frayman (1989), the resource-based approach by Heinrich and Jüngst (1991), the structure-based approach by Cunis et al. (1989), and the function-based approach by Najmann & Stein (1992). The ontology contains a detailed conceptualization of the compositional structure of a given product. The importance of the ontology lies in the way it supports the sharing of knowledge between different configurators which are based on different problem-solving methodologies. A generic ontology for configuration can also be used as a basis for documenting knowledge needed for the configuration task in an easy-to-understand format. By documenting the knowledge according to the ontology proposed, configuration knowledge can easily be modified to fit a given problem-solving methodology. In their ontology the authors define and distinguish between three different kinds of configuration knowledge that exist independently of the problem solving method: (i) Configuration model knowledge, (ii) configuration solution knowledge, and (iii) requirements knowledge.

2.3 Product Configuration Systems – a new Kind of Expert Systems

At the beginning of the nineteen nineties, the success of expert systems declined as they were replaced by more focused systems, namely product configuration systems. Product configuration systems are closely related to expert systems - in fact they are often framed as part of the expert systems discussion. During the ‘90s product configuration systems became more and more based on standardized software. Product configuration systems are aimed at solving a specific task for a specific product in a given company – the configuration task. The goal of the configuration task is to tailor a given product to the specific needs of a customer.

The introduction of research in the area of product configuration systems dates back to the ‘Product Modelling’ paper from Krause et al. from 1993. This paper frames a new field of research called product modelling. A product model is a model of a product related to a business process in a
company. Product modelling and product configuration are often used indiscriminately; the paper from Krause et al. curtails this confusion.

Following the discussion of Krause et al.’s paper we will turn to the doctoral thesis from Stephan Schwarze from 1996. This thesis is one of the first doctoral theses concerning the configuration of multiple product variants. Afterwards we look at more recent literature concerning product configuration systems, namely a short review of a paper from Lars Hvam on how to develop product models. The research group 10 under the supervision of Lars Hvam has been researching product configuration systems for many years. Furthermore, Franke and Piller (2004) provide an economical evaluation of product configuration systems in the watch market.


2.3.1 Krause et al. (1993) ‘Product Modelling’

This paper presents an overview of the 1993 state-of-the-arts and practices of product modelling. According to the authors product modelling consists of two interrelated aspects: (i) product models, and (ii) process chains. (Krause et al., 1993)

In the paper, product models are referred to as product model databases and associated management and access algorithms where the products are materialized, artificially generated objects which form a functional unit. Models contain relevant information including data, structures, and algorithms. Process chains represent the product modelling processes. These consist of a set of technical and management functions required when transforming initial ideas to final products.

During the introduction phase of CAD/CAM applications engineers and researchers realized that it is often necessary to store other engineering data and information together with the geometry models that a CAD system could provide. As products in general became more and more complex involving a lot of different disciplines (automation, mechanical, electronically), it was inevitable to integrate different kinds of product related information in different lifecycle phases of the product. According to the authors we see four different kinds of product models, which will be described below:

- Structure-oriented product models
- Geometry-oriented product models
- Feature-oriented product models
- Knowledge-based product models

The kernel in structure-oriented product models is a description of the products structure. The structure of a product can be represented in many ways, e.g. in bill-of-material types, UML or product family master plans. According to the purpose of the structure-oriented product model it can contain information on commonalities, variety, and versions of a product.

The purpose of geometry-oriented product models is representing the shape of the product through wire frames, surface, solid, or hybrid models (often referred to as CAD). Since the data structures of geometrical models are designed to represent geometry, it is often difficult to extend

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10 Information about the group of Lars Hvam (Centre for Product Modelling) can be found at www.productmodels.org.
these with additional product information. Approximately 15 years after the paper was published this is however exactly what is happening with systems such as Engineering Intent from Autodesk.

The feature-oriented product model is an extension of the geometric-oriented product model. The feature-oriented product model represents often used shape patterns as geometric items, called form features. A form feature is application independent and thus does not carry any specific non-geometric semantics.

Knowledge-based product models are often described as a model of the product based on artificial intelligence techniques such as object-oriented programming, rule-based reasoning, constraints, and logical systems.

Finally it is becoming more and more natural to integrate different kinds of product models. An integrated product model covers the abilities of geometry-, feature-, structure-, as well as knowledge-oriented product models. The integrated product model offers support to primary business processes throughout different stages of the product life cycle, and it forms a foundation for the generic product knowledge of the company.

While product models focus on modelling product related information in different phases of their lifecycle, product modelling also focuses on process chains. Process chains should represent all tasks to be carried out in the product lifecycle. Accordingly, process chains consist of product development workflows, production workflows, maintenance tasks, recycling considerations etc. According to the authors, the challenge is to first generate process chains for specific products, and then manage the cooperation and integration between process chains for all products. To compete in the dynamic marketplace of today, it is essential to optimise the efficiency of process chains within the company. For this reason, process chains should be the driving factor in the development of product models.

2.3.2 Schwarze (1996) ’Configuration of Multiple-variant products’

The aim of Schwarze’s paper is to strengthen the field of product configuration as industrial companies need improved product configuration to switch to a post mass production paradigm. At the time of this dissertation, the shift from make-to-market to make-to-order production has had a major influence on corporate strategies. Fast time-to-market and high flexibility towards customer requirements has been essential to survive in a dynamic market calling for orientation toward the specific need of the customer. As a result, the numbers of product variants have increased dramatically, and product configuration systems that can handle the customer requirements as direct input and transform the needs to a tailored product have arisen. Subsequent, Schwarze sets out to help companies in improving customer-oriented configuration as many configurators still have shortcomings.

Schwarze bases his definition of the configuration task on the definition from Mittal and Frayman (1989), see section 2.2.1, and Faltings and Weigel (1994). Consequently, the configuration task is to combine predefined building blocks into a product by using predefined interfaces so that the product fulfils the requirements of the customer. In this process, no new components can be designed, and no new interfaces can be created.

Although new components can not be designed, the task of configuration is quite similar to the task of design. They are both early in a product’s lifecycle, and the main goal of both tasks is to map functional requirements to a structural solution of the product. However, where the design task has a high degree of freedom, an open solution space, and is allowed to create new components, the
The configuration task is a more restricted task with a somewhat low degree of freedom, a closed solution space, and no permission to create new components.

Figure 2-3 illustrates how the configuration task relates to the sales process. The needs of the customer must be understood before an order can be proposed. The specifications are inferred from the needs of the customer until a complete and correct configuration is acquired.

**Figure 2-3: Configuration as part of the sales process (Schwarze, 1996, pp.14) (originally from (Frayman & Mittal, 1987))**

Schwarze (1996) separates the configuration process into three stages: Each stage concentrates on a specific phase within the configuration process. The three stages of the configuration process are: (i) Specification mapping, (ii) technical configuration, and (iii) choice and optimisation. The actors involved in a configuration project influence the process at the different stages, and have different perspectives on the product. This is illustrated in Figure 2-4.

**Figure 2-4: Different views on a product (Schwarze, 1996, pp.26)**

The goal of the specification mapping stage is to transform functional knowledge provided by the customer into a structural description of the product. The outcome of the specification mapping stage is a technical product specification which is used to find one or several possible configurations or to detect contradictions which is the purpose of the technical configuration stage of the configuration process. If the specification mapping has been carried out correctly, all the identified configurations will match the requirements of the customer. Important subtasks of the technical configuration stage are according to (Schwarze, 1996, pp.28):

- Selection of concrete components,
• dimensioning and
• finding consistent combinations of components

The outcome of the technical configuration stage is a set of possible products, and the aim of the choice and optimisation stage is to prioritise among these. Schwarze identifies two possible ways of choosing between several valid configurations: (i) Present valid solutions to the customer, and let the customer choose the solution he prefers, or (ii) apply one or more optimisation criteria given by the customer and find the best of the valid solutions according to these criteria.

In order to work with a product and with product related information in computer systems, it is necessary to store product knowledge in a structured manner, i.e. it is necessary to use a product model. The product model serves as basis for implementation, and an extended product model called the configuration data model is defined in this way:

“A configuration data model is a model that represents all of the information about a product and its application that is used during the configuration process in structured format. It is the basis for a configuration system because configuration algorithms use information described in the model.”

(Schwarze, 1996, pp.33)

To carry out the information modelling required to establish a configuration data model, Schwarze proposes the use of object oriented modelling techniques.

2.3.3 Hvam (1999) ‘A procedure for building product models’

The basic assumption of Hvam’s paper is that engineers must take responsibility for building product models in their domain. Rather than having computer science experts interviewing domain expert to extract domain knowledge, the domain experts must be able to carry out the modelling task by themselves. Accordingly, the paper presents well-defined concepts, modelling techniques, and a procedure for building product models (Hvam, 1999).

According to Hvam, product models contain a formalized description of a given product in a given phase of the products lifecycle. Product knowledge which usually only exists in the minds of skilled engineers (domain experts) is thus made explicit through formalized descriptions. In the paper a product model is:

“A model containing a description of the product’s functional and structural design”

(Hvam, 1999, pp.79)

The procedure for building product models consists of seven phases. Figure 2-5 provides an overview of the procedure for building product models.
The starting point for the development of a product model is an analysis of relevant products, related design activities, and actors. We assume that this analysis has been carried out prior to building a given product model.

The first two phases in the procedure concern the specification task which is to be supported by the product model. Phase 1 is an analysis of the specification task where potential areas for the application of product modelling are identified. Phase 2 is a synthesis where the overall structure and the product models to be built are determined. In this phase the purpose, view and context for phase 3 are also determined.

Phase 3 involves formalisation of features by means of the concepts and methods of object oriented modelling. The paper has its focal point on the identification and modelling of features in phase 3. The concept of a feature is defined as a knowledge element. Features are related to either a function or a domain, and consequently the specific concept of a feature can only be specified in relation to a specific application area. When the features have been listed, object oriented modelling techniques are used to model the features, their characteristics, and the relations between features into a rigid data structure.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Activity</th>
<th>Theoretical foundation</th>
<th>Extension/ modification of theoretical foundation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Determine content and structure for the modeling task. Determine purpose, view and context for Phase 3.</td>
<td>Reference models for product modeling [Krause, 1986; Andreasen, 1992], ICAM’s purpose, view and context [ICAM, 1981].</td>
<td>ICAM’s definition of purpose, view and context is modified against the use of product modeling.</td>
</tr>
<tr>
<td>3</td>
<td>Identify features and Prepare OOA-model (object oriented analysis)</td>
<td>Coad and Yourdon’s method supplied with Beck and Cunningham’s notation, The feature concept [Coad &amp; Yourdon, 1991; Beck &amp; Cunningham, 1990]</td>
<td>Identification of features form the basis for identifying and characterizing objects. Use adjusted CRC-cards for describing objects.</td>
</tr>
<tr>
<td>4</td>
<td>Prepare OOD-model (object oriented design).</td>
<td>Coad and Yourdon’s method for object oriented design [Coad &amp; Yourdon, 1991]. The OOD-model form the basis for programming.</td>
<td>OOD-model is prepared in cooperation between OOA-modeler and computer experts (program developer).</td>
</tr>
<tr>
<td>5</td>
<td>Programming.</td>
<td>Using object oriented programming languages [Booch, 1991; Graham, 1991].</td>
<td>Division of labor between OOA-modeler (domain expert) and computer expert.</td>
</tr>
<tr>
<td>7</td>
<td>Maintenance of the system.</td>
<td>Theory for maintenance of computer systems in relation to the O-C-project life cycle [Coad &amp; Yourdon, 1981, Booch 1991].</td>
<td>Necessary to perform simultaneous updating of OOD-model and program code.</td>
</tr>
</tbody>
</table>
In phase 4, the object oriented design (OOD) model is prepared, and the perspective changes from ‘what and which task’ to an implementation oriented perspective (how?). The OOD model, which is developed, forms the basis for the programming in phase 5, and also makes up the system documentation for the maintenance in phase 7.11

Finally the paper summarizes a case study where these modelling techniques have been used. The case study is carried out at Alfa Laval Separation A/S which manufactures decanter centrifuges to separate solid materials from liquids. The case study proves that the modelling techniques work as they are based on well defined concepts and methods. An important strength of these techniques is that they are simple and general and can be used for modelling all kinds of specifications in different phases of the product life cycle. Experience shows that the modelling techniques are easy to learn and apply by domain experts such as ordinary engineers.

2.3.4 Franke & Piller (2004) ‘Value creation by toolkits for user innovation and design’

The intention of Franke and Piller’s paper is to explore the value creation of toolkits used for user innovation and design. This is done by focusing on the watch market as entity of the analysis. According to the authors a toolkit is a design interface existing in various fields ranging from computer chips to individualized athletic shoes (Franke & Piller, 2004). More specific toolkits for user innovation and design provide the customer with the ability to design their own product. Toolkits enable customers to design their own product by simulating the outcome of a design by allowing trial-and-error experimentation. When a suitable design has been reached, the customized product is manufactured according to the specification of the customer.

Particularly in business-to-consumer (B2C) applications the value creation of toolkits is questioned. On the other hand, it is noted that a significant number of applications have been reported in recent literature. Sadly, most of these are anecdotal case studies which do not attempt a quantitative analysis of the value that toolkits deliver to the customer. It is not known whether customers are willing and able to make use of the possibilities that toolkits offer. Thus, the purpose of the present study is twofold.

(i) To establish evidence if customers actually make use of the solutions space offered by toolkits

(ii) To measure how much value the process of self-design actually creates

This calls for a precise definition of the concepts of toolkits. This is done by referring to Eric Von Hippel’s definition:

“Von Hippel (2001) defines toolkits for user innovation as a technology that (1) allows users to design a novel product by trial-and-error experimentation and (2) delivers immediate (simulated) feedback on the potential outcome of their design ideas.”

(Franke & Piller, 2004, pp.402)

Obviously, toolkits exist in different variations. The authors define two different types based on the solution space offered by the toolkit. These are: Very complex toolkits often employed in business-to-business (B2B) that offer a large solution space and cannot be employed without a very
precise technical understanding of the product, and toolkits often employed in B2C that offer a limited or small solution space and only allow users to combine relatively few options.

Even though the underlying principles are the same, the first kind requires that the customer is particularly active as a designer, offering possibilities for innovation, whereas the latter toolkits focus on the individuality and customization of products.

The study focuses on a single toolkit in a B2C setting which only allows design activities (not innovation activities). The chosen toolkit was intended for customizing watches, and it was fairly easy to use. The toolkit offered a wide variety of combinations (at least 650 million different designs of a watch).

To see, if customers actually did make use of the solution space offered by the toolkit, the concept of entropy was used. Entropy is a measure of the degree of disorder of a randomness of a probabilistic system. It has been used in management science e.g. to measure diversification. On the basis of observations and experiments made in this study, Franke and Piller conclude with some certainty that preferences were not completely heterogeneous but followed a weak pattern. However the entropy of the system was very close to maximum disorder signifying that preferences at this level were quite heterogeneous. This was backed up by an analysis of how many standard watches were needed in order to meet customer requirement as well as the toolkit does. There are two essential decisions to be made from the manufacturer’s point of view. (i) The manufacturer has to decide how large will be the share he wants to reach with the standard watches, and (ii) the manufacturer has to decide the satisfaction level of the individual customer. Having made these two decisions, the table below shows the number of standard watches the manufacturer would need to offer in order to meet the preferences of 165 customers.

**Table 2-1: Numbers of standard watches necessary (Franke & Piller, 2004, pp.408)**

<table>
<thead>
<tr>
<th>Decision 2: Satisfaction Level of Individual Customer</th>
<th>Decision 1: Share of Customers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0%</td>
</tr>
<tr>
<td>0%</td>
<td>1</td>
</tr>
<tr>
<td>20%</td>
<td>1</td>
</tr>
<tr>
<td>40%</td>
<td>1</td>
</tr>
<tr>
<td>60%</td>
<td>1</td>
</tr>
<tr>
<td>80%</td>
<td>1</td>
</tr>
<tr>
<td>100%</td>
<td>1</td>
</tr>
</tbody>
</table>

For example, if the manufacturer chooses to meet 80% of the customers preferences (the customer gets what he wants in 4 out 5 design parameters), and the manufacturer aims at 80% market cover of all 165 customers, he would need 101 standard watches.

So the conclusion the first part of the paper is that customers actually make use of the solutions space.

The second purpose of the paper is to measure, how much value the process of self-design actually creates. So far, the study by Franke and Piller has assumed that deviations from the ideal design are relevant for users. However, it could be that the observed heterogeneity of design solutions is purely random – perhaps because users simply do not care about the design. As a consequence, the authors investigate the value increment for self-designed watches by checking
whether people really care about their unique designs, and whether they would pay more to have their preferences met. In order to cross-validate the results, the authors use two different methods to measure willingness-to-pay (WTP): The contingent valuation method (CVM), and Vickrey Auction (VA).

The study provides evidence that the WTP for a self designed watch is almost twice as high compared to buying the bestselling standard model available on the market. Although, the product designs are indeed remarkably heterogeneous, it appears that offering individualized products by means of toolkits for user innovation and design is a promising way to exploit seemingly mature markets even further. Interestingly, there are hints that other potential customers (i.e. non-designers) liked user-designed products. The other potential customers were not informed about the source of the design of those products, yet the mean WTP for watches from non-designers is comparable to the WTP for the bestsellers made by professional designers.

2.3.5 Forza & Salvador (2007) ‘Product Information Management for Mass Customization’

In their book from 2007 entitled ‘Product Information Management for Mass Customization’, Forza and Salvador synthesise four years of research comprising of case studies, interviews with configuration system programmers, system engineers, managers, executives, and consultants. The book contains many case studies that provide the reader with practical implications of configuration projects. The book is divided into four parts.

Part I introduces the subject of product configuration by highlighting the difference of variety (when offering the customer different variants of the same product) and customisation (when one or more activities in the company’s value chain (design, fabrication, assembly and/or distribution) is carried out according to the customer’s specific needs). Figure 2-6 illustrates different types of customisation according to which activities are customised.

*Figure 2-6: Different types of customisation (Forza & Salvador, 2007, pp.10)*
Subsequently configuration processes and configurable products are defined. Configurable products are characterised by the possibility of associating product functions with customer needs without uncertainty and without the help of a designer. It is important to notice that the authors distinguish between two important subprocesses in the configuration process: (i) commercial configuration process, and (ii) technical configuration process. A commercial configuration process is:

“...all the activities carried out to identify the complete and congruent commercial description of the product that best fits customers requirements.”

(Forza & Salvador, 2007, pp.19)

A technical configuration process is:

“...all the activities that generate the documentation of the product variant based on the commercial description of such variant.”

(Forza & Salvador, 2007, pp.20)

The configuration process is as follows:

“...all the activities from the collection of information about customer needs to the release of the product documentation necessary to produce the requested variant.”

(Forza & Salvador, 2007)

Parts II of the book discuss how configuration systems are supported by product configurators\(^\text{12}\). According to the authors, a configuration system is a socio-technical system which requires human and computing resources, and consequently, a configuration system can be perceived as an open and dynamic system in relation to its external environment. To sum up, the authors define a configuration system as:

“The set of human and computing resources that contribute to accomplish the configuration and modelling processes.”

(Forza & Salvador, 2007, pp.56)

Forza and Salvador also provide a conceptual model of how different kinds of product configurators can be applied in different types of companies. This is illustrated in Figure 2-7.

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\(^{12}\) By configuration system, the authors refer to the set of human and computing resources that contribute to accomplish the configuration and modelling processes while they by product configurator refers to the IT system.
As illustrated, it makes sense to automate the configuration task with a product configuration system within the following three categories: Customized distribution, customized assembly and customized fabrication. By manufacturing products with varieties without customization the configuration task can easily be handled by more simple selectors. These are systems that help customers scan through the product variants offered, and identify the product that fits the customers’ needs. Finally, the complex configuration task of pure customization can only be handled by what Forza and Salvador (2007) refer to as meta-configurators. These are expert systems that support the designer in evaluating what is the best, most economical, fastest and most suitable solution from a technical point of view to satisfy the requirements of the customer in the preliminary design, not providing the detailed definition of all design parameters.

Finally, part II of the book also treats issues with the establishment of product models. The following two modelling tasks are treated separately: (i) Commercial product modelling, a sales oriented description of the product family to support the commercial configuration process, and (ii) technical product modelling, a description of the product from a technical point of view to support the technical configuration process.

Part III has the selection of product configurators, implementation, and links with other parts of the company’s information system as turning point. Primarily, the links between product configurators and different management information systems are described. The linkages with overall management information systems are important as no product configuration system operates independently. Product configuration systems always interact with several subsystems. The authors explore interfaces supporting such interactions, possible overlaps, complementarities, and synergies.

Finally, part IV looks at how the implementation of a configuration system affects the organisation. Configuration systems are socio-technical systems characterised by a technical system (the configurator) and organisational components such as people, procedures, and processes. Therefore it is necessary to act on both technical as well as organisational dimensions when one implements a configuration system. The two chapters in part IV of the book reflect on such issues.

2.3.6 Hvam, Mortensen & Riis (2008) ‘Product Customization’

Hvam, Mortensen and Riis (2008) have recently published a book about product customisation and the development of product configuration systems. The book is based on experience from more
than 40 configuration cases where the following benefits have been observed: shorter lead times, increased productivity, fewer mistakes in delivered goods, and more satisfied customers. The authors present an operational procedure for developing product configuration systems in industrial companies as well as service companies. The procedure covers the steps from the identification of needs through the operation to maintenance of the configuration systems and involves analysis and design of the business processes (which are to be supported by the configuration system), analysis and modelling of the product portfolio, selection of configuration software, programming the software, and implementation and further development of the configuration system. The starting point of the procedure is the Ph.D. project of Hvam (1994). The procedure has since been further developed in more Ph.D. projects (see (Riis, 2003; Hansen, 2003; Malis, 2005).

The book starts out by describing central terms. First, we find a description of the kind of business processes that involve the establishing of specifications for customised products. In the book, these are denoted specification processes. Specification processes are the part of a company’s operational system which produces specifications of customised products. This includes activities performed as part of the sales and order execution. Specification processes, as opposed to the development of new products, take place inside a relatively stable and closed solution space and they are often routine activities which take place on a regular basis. Secondly, configuring and configuration systems are treated. To configure means to put together a product from well-defined building blocks according to a set of pre-defined rules and constraints, and configuration systems denotes an IT system which is mainly based on constraint-based programming. Thirdly, product models are described as models of a product’s structural and functional properties, and how the product interacts with life cycle systems.

The rest of the book describes the procedure for developing configuration systems. The object-oriented project life cycle is used as starting point for the description of the procedure. The procedure for developing configuration systems consists of seven phases (see Figure 2-8).

*Figure 2-8: Procedure for development of product configuration systems. (Hvam et al., 2008)*

<table>
<thead>
<tr>
<th>Phase</th>
<th>Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>1  Development of specification processes</td>
<td>Step 1. Identification and characteristics of the most important specification processes.</td>
</tr>
<tr>
<td></td>
<td>Step 2. Formulation of goal and requirements for the specific specification processes. Measuring and gap analysis.</td>
</tr>
<tr>
<td></td>
<td>Step 3. Construction of new specification process. Definition of the configuration system(s) intended to support specification processes.</td>
</tr>
<tr>
<td></td>
<td>Step 4. Estimation and selection of scenario.</td>
</tr>
<tr>
<td></td>
<td>Step 5. Plan of action and organisation of the work to come.</td>
</tr>
<tr>
<td>2  Analysis of product portfolio</td>
<td>Analysis of product range. Definition of the over all content and structure of the configuration system. Construction of the product variant master.</td>
</tr>
</tbody>
</table>
3 Object-oriented modelling
Building of object-oriented analysis model (OOA).

4 Object oriented design
Selection of configuration software. Adaptation of OOA-model to the selected configuration software. Making of requirement specification for programming, including user interface, integration to other systems and program dynamics.

5 Programming
Programming and test

6 Implementation
Implementation of configuration system and the future specification process

7 Maintenance and development
Measuring and follow-up on the new specification process. Maintenance and running further development of configuration system. Nomination of those responsible for maintenance and further development.

The authors focus mostly on the initial phase of the procedure which involves analysis and redesign of business processes and the modelling of the product range (Phase 1-4). The actual programming, implementation, and maintenance and development of configuration systems are not described in detail.

In the first phase of the procedure we must identify and characterise the relevant specification processes for the project and formulate aims and requirements for these. In this initial phase of the project, scenarios for the new specification process are worked out and evaluated. Finally, a scenario for the new specification process is selected, and a plan of further actions and work is made.

In phase 2 the product range is analysed with the purpose of getting an overview of the product family and of identifying possible variations within individual product families. The authors propose the ‘product variant master’ as tool for the analysis of the product range. By making a product variant master you get a description of the product in terms of a specification of parts and modules included in the product and how the different parts and modules are related. The product family master serves as basis for identifying objects and hierarchies in phase 3.

In phase 3 the object oriented modelling is carried out by making an object oriented analysis (OOA) of the product. The OOA model forms the foundation for the subsequent choice of software, adaptation of the model to match selected software, and programming.

In phase 4, software for the configuration system is selected, and the OOA model is aligned to the selected software. This is called object oriented design. Before the choice of configuration software is made, a software requirement specification is made. When the software has been chosen, the final step in phase 4 is to make a requirement specification for the programming phase which also describes the user interface, integration with other systems, and program dynamics.
The fifth phase of the procedure describes the programming of the configuration system. In this phase the configuration system is programmed with the foundation of both the object oriented model and the requirement specification for programming made in phase 4. When the configuration system has been programmed, the configuration system has to be implemented. This is the aim of phase 6. It is of great importance that the users accept both the configuration system as well as the new specification process. When the system has been programmed and implemented, the configuration system is transferred to an operational phase, where it has to be maintained and further developed. This is described in the seventh phase of the procedure.

Finally the book reports on a successful case study carried out at F.L. Smidth. This case study is also referred to in the introduction of this thesis, and consequently a summary will not be given.

2.3.7 Reflections on ‘Product Configuration Systems – a new Kind of Expert Systems’

While the literature on configuration and the configuration task was reasonably homogeneous regarding research area, the literature on product configuration systems is rather inhomogenous. For that reason, a synthesis of the literature is valuable.

The first paper of Krause et al. (1993) gives a comprehensive presentation of the concepts of product models. Product models are presented as a necessity to cope with the more and more complex products of today. As products in general become more and more complex involving many different disciplines (e.g. automation engineering, mechanical engineering, and electronical engineering) integrating different kinds of product related information in different lifecycle phases of the product is unavoidable. The idea that integrated product models which consist of geometry, feature, structure, and knowledge-oriented knowledge could support the different stages of the product life cycle is visionary and ambitious. However, the paper fails to consider organisational and use related issues. While developing an integrated product model seems intriguing, it is complicated without a thorough understanding of how the needs of the users should be identified, and it is difficult to develop and implement a system that supports the key business processes in a company without any organisational knowledge. What the paper brings us is technical considerations as to what kind of product models there are and how the product models support business processes in companies. The most important contribution to the present thesis is that product models can not stand alone. On the contrary, product models must be related to business processes before they can offer value for the money.

Schwarze (1996) provides a general framework to understand configuration, configuration processes and product models for configuration. He also gives recommendations regarding the development of configuration systems. He points out that the actors involved in a configuration project influence the process in different stages, and have different perspectives on the product, and that a product model including only technical knowledge might not be sufficient. In order to be true to the definition of product models, he defines an extended product model called the configuration data model which is a data model that represents all the information about the product and its application used during the configuration process.

The paper from Hvam (1999) provides a procedure for building product models, and for supporting them with IT. It is not clear whether the intention of the procedure is to model product data (establish product models) or develop configuration systems. The paper does not refer to any of the papers presented in the previous chapters concerning the definition of configuration and the configuration task. Furthermore, it is not quite clear how Hvam (1999) defines configuration, configuration systems and product models.
Franke & Piller (2004) explore the value creation of toolkits for user innovation and design. Toolkits for user innovation and design provide the customer with the ability to design their own product by simulating the outcome of a design allowing for trial-and-error experimentation, and after a suitable design has been reached, the customized product is manufactured according to the specification of the customer. In this sense toolkits are closely related to configuration systems. The authors focus on the operation of configuration systems, and the benefits that can be obtained by implementing a toolkit, and they use the watch market as object of the analysis. The purpose of the study is twofold. (i) To prove if customers actually make use of the solutions space offered by the toolkits and (ii) to measure how much value the process of self-design actually creates. The answers to the two questions are: (i) customers use a large part of the solutions space, and (ii) the study provides evidence that a customer is willing to pay almost twice as much for a self designed watch compared to the bestselling standard model. This calls for reflection. If the idea of configuration is to involve the customer in the customisation of a product, and the customer on the other hand is willing to pay considerably more for the product, why then is the customer not more in focus when we develop configuration systems? Usually, configuration projects are seen as merely technical projects.

Forza & Salvador (2007) cover a wider array of topics in their book from 2007. The authors diverge from the other authors presented in this chapter by their definition of a configuration system. They define a configuration system as a socio-technical system which requires human and computing resources, and therefore a configuration system can be perceived as an open and dynamic system in relation to the external environment. This is very important to notice because the authors in this way divert from other researchers in the community. Furthermore, the book deals with how the implementation of a configuration system has an effect on the organisation. Configuration systems are socio-technical systems characterised by a technical system (the configurator) and organisational components such as people, procedures, and processes. Consequently, it is necessary to act on both technical as well as organisational dimensions when we implement a configuration system. Forza & Salvador also present a model of different kinds of configuration systems characterised by the degree of customisation in a given company’s value chain. The model of different types of configuration systems has some obvious weaknesses. It tries to make some general suggestions as to what kind of product information systems can be used in which types of companies. However, any of the three kinds of systems described can be used in engineering companies for different purposes and at different stages of the design process. For instance, meta-configurators are often used in the sales process, in the front-end studies or in the early conceptual studies to provide quick rough calculations and estimates on capacity, prices, etc. while configurators (based on a CAD-engine) are used in later design phases to give an exact specification of a tank according to some requirements provided by the user. By the same token, selectors can be used in engineering companies to aid engineers in identifying a solution when they browse catalogues of existing solutions. Taken together, it should not be the company’s value chain which is used as factor when distinguishing between different configuration systems.

Finally, Hvam et al. (2008) sum up years of experience and research in their book from 2008. The book describes a procedure for developing configuration systems. The object-oriented project life cycle is used as starting point for the description of the procedure, and the procedure consists of seven phases. The authors focus mostly on the analysis and redesign of business processes and the modelling of the product range (Phase 1-4), while actual programming, implementation, and maintenance and development are not described in detail. Hvam et al. (2008) cover the area of research from a technical point of view, and although the focus of the book is on a procedure for
developing configuration systems, there is, in reality, not much guidance on how to carry out projects in organisations.

### 2.4 Summary

The reviewed literature shows a progression from the early development of expert systems to today’s use of product configuration systems. It covers many subjects from application of new technology to science (isolated technical systems) to socio-technical systems and even why a user willingly spends 100% more on a configured product than a similar standard product.

However it also shows a deterioration of the understanding of the configuration task and what configuration is i.e. a design task. Most recent literature reports on configuration systems in the shape of anecdotal reporting on the development of information systems that perhaps support the configuration task – perhaps not. Furthermore, the definition of configuration becomes ambiguous as it is evident that the different research groups defines configuration differently.

In this chapter a selection of papers have been summarised and discussed. These 13 papers form the theoretical foundation on which this present thesis stands. The papers provide the reader with knowledge of how the field of product configuration arose, and what the development in the field has been from the beginning of the ‘80s up until 2008.

In section 2.1 we learned that in order to master configuration projects, it was necessary to master and carefully balance three perspectives: (i) The strategic/business perspective, (ii) the technical perspective, and (iii) the human resource/organisational perspective.

In section 2.2 we explored different conceptualisations of configuration: the connection-based approach (Mittal & Frayman, 1989), the resource-based approach (Heinrich & Jüngst, 1991), the structure-based approach (Cunis et al., 1989), and the function-based approach (Najmann & Stein, 1992). Furthermore we looked at a general ontology for configuration (Soininen et al., 1998).

In section 2.3 we explored recent research on configuration of products, how to develop product configuration systems, and how configuration systems are applied in organisations. Although there researched shows an interesting interplay between the user and the configuration system, there is little user-focused research on this topic. What is more, knowledge on how to integrate configuration systems from an organizational point of view in existing sales systems is lacking, more or less. Publications focus for instance on how organisations implement and use toolkits, not on how users interacting with them (an exception is of course (Franke & Piller, 2004)). Apparently, users are willing to pay more for a customised product but this has not been investigated further in the community.
3 Research Questions and Methodology

This Chapter starts out with a discussion of the scientific point of view concerning the research conducted in this Ph.D. study. Then the research questions are developed by an investigation into shortcomings and strengths of the contributions presented in the previous chapter. Finally, the methodology employed and the empirical sources used are presented.

At the Technical University of Denmark, the prevalent scientific point of view concerning research into product configuration is critical rationalism (Svensson, 2003; Riis, 2003; Hansen, 2003; Malis, 2005). Consequently, it would be natural if this thesis followed the tradition of critical rationalism. However, it does not. Haug (2007) has carried out a thorough investigation into whether the critical rationalistic perspective is a reasonable tool in the context of conducting configuration research and if critical rationalism corresponds with how such research has been carried out at Technical University of Denmark till now. The outcome of Haug’s investigation is a rejection of the positivistic notions, and a recommendation of allowing interpretation of experiences. Haug (2007) finally notes that, in fact, interpretation of experiences corresponds well with how the above mentioned research is actually carried out. Thus, although previous research claims to have followed critical rationalistic approach for the creation of scientific knowledge, it has actually not done so.

According to Fuglsang and Olsen (2004) there are three lines of scientific theories: (i) Demarcationism, (ii) scientific realism, and (iii) complex realism. Demarcationism comprises scientific theories whose main purpose is to derive empiric regularities (objective facts about the reality) and to distinguish between theories which are scientific and theories which are not. Scientific realism, on the other hand, is based on the assumption that interpretations are necessary in order to uncover structures and mechanisms behind the observable reality. Complex idealism tries to revoke the distinction between subject and object as the basic assumption is that the society consists of webs of thoughts and materiality.

As described above, the analysis of Haug (2007, pp.43) dismisses the use of demarcationism when one investigates the application of procedures or configuration systems where social elements plays a role. At the other end of the spectrum of the theory of science, we find complex realism which recognises the importance of social factors. An example of a theory which belongs to complex realism is social constructivism – a theory which concerns the development of social phenomena in social contexts. Social constructivism argues that our cognition is not independent of the social context which we are part of, and the reality is shaped in a significant way by our cognition of it. Social constructivism focuses on an individual’s learning that takes place as a consequence of the individual’s interaction in a group, and the objective of social constructivism is to ask how knowledge is created, not whether it is true or false.

Taking social factors into consideration is important in configuration research, but the author of this thesis believes that reality has an independent existence and that reality is not only what is observable by human senses. Following the assumptions of critical realism (which is part of scientific realism) suits this Ph.D. study well. Critical realism understands science as an ongoing process in which researchers improve the models and concepts they use to understand the mechanisms that they study. The ontological basis of critical realism is realism – there exist an independent reality that we may not have fully access to. The epistemological basis of critical realism is relativism – all knowledge is produced in social contexts based on existing knowledge. Finally, critical realism is based on rational judgement – knowledge may be relative and fallible but not equally fallible. (Buch-Hansen & Nielsen, 2007)
The implication of this is that science should be understood as an ongoing process in which scientists improve the concepts they use to understand the mechanisms that they study. It should not, in contrast to the claim of empiricists, be about the identification of a correlation between a postulated independent variable and a dependent variable. Furthermore, the methodological core perception of critical realism is ‘clarity of concepts’. Social science – the central field of critical realism - is subjected to limitations as the objects of research are often based on meanings and concepts. Consequently, Buch-Hansen & Nielsen (2007) advocate that clarifying concepts is given the same status in social science as exact measurements are given in natural science. Consequently, the project of clarifying concepts will be central in the present Ph.D. project.

3.1 Developing Research Questions

Until now, the purpose of the present thesis has been vague: “How are configuration projects carried out in engineering companies?” Answering this question requires a clear understanding of key concepts of configuration, a clear understanding of what different types of product configuration systems there are, and a clear understanding of the prerequisites for configuring. Before developing research questions, an analysis of strengths and shortcomings in the papers presented in chapter 2 is conducted in order to determine whether the existing literature can provide a satisfactory answer to the meta-question of the present thesis.

The variety of product configuration systems is large, and thus the configuration projects which are carried out vary a lot. The literature presented in chapter 2 provides a good overview of the research carried out concerning product configuration systems. Digging into the literature of product configuration and product configuration systems yields an ambiguity of definitions which is confusing. It is not quite clear what different kinds of product configuration systems there are and how they differ, what configuring denotes, how the configuration task is defined, and what a configuration system is. The concept of ‘product configuration system’ is used on many different types of information systems ranging from sales support systems to the detailed engineering of complex technical systems. Furthermore, the meaning of ‘configuring’ and ‘configuration system’ has become ambiguous due to a lack of clarity of concepts and meanings. A recent example of this is how Forza and Salvador define configuration systems differently than other communities\(^\text{13}\). To provide a clear answer to the meta-question, it is necessary to establish clear definitions and concepts regarding configuration.

Furthermore, one cannot give a satisfactory answer to the meta-question without knowing what characterises a product configuration system, and what different kinds of configuration systems there are. Looking across different configuration cases\(^\text{14}\), it seems there is a need for distinguishing between different kinds of configuration systems concerning the level of complexity. Franke and Piller (2004) also reflect on this. They identify two different subcategories of configuration systems, or toolkits for user innovation as they call it. They define two different types based on the solution space offered by the toolkit. These are: very complex toolkits often employed in B2B that offer a large solution space and cannot be employed without a very precise technical understanding of the product, and toolkits often employed in B2C that offer a limited or small solution space and only allow users to combine relatively few options. Even though the underlying principles are the same,

\(^{13}\) Forza and Salvador defines configuration systems as the combined set of human and computing resources that contribute to accomplish the configuration and modelling processes.

\(^{14}\) E.g. configuration projects at NNE Pharmaplan, GEA Niro, F.L. Smidth, American Power Conversion, Linak, Demex, Fritz Hansen, and more.
the first kind depends on the customer to take a very active role as a designer, offering possibilities for innovation whereas the latter toolkits focus on the individuality and customisation of products. This is a distinction between configuration systems in B2B and systems in B2C which offers a good distinction between two different extremities of configuration systems based on the solution space as classifier. However, as we belonging to the engineering world, which again technically belongs to the B2B market segment, we are often faced with the task of developing large and complex configuration systems with large solution spaces. If engineering companies were to support the entire engineering process, the task would certainly be to develop large and complex configuration systems. However, the question is rather if this is feasible or even possible. So when we work with support of engineering processes with configuration systems this classification is not good enough. Forza and Salvador (2007) have a similar classification of configuration systems. They classify types of configuration systems in relation to the customisation scope of the company. Again, this classification provides some new insights; but it hardly provides a satisfactory explanation of what kinds of configuration systems there are. Indeed, looking into this classification can be rewarding. If the customisation scope of the company is seen as the customisation scope of the configuration task, it immediately gives new meaning to the classification of configuration systems. Suddenly, the configuration system is tightly related to the business process which the product configuration system should support. As we recall, a configuration systems is a product model put in relation to a chain of processes. Often a company has many different configuration tasks. One distinct configuration task per product family is easily imagined and not unusual. In companies without formalized business processes - one configuration task per employee can be imagined. So it does not make sense to classify configuration systems on behalf of the kind of company or on behalf of the customisation scope of the company. Often product configuration systems are classified as sales configurators, production configurators or such. For instance, they are classified according to which life phase of the product that they support. Again, taking the definition of configuration systems into account, it is evident that a configuration system is a model of the product related to a business process. A product configuration system contains a product model and affects the workflow of the configuration process. However, it is also dangerous to classifying configuration systems by the life phase of the product they support. A sales configurator in an engineering company can be more complex than a production configurator in a B2C industry.

Finally, it will be difficult to understand how configuration projects are carried out in engineering companies without understanding the basic mechanisms in a configuration project i.e. understanding what the basic prerequisites for configurering are. Again, it is difficult to get a satisfactory answer from the literature presented in chapter 2. In chapter 2 we learned that in order to master configuration projects, it is necessary to carefully balance three perspectives: (i) Strategic/business, (ii) technical, and (iii) human resource/organisational. We also encountered an operational procedure which illustrated how to develop configuration systems, how to solve configuration problems, how to document knowledge, and the economic side of configuration projects. It seems, what is missing is a discussion of the prerequisites for configurering – to discuss what it takes for a company to be configuration ready. This has so far only been discussed on a high abstraction level, and the presented literature does not give a satisfactory account.

In conclusion, answering the meta-question requires a clear understanding of key concepts of configuration, a clear understanding of what different types of product configuration systems there are, and a clear understanding of the prerequisites for configurering.
3.1.1 What We Know

The configuration task is described and analysed in the works of (Mittal & Frayman, 1989; Cunis et al., 1989; Heinrich & Jüngst, 1991; Najman & Stein, 1992). What is more, Soininen et al. (1998) synthesise the work (ibid) and present a general ontology for configuration. Furthermore, the research group at Helsinki University has actively been researching definitions, and ontology of configuration.

At the Technical University of Denmark, a considerable amount of work has been carried out regarding how product configuration systems are developed, implemented, and documented. Thus, how you develop, implement and document product configuration systems has been well documented. The group at Klagenfurt University has actively been researching the modelling and documentation of product knowledge in various contexts, and the group at Helsinki University also contributes to this discussion. Finally, Forza and Salvador have, among others, been researching management implications of the implementation of product configuration systems.

To summarise, we know:

- How to model and document product knowledge
- How the configuration task is defined and how the configuration task can be solved
- How configuration can be described according to a general ontology
- How to develop, implement and document product configuration systems and industrial variant specification systems

3.1.2 What Should be Researched

The aim of the present thesis is not to present yet another case story of how you should develop, operate, and maintain a product configuration system – only this time with engineering companies as the centre of attention. The goal of the present thesis is to understand how configuration projects are carried out in engineering companies. Being able to do so require a structuring of the research area of product configuration, in other words, it requires the establishing of clarity of concepts and meanings related hereto. Configuration systems will differ concerning the knowledge needed for implementation, the amount of process consistency needed, the types of employees that need to be involved, and finally how complex it is to model the product knowledge needed for the product configuration system.

Distinguish different kinds of configuration systems from each other is a complex task. However, if we managed to betterunderstand and be able to distinguish between different kinds of configuration systems, it would strengthen our understanding of configuration system by: (i) Making it easier to see who should be involved in the configuration project, (ii) making it easier to see what knowledge is necessary to harvest, and (iii) making it easier to see what level of product and process consistency is needed to implement the product configuration system.

Presumably, in a given company there are many different tasks that can be supported in different ways by different types of product configuration systems. When we know what characterises different product configuration systems, it will then be easier to describe motivations and barriers for configuration projects in companies if we were able to say something about the prerequisites for configuration.

In conclusion, if we want to better understand how configuration projects are carried out, research in the field of configuration should:

- Establish clarity of key concepts related to configuration,
• establish a typology, and
• investigate prerequisites for configuring

3.1.3 Research Questions

In order to become more specific in relation to understanding how configuration projects are carried out in engineering companies it is necessary to create clarity concerning key concepts related to configuration, what different types of product configuration systems there are, how different types of configuration systems differ, and what the prerequisites for configuration are in general.

As a consequence, the research questions in this thesis proceed down two different lines of inquiry. First, a line aimed at establishing clarity of concepts. Thereby, building a frame of reference, formulating a typology to describe different types of configuration systems, and understanding the prerequisites for configuration. The frame of reference clarifies the expected results and the interpretation of the gathered data. Secondly, the research questions follow the lines of an empirical study aimed at understanding motivations and barriers in relation to configuration projects in engineering companies. Indeed, the empirical study is aimed at understanding how configuration projects are carried out in engineering companies.

To summarise: The meta-question of the present PhD project is: "How are configuration projects carried out in engineering companies?” A product configuration system is not just a product configuration system. Not many product configuration systems are alike, and they are often difficult to compare because they lack homogeneity. Consequently, in order to answer the meta-question, and to make the following discussion more tangible and distinct, it is necessary to propose a frame of reference for configuration, a typology of product configuration systems, and to understand the prerequisites for configuring. This will establish clarity of concepts and meanings. The first three research questions will do so:

RQ1: How can the concepts of a product configuration be understood?
RQ2: How can different types of product configuration systems be distinguished?
RQ3: What are the prerequisites for configuration?

The next two research questions will explore what motivations and barriers which underlie the carrying out of configuration projects in engineering companies.

RQ4: What is the motivation for configuration in engineering companies?
RQ5: What are the barriers for configuration in engineering companies?

Having answered these two research questions, it is now possible to answer the meta-question: ‘How are configuration projects carried out in engineering companies?’

3.2 Methodology

Critical realism confronts and breaks away from the dominating perception of social constructivism (which asserts that all knowledge is relative), and from the perception of positivism (which asserts that our knowledge is limited to what can be extracted from objective facts from reality) (Jespersen, 2004). On the other hand, critical realism emphasises that there exists an independent reality which is to be understood. Theories are fallible attempts that try to describe the real structure of reality. For this reason, the development of theories and knowledge must be seen in a historical setting, and knowledge about the reality is improved over time (Buch-Hansen & Nielsen, 2007). Development of knowledge is a social activity that builds upon and/or extends existing knowledge. Besides actual events and empirical observations, the research domain contains
an independent reality that researchers may not have full access to. Accordingly, the objective of critical realism is to understand events by describing mechanisms and not to predict outcome of future events, as the outcome of events depends on many underlying structures and mechanism. (Buch-Hansen & Nielsen, 2007)

Critical realism is at its most basic level an understanding and elaboration of what science is, and what characterises good scientific research (Buch-Hansen & Nielsen, 2007). In the following, this is converted into a more practical procedure (the methodology) for studying the meta-question of this thesis. It is worth noticing that, according to one of the founders of critical realism (Bhakar), it is vital that the domain determines what knowledge is possible to obtain and consequently how the knowledge can be obtained. You should be very careful with applying universal methods as you cannot be certain that a given recognised procedure suits the particular domain (Buch-Hansen & Nielsen, 2007). While it is not possible to say anything about the ‘correct’ choice of method, the overall methodological reflections you carry out prior to the study must be (according to Jespersen (2004):

1. What are we looking at?
2. What knowledge can we acquire?
3. How can this knowledge be acquired?

Ad. 1: The preliminary literature study aimed at clarifying what we are looking at when researching configuration systems. In the previous section it was established that the existing literature could not provide a satisfying answer to the meta-question. If we remember that knowledge must be seen in a historical setting, and new knowledge modifies, extends and builds upon existing knowledge, we must allow that the existing knowledge is very central when explaining the scientific contributions of this thesis. This thesis is closely related to other pieces of research carried out at the Technical University of Denmark, and therefore it is only natural to position it amongst the work of (Svensson, 2003; Riis, 2003; Hansen, 2003; Malis, 2005; Haug, 2007; Oddsson, 2008). Establishing clarity of concepts is vital to critical realism in social science, and it will improve the understanding of what we are looking at. Research questions 1 through 3 do this. These three research questions establish a frame of reference that can be used to understand how configuration projects are carried out in engineering companies by carrying out a theoretical study.

Ad. 2: Obviously, all relevant mechanisms and objects cannot be included when the overall research question is: “How are configuration projects carried out in engineering companies?” Remembering that, our knowledge is limited to what can be extracted from objective facts from reality, the mechanisms I choose to research in present thesis is, the motivations and barriers to configuration projects in engineering companies. This is carried out in research question 4 and 5.

Ad. 3: The empirical starting point of this Ph.D. thesis was NNE Pharmaplan where I was employed as a researcher during my Ph.D. study. I also worked at NNE Pharmaplan during my one year leave of absence. The empirical basis of the project is nine semi-structured interviews conducted with specialists from NNE Pharmaplan and GEA Niro, two engineering companies geographically placed in the area of Copenhagen in Denmark. All interviews were taped and transcribed for later analysis. The Interviews are in Danish. The interviews are confidential and cannot be obtained at request. A copy of the transcribed interviews was handed over to the evaluation committee for evaluation purposes. Thus, the transcriptions are not accessible.
3.3 Summary

This chapter presented this thesis’s scientific point of view, the development of research questions, and methodological considerations.

The review of literature revealed ambiguities in the definitions of key concepts, and a lack of understanding of how configuration projects are carried out in general as well as in engineering companies. Given the current level of understanding of configuration, it is vital for this project to establish clarity of concepts, and this clarification will be based upon a theoretical approach. This thesis differs from other kinds of research in that it focuses on establishing clarity of concepts. The first three research questions do this, and they are:

- **RQ1:** How can the concepts of a product configuration be understood?
- **RQ2:** How can different types of product configuration systems be distinguished?
- **RQ3:** What are the prerequisites for configuration?

Unlike other kinds of research this thesis focuses exclusively on engineering companies and how configuration projects in engineering companies are carried out and can be understood. This focus can be seen in research questions no. 4 and 5:

- **RQ4:** What is the motivation for configuration in engineering companies?
- **RQ5:** What are the barriers for configuration in engineering companies?

Having answered these two research questions, it is now possible to answer the meta-question: ‘How are configuration projects carried out in engineering companies?’ This thesis differs in the qualitative approach to how configuration projects are carried out in engineering companies. Given the lack of clarity in key concepts in the product configuration society, a qualitative approach is clearly the best choice.
Part II: Understanding Configuration

“Theory belongs to the family of words that includes guess, speculation, supposition, conjecture, proposition, hypothesis, conception, explanation, model.”

(Weick, 1995, pp.386)
4 Developing a Frame of Reference

As the review of existing literature has pointed out, we have several definitions and perceptions of configuration. The term is loosely used in many different contexts. Unfortunately, not only the term configuration carries an ambiguous meaning. It is a more widespread problem. This chapter aims to clarify the definitions of the most important terms and concepts related to this Ph.D. The definitions will form a frame of reference for the rest of the Ph.D. In this way, chapter 4 will answer the first research question:

RQ1: How can the concepts of a product configuration be understood?

In order to create a frame of reference, it is essential to clarify the definitions of the most important concepts. These theoretical elements base a foundation for the research carried out in this thesis.

“Product configuration systems configure a product on the basis of a formalised product model.” This sentence contains the four most central concepts of this thesis: (i) A product i.e. the technical system being configured, (ii) configuring i.e. the configuration task, (iii) a product model, and (iv) a configuration system. We will start out by defining these four terms in section 4.1 through 4.4. In section 4.5 we will try to understand the context of a configuration system.

4.1 Technical Systems (the Product)

The following is based on the theory of technical systems by Hubka & Eder (1988). We define technical systems (TS) as:

**Technical systems** are objects, products, things, machines, implements, technical objects, etc. which are made by humans to fulfil a specific need.

In other words, TS refer to all types of human artefacts. The primary aim of Theory of Technical Systems (TTS) is to:

“...classify and categorise the knowledge about technical systems into an ordered set of statements about their nature, regularities of conformation, origination, development, and various empirical TS-related observations.”

(Hubka & Eder, 1988, pp.8-9)

Humans have many varying needs, and for centuries philosophers and sociologists have discussed the nature of these needs, and how we prioritise them. For instance, a theory of this prioritisation is Maslow’s hierarchy of needs which is commonly known (Maslow, 1943). However, a detailed discussion of this topic is beyond the scope of this thesis. The essential point is that, in general, people will tend to formulate their needs in terms of existing technologies. In this way, an introduction of a novel product on the market can change our perception of our needs.

If the means to fulfil a need exist at the time, if the need can be realised, then a process of designing and manufacturing a product (a TS) can supply the means to fulfil that need. As TS have no intention and can not fulfil needs of humans by themselves, it is necessary to describe the process where the TS are applied to fulfil a need. Hubka and Eder (1988) define processes in which TS are applied to fulfil a need technical processes. A technical process transforms an operant from

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15 A compressed version of this chapter is presented at the IMCM’08 and PETO’08 conference (Ladeby & Edwards, 2008).
an existing state to a desired state by the use of operators. Hubka and Eder (1988) describe three kinds of operators that have an effect on the transformation process: (i) Human systems, (ii) technical systems, and (iii) active environments. The effect posed on the transformation system can be described as material, energy or information, or any combination of those. A system of operators that transforms an operand through a technical process from an existing state to a desired state is called a transformation system.

Each transformation system has a well-defined purpose which is to perform the intended transformation on the appropriate operands. Hubka and Eder (1988) divide the major elements of the total transformation system into a process (the operand which is being transformed), and the operators that drive and guide the process.

The total transformation system can be divided into four subsystems.

(i) A technical system (TS - the product),
(ii) a human system (HuS – a human operator),
(iii) the active environment (AEnv – the influence from the environment), and
(iv) a technical process (TP - where an operand is transformed by effects from the three subsystems mentioned above).

These four subsystems are depicted in Figure 4-1.

Figure 4-1: Model of the transformation system (Hubka & Eder, 1988, pp.35)

Let us examine this operand. One can differentiate between four classes of operands: (i) Biological objects, (ii) Materials, (iii) energy, and (iv) information. These four classes of operands are not exclusive, most often an operand consists of a combination of the classes. The technical process transforms an operand from an existing state to a desired state (the attributes of the operand change). Like in mathematics an operand is modified by operators. When TS are used by humans as artificial tools to carry out the transformation, the transformation process is referred to as the technical process.
The TP can be described by using a variety of tools. In management science and operations management the methodology mostly frequently used to describe processes is called Business Process Modelling Notation (BPMN) (White, 2006). Hubka and Eder (1988, pp.55) mention six main kinds of representation, but we will not go deeper into the issue of representation for now. The technical process is often actualised by various structures of processes, consequently by different technologies, TS, HuS, and AE:\n
To recapitulate, The TP transforms an operand in an existing state to a given desired state by the use of the operators. Let us explore the operators of the total transformation system. A HuS is the subset of humans who exert any effect on the operand, in a particular the TP. Likewise, the TS as operators are that subset of technical systems which exert a direct effect on the particular operand. These two – the HuS and the TS - are main elements in the execution system which drives the technical process. The AE\n
Every operation in a technical system is the consequence of one or more causes, and the operation is simultaneously the cause of one or more other consequences. Consequently, TS can be described as being fully deterministic (Hubka & Eder, 1988). However, in many cases, the causes are so complex and with such a multitude of interactions that it is difficult to assign a cause to each consequence (this is particularly significant when humans or an active environment is involved). On the other hand, each TS has an element of natural variation inherent in the shape of the variance through production, assembly etc. TS wield planned and goal-oriented effects on the operands of the technical transformation process (see Figure 4-1). (Hubka & Eder, 1988) \n
Here it is necessary to distinguish between purpose and actual abilities. What we define as the purpose of the TS is the effect of a TS to satisfy the need of the humans. Thus the purpose of the TS is represented by the system of its output effects to the technical process. The actual abilities of the TS are referred to as functions. Functions represent an introvert view of how the effects of the TS are derived at. \n
So, the constituents of TS are fitted together so that a given input will lead to a given output in the shape of effects on the operand. In order to obtain a certain result (i.e. an output effect), various phenomena are linked together in an action chain (the TS-internal processes). \n
The TS-internal processes convert the input to an output, and this can be described through two structures: (i) describing the function structure, or (ii) describing the organ structure (Hubka & Eder, 1988). Two questions now arise: (i) How and with what means can one accomplish the planned output effects on the operand, and (ii) how can the interior of the TS be described at various levels of abstraction? \n
The highest level of abstraction is the design specification. The design specification states only the requirements, the needs and the constraints, independent of the process or the hardware (Hubka & Eder, 1988). The next level of abstraction is to perceive a given TS as a ‘black box’. Based on inputs from the active environments, human systems, and other technical systems this box yields outputs in the shape of an effect to a given operand. This does not per se describe the technical system in detail but it recognises the effects that the technical system exerts onto the operand in the technical process (i.e. the purpose of the TS). Thus, the ‘black box’-view of a given TS shows the functional connections (at the TS output between the TS and the technical process) and the input of various operators (Hubka & Eder, 1988). \n
If we return to the TS, according to (Hubka & Eder, 1988) the TS can be described as three structures: a functional structure, an organ structure, and a component structure. The three TS
structures (function, organ, and component) are different views or representations of the same TS at different levels of abstractions (Hubka & Eder, 1988). The terminology is related as follows:

- “the effects of the TS (as aims) are achieved by certain function structures (as means);
- these function structures (as aims) can be realized by various organ structures (as mean);
- the organ structures (as aims) can only be realized from various component structures (as mean).”

(Hubka & Eder, 1988, pp.72)

The three levels of abstraction will be described in the following three sections.

4.1.1 Function structure of TS

“The function is a property of a technical system, and describes its ability to fulfil a purpose, namely to convert an input measure into a required output measure under precisely given conditions.”

(Hubka & Eder, 1988, pp.72)

As the opening quotation from Hubka and Eder states, the TS as object is defined for the purpose of the function structure in term of its functions. The functions of TS can be understood as a unique coupling of independent input measures to dependent output measures. Each function can be described more or less concretely. The level of concreteness influences the number of possible or available organs that can be used to realise the function. Hubka and Eder (1988) use the following example to illustrate this:

“If, for instance, the given description refers to the function “alter motion”, then the range of available means is very broad. With an increased number of additional data about the function, selected from the ranges of effects, conditions, operations or working means, the range of available means of fulfilling a function is progressively narrowed until a single concrete TS remains.”

(Hubka & Eder, 1988, pp.73)

Figure 4-2 is an illustration of the degrees of abstraction of functions, and how functions can be made more and more concrete by adding more and more conditions.
There are two fundamental ways to work out a function structure. One is analytical, where you start by abstracting from the component or organ structure. The other is to concretise from the higher abstraction level, which involves identifying functions and their relationships in order to achieve the desired output effect which will drive the technical process.

4.1.2 Organ structure of TS

"An organ is defined as a system that realizes a given internal function of a technical system. Organs may also be termed ‘functional carrier’ or ‘functional unit’."  
(Hubka & Eder, 1988, pp.77)

The organ structure is an abstract model of TS which permits analysis and representation of the operational state of TS. Organs are carriers of functions and they are coupled in the action chain to yield desired effects. These couplings are the main relationships between organs, as the output from one organ is the input to the next organ. As for the function structure, the organs can be defined at various levels of abstraction. The organ structure can be established by either concretising the function structure or abstracting from the component structure of TS. (Hubka & Eder, 1988)

4.1.3 Component structure of TS

Using a component structure is the most tangible way to represent a TS. When you work with the constructional elements of the TS, and the relationship between them, working with the component structure is the most concrete stage in the design process of a technical system. (Hubka & Eder, 1988, pp.81)
The component structure contains all necessary properties to describe how the TS fulfils the user requirements. When the component structure is compared with the more abstract structures described above it is clear that the number of criteria used to evaluate the TS have increased by a large amount. The more abstract structures are mainly assessed from a functional viewpoint, whereas the component structure is a detailed description of every constructional element down to the last bolt and washer (Hubka & Eder, 1988). A component structure is typically established by concretising from a functional or organ structure, and this task is often complicated (Hubka & Eder, 1988).

To sum up, a product can be described on different levels of abstraction, and these are:

(i) Purpose – a description of the effects which the technical system gives to the transformation process.
(ii) Function structure – a description of the functions of a technical system.
(iii) Organ structure – a description of systems which realise functions.
(iv) Component structure – the constructional elements of a technical system.

At the highest abstraction level the number of variables are fewer than at the most concrete abstraction level. This is illustrated in the figure below:

**Figure 4-3: Description of TS on different levels of abstraction**

4.2 **Configuration Task**

There is a fine line between product configuration and design. Many refer to configuration as a subclass of the design activity. Traditionally, configuration has often been considered a part of the design science discussion, even a special case of the general field of design activities. In Stumptner (1997) it is assumed that in configuration the design goals and requirements are fully specified, and that the subcomponents and functions are already known. This belief is also supported by Sabin & Weigel (1998, pp.42-43), who note: “…product configuration is informally a special case of design activity and consists of two key features: a) the artefact being configured is assembled from instances of a fixed set of well-defined component types, and b) components interact with each other in predefined ways.”
The most precise definition of configuration is given by Mittal & Frayman (1989), and even that definition is not unproblematic. Before going into the problems, let us revive the definition: According to Mittal & Frayman (1989) configuration is:

“Given: (A) a fixed, pre-defined set of components, where a component is described by a set of properties, ports for connecting it to other components, constraints at each port that describe the components that can be connected at that port, and other structural constraints (B) some description of the desired configuration; and (C) possibly some criteria for making optimal selections. Build: One or more configurations that satisfy all the requirements, where a configuration is a set of components and a description of the connections between the components in the set, or, detect inconsistencies in the requirements.”

(Mittal & Frayman, 1989, pp.1396)

Mittal & Frayman (1989) then notes that there are three important aspects to this definition:

“[1], the components that can be used to design some artifact are fixed, i.e., one cannot design new components. [2], each component can be connected to certain other components in fixed and pre-defined ways, i.e., the components cannot be modified to get arbitrary connectivity. [3], a solution not only specifies the actual components but also how to connect them together.”

(Mittal & Frayman, 1989, pp.1396)

Thus the core of the configuration task is selecting and arranging combinations of parts that satisfy given specifications. No new component types can be created nor can the interface of the existing components be modified. The configured solution must provide a list of selected components, describe the product structure and topology of the product. This is also supported by (Sabin & Weigel, 1998).

Felfernig’s group at Klagenfurt has a similar approach or definition to the configuration task. However, they add that attributes can have variable values. According to (Felfernig et al., 2000b) (a similar definition is given in (Felfernig, 2007)):

“A configuration task can be characterized through a set of components, a description of their properties, namely attributes and possible attribute values, connection points (ports), and constraints on legal configurations. Given some customer requirements, the result of computing a configuration is a set of components, corresponding attribute valuations, and connections satisfying all constraints and customer requirements.”

(Felfernig et al., 2000b, pp.450)

The group at Helsinki University of Technology and Science provide the following definition, which is in line with the definition of Mittal & Frayman (1989):

“Configuration as a task can be roughly defined as the problem of designing a product using a set of predefined components while taking into account a set of restrictions on how the components can be combined.”

(Soininen et al., 1998, pp.357)
At the Technical University of Denmark, Anders Haug provides a definition of the configuration task which uses the term *entity* instead of the term *component* in order to escape the world of physical products.

“Configuration means to combine predefined entities (physical or non-physical) and define their variable properties, while obeying constraints and legal interface combinations, in a way that satisfies given requirements”

(Haug, 2007, pp.18)

The group around Forza and Salvador also complies with the definition of Mittal and Frayman (1989). However they note:

“A pre-defined component is to be meant as either a standard component, or a standard component with variants or a parametric component, i.e. a component for which one or more attributes vary continuously”

(Salvador & Forza, 2004a, pp.275)

As Brown (1998) points out, there are some problems with the definition of configuration by Mittal and Frayman (1989). The use of the term ‘connect’ throughout the definition indicates that the components in the configuration actually physically connect. Brown (1998) indicates that this is not always the case, and that a logical explanation of the use of ‘connect’ is that Mittal & Frayman have a background related to the configuration of computer equipment. Configurations are more often about relationships between components, where “touch” and “connect” are examples of relationships.

As with the term ‘connect’, there is also an issue with the use of the term ‘ports’. While the term ‘port’ seems logical when configuring computer systems (i.e. a motherboard has ports for connecting with other kinds of hardware), it is more complicated to make a meaningful explanation of the term ‘port’ when configuring mechanical products. The use of the term is again connected with the idea of components which physically connects, and again this might no be valid for all configuration problems (Brown, 1998).

Another issue is the term ‘predefined components’. It is not clear in the definition of Mittal and Frayman (i) at what level of abstraction the components have to be predefined, and (ii) whether all or just some components have to be used in the configuration. If the components allow additional refinement of attributes in terms of colour, shape, dimension, material, etc., there is a possibility of creating something new, which again conflicts with the first point of the definition of Mittal and Frayman. This problem is most outspoken for dimensional refinements. An abstraction of the shape of a component might be specialized into a square or a variety of different rectangles. This might affect the components’ relationship with other components, changing how the components connects or touch other components. Hence there is a contradiction between point 1 and point 2 in the definition of Mittal & Frayman, as refining or concretising an abstract component can modify the component’s allowed connections. (Brown, 1998)

This illustrates the point that configuration is on the edge of design. By allowing random refinement or the concretising of abstract components, we are on the edge of the class of problems we can describe as configuration. One must refine the definition of configuration.

To refine the understanding of configuration one can find inspiration in (Brown, 1998) and in (ten Teije et al., 1998). From now on we will use the term ‘configuring’ when referring to the process itself, ‘configuration’ when referring to the output of the process, and ‘configurator’ or
‘configuration system’ when referring to the system that supports the configuration task. Anders Haug (2007) develops a definition of ‘configuration’ in his thesis. Please note that configuration in this terminology refers to the output of the configuration task. Haug’s definition is stated below:

“Configuration means to combine predefined entities (physical or non-physical) and define their variable properties, while obeying constraints and legal interface combinations, in a way that satisfies given requirements”

(Haug, 2007)

The definition of Haug (2007) builds upon the definitions of Mittal and Frayman, Sabin and Weigel, and Soininen et al. Haug’s definition is mostly correct. However, it is necessary to point out that ‘configuration’ is equalled with the term ‘configuration task’. In the terminology of the present thesis, a configuration is the output of the configuration task i.e. it is a description of a product that satisfies the given requirements. In this way, according to this thesis, the definition of the configuration process is:

**Configuration process:** To combine predefined entities (physical or non-physical) and define their variable properties, while obeying constraints and legal interface combinations in a way that satisfies given requirements.

Logically, the definition of configuration can be derived from the definition of the configuration process. Taking the definition of Mittal and Frayman, Sabin and Weigel, and Soininen et al. into consideration it is necessary to point out that the component structure of the product has to be specified including any connections between components.

A **configuration** is the output of the configuration process, e.g. a description of the component structure of the product and any connections between the components in the set or a description of inconsistencies in the requirements.

### 4.3 Product model

The term **product model** has been commonly used in the literature related to product configuration systems, and a number of different definitions of a product model can be found, as illustrated below:

“...the product model is defined by a total set of characteristics, defining the transformation, function, organ and component structures of a machine system.”

(Andreasen, 1994, pp.111)

“A model containing a description of the product’s functional and structural design”

(Hvam, 1999, pp.79)

“A product model is an abstract representation or description, describing (a) the structure of P and (b) facts, object, concepts and properties that are relevant in any life cycle phase of P. P can be a single product or a family of products. A product is a thing, a substance or a service produced by a natural or artificial process.”

(Schwarze, 1996, pp.33)

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16 A product family is a set of products which differ only in a limited number of less important features (Schwarze, 1996, pp.33).
"A Product model is usually intended to define various data generated through the product life cycle from specification through design to manufacture”

(Shaw, Bloor, & de Pennington, 1989)

According to (Krause et al., 1993) there are four kinds of product models:

- The kernel in **structure-oriented product models** is a description of the products’ structure. The structure of a product can be represented in many ways, e.g., bill-of-material types, UML, product family master plans. According to the purpose of the structure-oriented product model it can contain information on commonalities, variety, versions of a product.

- The purpose of **geometry-oriented product models** is representing the shape of the product, through wire frames, surface, solid, or hybrid models (often referred to as CAD). Since the data structures of geometrical models are designed to represent geometry it is often difficult to extend these with additional product information. Somewhat 15 years after the paper was published this is however exactly what is beginning to happen with systems such as Engineering Intent from Autodesk.

- The **feature-oriented product model** is an extension of the geometric-oriented product model. The feature-oriented product model represents often used shape patterns as geometric items, called form features. A form feature is application independent and thus does not carry any specific non-geometric semantics.

- **Knowledge-based product models** are often described as a model of the product based on artificial intelligence techniques such as object-oriented programming, rule-based reasoning, constraints, logical systems, etc.

Hvam, Mortensen, and Riis (2008) provide a description, a framework, of relevant product models in a configuration context. The purpose of the framework is to define limits and impose structure on the knowledge of the product range which is to be modelled and implemented in the configuration system. The framework describes product models in terms of three different types of models: (i) Property models that describe the properties and the functions of the product, (ii) product structure models that describe the organs and parts of the product, and (iii) models of the product’s meeting with life cycle systems. The structure of the framework is inspired by the ‘theory of domains’ by Andreasen, M.M. (Andreasen, 1992; Andreasen, 1994; Andreasen, 1998), and is illustrated in Figure 4-4.
Figure 4-4: Framework for modeling product families (Hvam et al., 2008, pp.30)
In conclusion, there is an important thing to observe about the definition of product models. The product model in a configuration system must be a constitutional genetic model capable of instantiating many different configurations. For this reason the following definition of Schwarze’s is the most correct one:

“A **product model** is an abstract representation or description, describing (a) the structure of P and (b) facts, object, concepts and properties that are relevant in any life cycle phase of P. P can be a single product or a family of products. A product is a thing, a substance or a service produced by a natural or artificial process.”

(Schwarze, 1996, pp.33)

**4.4 Configurators or Configuration Systems**

Having described the configuration task and the product knowledge formalised in a product model, the next step is to look at software tools – the product configuration system. In literature, three terms are often used to define these types of IT-systems. To be exact, ‘configurator’, ‘product configuration system’, and ‘configuration system’ are often used interchangeably. As Haug (2007) notes, this would not represent a problem if there was consensus on using the three terms interchangeably. However, as the following quotation illustrates, by configuration system e.g. Forza and Salvador mean more than merely the software application:

“Configuration system: The set of human and computing resources that contributes to accomplishing the configuration and modelling processes”

(Forza & Salvador, 2007)

Therefore, it is important to strictly define what is meant by configuration system. In the present thesis, the terms “configurator,” “configuration system,” and “product configuration system” will be used interchangeably, and all the terms refer to the software application. The social-technical system that Forza and Salvador refer to is in the present thesis referred to as a ‘total configuration system’ (see section 4.5 for further explanations).

Configuration systems are often described as belonging to expert systems or knowledge-based systems. Although it is argued that expert systems are a subset of the more general knowledge-based systems (Hopgood, 2001; Jackson, 1999), expert systems are typically defined as computer programs that represent and reason with knowledge of specialist matters with the purpose of solving problems or giving advice (Jackson, 1999). A knowledge-based system is defined more broadly as a computer system which is programmed to imitate human problem-solving by means of artificial intelligence and with reference to a database of knowledge on a particular subject.

In conclusion, a configuration system can be both an expert system and a knowledge-based system. It depends on the configuration task it needs to perform. However, the basis of any product configuration system is knowledge.

According to Hopgood (2001), the principal difference between a knowledge-based system and a conventional program lies in the structure:

“In a conventional program, domain knowledge is intimately intertwined with software for controlling the application of that knowledge. In a knowledge-based system, the two roles are explicitly separated.”

(Hopgood, 2001, pp.2)

Figure 4-5 shows the main components of a knowledge-based system. Note the essential components. The knowledge base which contains the knowledge about the domain, and which the
inference engine uses to draw conclusions. The results are presented to the outside world by an interface which handles connections to humans, hardware, data, and/or other software. Expert systems often have extra frills in terms of a knowledge acquisition module or an explanation module to explore the knowledge base.

Figure 4-5: The main components of a knowledge-based system (Hopgood, 2001, pp.3)

In this way, the goal of a configuration system is to build a specification in which a selection of components satisfies the needs of the configurer or to detect inconsistencies in the requirements given by the user. In this case, the definition of configuration system given by Haug (2007) is accurate:

“A product configurator is a software-based expert system that supports the user in the creation of product specifications by restricting how predefined entities (physical or non-physical) and their properties (fixed or variable) may be combined”

(Haug, 2007, pp.19)

As Haug (2007) notes, configuration systems should not be mistaken with systems that are capable of combining components without any restrictions.

To sum up, a product configuration system is a product model that relates to a configuration task. It is often an iterative process, where the user slowly becomes more and more clarified about his needs. The clarification happens when the user explores the solution space and learns about possibilities and design options in general. This clarification process is illustrated in Figure 4-6.
4.5 Understanding the Total Configuration System

The purpose of this section is to describe the configuration system in a context of users i.e. in an organisation. We define the total configuration system (TCS) as the configuration system including the context in which the configuration system operates. In section 4.4, Forza & Salvador (2007) define a configuration system as the set of humans and computing resources which contribute to accomplishing the configuration process. This definition correctly points out that the human systems greatly influence the configuration task, and that human systems can choose to use a configuration system to support them, or they can choose not to be supported by a configuration system.

While Forza & Salvador (2007) describe two subsystems (the human system, and the computing system), the theory of technical systems delineates three important elements in a total transformation system: (i) A process, (ii) an operand which is being transformed, and (iii) the operators which drive and guide the process (Hubka & Eder, 1988). If one applies the same logic to a configuration system, the total configuration system also consists of an operand, operators, and a process. This is illustrated in Figure 4-7.

Figure 4-7: Elements in the total configuration system

The total configuration system

Operand in existing state

Configuration Process

Operand in desired state

Input or Output

Effect

Feedback

\[ \Sigma \text{Operators} \]

Effects \[ \Sigma \text{Ef} \]
These three key elements of the total configuration system will be described in the following three sections. The primary key element is the operand which is a very central part of the TCS. The second key element is the operators, as they operate and guide the configuration process. Finally the configuration process is described as the third key element.

4.5.1 Understanding the Operand of the TCS

In order to perceive product configuration systems as technical systems it is important to define the operand. The operand is a passive member of the TCS. The operand can belong to one of the following classes: biological material, non-biological material, energy, and information. As none of these classes are exclusive, an operand can also be a combination of the classes mentioned above.

In order to define the operand in a more formal way we will leave out some of the classes mentioned above. The operand is neither biological material nor non-biological material, as no physical transformation is performed by the TCS. The output of the configuration process is a specification of a given product’s component structure which satisfies the needs of the customer, and specifies how the components are connected. It is most natural then to relate the operand in the existing state to the needs of the customer. Consequently the following must be delineated:

- A clear starting point (a user that needs a product)
- A clear ending point (a configuration of a product that fulfils the needs of the user)
- How value is delivered to the customer

The operand is the description of a product (TS). In the existing state it is a description of the product at a high abstraction level yet it describes the needs of a customer. The operand in the desired state is a configuration of a product. Accordingly, the TCS is defined as the total system which transforms the need of a customer to a specification of the product’s component structure. In other words the TCS transforms a description of the requirements of a product (on a high abstraction level) to a description of the product that satisfies the requirements (which are given on a very concrete level).

What characterises the description of a product in the existing state? One characteristic is that the customer is aware that he needs a product to perform, apply, or do something with. The product can be described using different levels of abstraction as previously described in section 4.1, and as illustrated in Figure 4-8.

Figure 4-8: Description of TS on different levels of abstraction
The Customer’s knowledge of the TS or the product he wishes to configure/buy is not complete. The customer is only rarely able to describe the product completely on any one of the four different abstraction levels described in the figure above. Usually (especially when talking about complex products) the customer has knowledge about the product on different abstraction levels. He might have complete knowledge of the purpose that the product has to fulfil, some knowledge about the function structure, no knowledge of the organ structure, and a perhaps a bit of knowledge about the component structure of the product.

The goal of the configuration process is to concretise the user’s understanding of the product, that is to satisfy the configuration task. In other words, the configuration process combines predefined entities (physical or non-physical) and defines their variable properties while obeying constraints and legal interface combinations in a way that satisfies given requirements. This is illustrated in Figure 4-9.

**Figure 4-9: Concretising the needs of the customer to a description of the solution’s component structure.**

Hence on must focus on the conversion of a description of needs for a product into a specification of a product which fulfils these needs. What is changed by the total configuration process is the description of the product, and thus, the operand is defined as the description of the product. Consequently, the operand in the existing state is the description of the product before it is configured, and the operand in the desired state is the description after the product has been configured. This is the process which is typically called configuring, configuration process or configuration task, and it is the theme of section 4.5.6. The result of the configuration process is a fully described component structure of the product. This is illustrated in Figure 4-10.

**Figure 4-10: An incomplete description of the product (existing state (left)) is transformed to at least a complete description of the component structure of the product (desired state (right))**
4.5.2 Understanding the Operators of the TCS

Operators guide and drive the configuration process. One can identify the following classes of operators in the total configuration system (the references given in parenthesis are to the theory of the technical systems):

(i) Users (human system),
(ii) Product configuration system (technical system)
(iii) Organisation (active environment)

In configuration literature all three classes of operators have traditionally been perceived as rational operating systems that act in a rational or at least a predictable way. Often this has been justified by referring to general system theories such as the one by Bertalanffy (1950; 1972). As it is not always sufficient to understand all three systems as rational systems, they will be described in the following three sections.

4.5.3 Understanding the User as an Operator

The knowledge needed to solve the configuration task depends on the abstraction level of the user. If the user has extensive knowledge of the product, he might wish to configure the product on a fully structural level, selecting and configuring components. A user with less product knowledge might wish to configure the product on a more functional level, ensuring that the product gets the desired functionality thus paying no attention to the components used, as long the desired functionality is delivered.

The user interface affects how the product configuration system is accepted by the users. Andreasen (1994) describes the relation between man and machine as the man-machine interface, and notes that it is vital that the designer of the machine decides which tasks are technical and done by the machine, and which tasks are done by the operator. Likewise, the relation between the user and the product configuration system is carried out through the user interface (see Figure 4-11), and according to Beyer & Holtzblatt (1998) it is important to consider how the work model of the system can be aligned to the work model of the user. As it is not in the scope of this thesis to look into usability, the relationship between product configuration system and the user will not be described any further.

Figure 4-11: User and configuration system as operators for the configuration process
4.5.4 Understanding the Product Configuration System as Operator

As one can recollect from section 4.4, a configuration system is a software-based expert system that supports the user in the creation of product specifications by restricting how predefined entities (physical or non-physical) and their properties (fixed or variable) may be combined.

The basis of any product configuration system is knowledge; knowledge of the product that is configured, and knowledge about the process which the configuration system supports. As previously mentioned, the purpose of any configuration system is to support parts of the configuration process.

The product knowledge needed to solve the configuration task depends on the abstraction level of the user and the abstraction level at which the customer presents his needs as input to the configuration process.

If the user has a high degree of knowledge of the product, he might wish to configure the product by picking and configuring components. A user with less product knowledge might wish to configure the product on a more functional level, ensuring that the product gets the desired functionality without paying any attention to the components which are used.

The foundation of the product configuration system is an abstract model of the product (a product model) that can transform user requirements into a more or less concrete component structure of the product. The effect delivered to the configuration process can be devided into three different effects that a product configuration system exerts onto the configuration process:

- Concretising knowledge about the product
- Abstracting knowledge about the product
- Validating knowledge about the product

As these three effects are not exclusive, a configuration system can be designed to concretize from i.e. function structure to component structure, and then validate the component structure as components are interchanged by the user, finally presenting the results of the configuration process by abstracting to a higher abstraction level. The three effects of product configuration systems are illustrated in Figure 4-12.

*Figure 4-12: The three possible effects of a PCS, abstracting, concretising and validating product knowledge*

4.5.5 Understanding the Organisation as Operator

The active environment of the configuration process is comprised of actors, technical systems, and structures. The active environment is the part of the total environment which has a direct
relationship to the product configuration system which is being analysed. The active environment is of course dependent upon how the total configuration system is defined. In the present model for the application of product configuration systems and how they are applied in engineering companies we will focus on the organisation as the active environment. Since the XCON project it has been known that any technological development will result in an organisational change. The greater the benefits to be realised from the introduction of a new technical system, the greater the amount of organisational change that should be anticipated, and successful process innovation requires management of the mutual adaptation of technology to organisation and organisation to technology during design and development (Leonard-Barton, 1987a; Leonard-Barton, 1987b; Leonard-Barton, 1991).

In order to describe the organisation in the total configuration system we will look at the different pulls that exist from different parts of the organisation. The purpose of doing so is to identify the motivation for development of the product configuration system. Is the system developed to sustain the power of the technostructure in the organisation or is it developed to reduce the power of the professionals by formalising their expert knowledge? Nevertheless, the answer to this question is, a product configuration system is an instrument to support or diminish a given pull in the organisation.

A configuration system might have a very successful implementation phase and then slowly deteriorate because the experts are not willing to help maintain the system. There might be many explanations to this case but if one uses the structures in fives by Mintzberg (1980; 1993) the explanation would be: The strategic apex needs a reduction in the power of the experts in the organisation, and it initiates a move towards a structure that depends more on standardisation. This motivates the company to build a product configuration system. Apparently, the system is a success, but behind the scene there is an even bigger pull to professionalise rather than standardise the work. This leads to the slow deterioration of the knowledge in the product configuration system, the knowledge in the system eventually becomes insolvent, and the use of the system is dramatically reduced.

A product configuration system is implemented in an organisation. So in order to understand how PCS are applied in companies in general and in engineering companies in particular, it is important to be able to describe organisations and how they relate to the PCS. A good starting point is Mintzberg’s structures in fives (Mintzberg, 1980; Mintzberg, 1993). It is claimed that the effective organisation will favour one of the five configurations. The premise for this conclusion is:

"Organisational structuring can better be understood through the combination of groups of elements into ideal or pure types, which we call configurations."

(Mintzberg, 1980, pp.323)

Of course the division into five is theoretical, the five ideal types are often not found in reality. Indeed, organisations are often a mix of or hybrid between some of the pure types. However, using these archetypes is useful when we analyse and understand product configuration systems in organisations.

Mintzberg describes the following five basic parts of the organisation, as shown in Figure 4-13:

(i) The operating core includes all those employees who themselves produce the basic products and services of the organization, or who directly support their production.

(ii) The strategic apex consists of the top general managers of the organization, and their personal staff.
(iii) The middle line comprises those managers who sit in a direct line of formal authority between people of the strategic apex and the operating core.

(iv) The technostructure consists of those analysts from the formal "line" structure, who apply analytic techniques to the design and maintenance of the structure and to the adaptation of the organization to its environment (e.g. accountants, work schedulers, long-range planners).

(v) The support staff includes those groups that provide indirect support to the rest of the organization (e.g., in the typical manufacturing firm, legal counsel, public relations, payroll, cafeteria)."

(Mintzberg, 1980, pp.323-324)

Figure 4-13: The five basic parts of the organisation (Mintzberg, 1993)

The organization is pulled in different directions by each part in the organisation (see Figure 4-14). If one pull is dominant, the organisation is drawn towards structuring itself as one of five configurations. The five pulls and corresponding ideal types of configurations are described below:

- “First is the pull exercised by the strategic apex to centralize, to coordinate by direct supervision, and so to structure the organization as a Simple Structure.
- Second is the pull exercised by the technostructure, to coordinate by standardization – notably of work processes, the tightest kind – in order to increase its influence, and so to structure the organization as a Machine Bureaucracy.
- Third is the pull exercised by the operators to professionalize, to coordinate by the standardization of skills in order to maximize their autonomy, and so to structure the organization as a Professional Bureaucracy.
- Fourth is the pull exercised by the middle managers to Balkanize, to be given the autonomy to manage their own units, with coordination restricted to the standardization of outputs, and so to structure the organization as a Divisionalized Form.
- Fifth is the pull exercised by the support staff (and by the operators as well, in the Operating Adhocracy), for collaboration (and innovation) in decision making, to coordinate by mutual adjustment, and so to structure the organization as an Adhocracy.”

(Mintzberg, 1993, pp.285)
Every organisation experiences all of these five pulls. What structure the organisation ends up with or designs depends on how strong each pull turns out to be. When a given pull dominates, Mintzberg (1993) expects the organisation to emerge rather close to one of the pure types of configurations. When two or more pulls coexists in a dynamic balance, Mintzberg (1993) expect a hybrid of the pure types to emerge. And finally if one pull displaces another as dominant, it should be possible to describe the organisation as being in a state of transition between two of the configurations. The five pulls are illustrated in Figure 4-14.

Figure 4-14: Five pulls on the organisation (Mintzberg, 1993, pp.154)

4.5.6 Understanding the Configuration Process of the TCS

Previously we established that the configuration task is to combine predefined entities (physical or non-physical) and define their variable properties while obeying constraints and legal interface combinations in a way that satisfies given requirements. The configuration process is driven and guided by the operators of the total configuration system.

An important lesson learned from the theory of technical systems is that the technical process cannot be designed. The only thing which a designer can be totally in control of and design is the technical system. Likewise the configuration process cannot be designed either.\(^\text{17}\) The only thing one can control, and which behaves in a deterministic way, is the product configuration system. If it is presumed that humans do not behave entirely rational but instead operate within the confines of a bounded rationality, it is difficult to argue that one must start a configuration project by designing the configuration process. Actually, this fact can be extended to the level of the organisation, as the organisation also acts with bounded rationality.

However, when you start a configuration project, you can organise the user interface of the product configuration system and design the system by using user-centred development techniques.

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\(^{17}\) This is less true when the users of a configuration system are internal (employed by the company) but it is more true when the users are external (customers who are not employed by the company).
such as contextual design as presented by Beyer & Holtzblatt (1998). In that way, you can motivate the users to perform a sequence of tasks in a given order.

### 4.6 Summary

Chapter 4 develops a frame of reference for the project by defining the following basic concepts.

- **Technical systems** are objects, products, things, machines, implements, technical objects, etc. which are made by humans to fulfil a specific need.
- A **product model** is an abstract representation or description, describing (a) the structure of P and (b) facts, object, concepts and properties that are relevant in any life cycle phase of P. P can be a single product or a family of products. A product is a thing, a substance or a service produced by a natural or artificial process.
- A **product configurator** is a software-based expert system that supports the user in the creation of product specifications by restricting how predefined entities (physical or non-physical) and their properties (fixed or variable) may be combined
- **Configuration process**: To combine predefined entities (physical or non-physical) and define their variable properties, while obeying constraints and legal interface combinations in a way that satisfies given requirements.
- A **configuration** is the output of the configuration process, e.g. a description of the component structure of the product and any connections between the components in the set or a description of inconsistencies in the requirements.

This chapter also defines the total configuration system. The total configuration system consists of three operators (users, configuration system, and organisation) that operate a configuration process. The configuration process combines predefined entities in a way that satisfies the requirements given by the user. The input to the configuration process is an incomplete description of the component structure of the product (a description of the needs of a customer), and the output of the configuration system is a complete description of the component structure of the product (that satisfies the needs of the customer). The total configuration system is illustrated in Figure 4-15.

**Figure 4-15: The total configuration system**
5 Developing a Typology of Product Configuration System

Chapter 5 develops a typology of product configuration systems. This work was first published in Ladeby, Edwards & Haug (2007). The purpose of the present chapter is to answer research question 2:

RQ2: How can different types of product configuration systems be distinguished?

In other words, the aim of the typology is to be able to distinguish between different types of configuration systems. A Typology is (according to Encyclopaedia Britannica18) a:

“system of groupings (such as “landed gentry” or “rain forests”), usually called types, the members of which are identified by postulating specified attributes that are mutually exclusive and collectively exhaustive-groupings set up to aid demonstration or inquiry by establishing a limited relationship among phenomena. A type may represent one kind of attribute or several and need include only those features that are significant for the problem at hand.”

The purpose of this chapter is to develop a typology of configuration systems in order to classify members or types of configuration systems. Classification of product configuration systems can be made on different levels. A popular classification is Forza & Salvador’s which defines different configuration systems on the basis of the customisation scope of the company (see Figure 5-1).

Figure 5-1: Application scope of selectors, configurators, and meta-configurators (Forza & Salvador, 2007).

While the illustration above offers an explanation and descriptions of different systems on the customisation level of the company, there are some issues with this simplified model. For example, if an engineering company wishes to support the trivial detailed engineering process of selecting the right valve for a specific task, is it then proper to use a selector, a configurator, or a meta-configurator? From the figure it can be learned that the answer is a meta-configurator, as the customisation scope of the company is pure customisation.

This thesis proposes to classify configuration systems according to the product knowledge contained in them instead, and this will be described below. The basis of any product configuration system is product knowledge. As previously defined, the purpose of any configuration system is to support parts of the configuration task. The knowledge needed to solve the configuration task depends on the abstraction level of the user. If the user has extensive knowledge of the product, he might wish to configure the product on a fully structural level, picking and configuring components. A user with less product knowledge might wish to configure the product on a more functional level, ensuring that the product gets the desired functionality without paying attention to the components used.

5.1 Typology of Product Configuration Systems Based on Product Knowledge

In section 4.1 it was explained how a product could be described on different abstraction levels. The breakdown into different abstraction levels tells us something about, how the user wishes to view a given product. In some cases the user is interested in the functionality of the product and does not care about the components which the product consists of. In other cases the user is at an even higher abstraction level, and can only express their requirements on a performance level (in this thesis we perceive performance knowledge as an aggregation of functions).

Hubka & Eder (1988) suggested four abstraction levels: (i) Purpose, (ii) function structure, (iii) organ structure, and (iv) component structure. Forza & Salvador (2004b; 2007) have a similar definition of abstraction levels, and they identify three important levels (depicted in Figure 5-2): (i) Purpose level – a description that focuses on the performance of the product, (ii) functional level – a description focused on the product functions, and (iii) component level – a description focused on the physical components of the product.

Figure 5-2: Product descriptions with different degrees of abstraction (Forza & Salvador, 2007).
Systems engineering has a similar approach. Systems engineering, the application part of system thinking (theory), is defined as a three-part view on certain problems: a view on structure, a view on functions and a view on purpose. This is shown in Figure 5-3.

Figure 5-3: Systems engineering (Sage & Armstrong Jr, 2000)

Harlou (2006) describes re-use of knowledge in product platforms and families. According to Harlou (2006) it is necessary to describe re-usable solutions by means of three characteristics to enable standard designs:

(i) Application characteristics,
(ii) functional properties, and
(iii) structural elements.

From this viewpoint, a standard design is one of the key building blocks of product architecture. Standard designs are interesting in the field of product configuration, as standard designs, or generic or partial models of the product, form the basis of the product model which is the basis of the configuration system.

Mittal and Frayman (1989) provides a suggestion on what knowledge is needed for the configuration task, and they categorise the knowledge in the following three categories: (i) Knowledge of components, (ii) knowledge of the functional architecture, and (iii) knowledge of the mapping from function to components.

It is obvious that knowledge of what Hubka and Eder (1988) call the function carrier or the organ structure is important when one designs products. Organs are more than the composition of a product’s constructional units into sub-assemblies and larger wholes. Organs provide the functional connections between components. (Hubka & Eder, 1988) An organ is a system that realises an internal function in the system, and organs can be gathered in organisms to establish more complex functions.

When Mittal and Frayman (1989) and later Forza and Salvador (2007) do not mention organs in their works on configuration knowledge, and Harlou (2006) likewise does not mention organs in his work on product platforms, it is not due to ignorance. A customer can intuitively relate to the meaning of purpose, function structure, and component structure. I perceive organs as an intermediate result when designing products. Engineering designers use the organ structure to reflect on the mapping of functions structure to component structure. However, configuration is not like the process of engineering design. When we work with configuration, the solution space is closed, the components and the constructional elements of the product are defined, and how functions and purpose of the product should be realised is already given. Thus the task should be easier to comprehend than the task of engineering design in an open solution space. For this reason, knowledge about organs is not essential for the configuration process.
Having the concept of different abstraction levels present, the conclusion must be that the following categories of knowledge are common to the configuration task:

(i) Knowledge of component structure,
(ii) knowledge of the function structure,
(iii) knowledge of the mapping from function structure to component structure,
(iv) knowledge of product purpose, and
(v) knowledge of the mapping from product purpose to the function structure of the product.

These five types of knowledge needed for implementing a product configuration system are depicted in Figure 5-4 and described in the following sections.

Figure 5-4: The five types of product knowledge in product configuration systems

5.1.1 Component Structure

The structure of a given product consists of components. Knowledge related to a given component can generally be described independently of other components by a set of physical properties. Typically, components have an interface by which the components connect to other components. (Mittal & Frayman (1989) use the term ‘port’ which corresponds to our understanding of interface). Interfaces can also be described from a set of properties, and one can specify the components which can be attached through a given interface. Often, some components consist of sub-components, and these have to be explicitly stated. A common way of describing the product assortment is to use a notation tool called a product variant master. This tool is well described in (Hvam, 2001; Haug & Hvam, 2005; Haug & Hvam, 2006b; Riis, 2003)

5.1.2 Function Structure

The functional architecture specifies a functional decomposition of the product and any constraints on their composition. Any given function can be modelled by a set of properties that characterise them.

5.1.3 Mapping Between Function Structure and Component Structure

In theory, the goal of modularization is to achieve a one-to-one mapping of function and component but in reality this is rarely achieved. Even though mapping the function structure to the
component structure seems to be a simple task, it is not. Although mapping between functions and components is often one-to-many or many-to-one, in reality many-to-many also exist. This makes the task of mapping functions and components remarkably complex (Ulrich, 1995). To sum up, a given function can be implemented by a set of components, but, on the other hand, actual components are most often multi-functional which makes it a rather complex task.

5.1.4 Purpose

Purpose knowledge is knowledge about the performance of the product. The purpose of the product can be described with a set of properties describing the overall performance of the product (often ‘product’ is referred to as application or performance of the product). Consider an example with a computer: A grandmother wants a new computer, but she is not interested in reading computer magazines. She only wants a reliable computer for internet access and small office assignments. In this way she does not care for the components or functionality of the computer, she wants a computer that can fulfil specific purposes. At the other end of the spectrum, a nerd with more knowledge about the product would probably prefer to configure the product in terms of components rather than purpose. Thus he might require a PC with a specific high resolution display from a specific vendor and a specific DVD drive. The grandmother specifies her needs for a product on a different abstraction level than the nerd with extensive technical knowledge.

5.1.5 Mapping Between Function Structure and Purpose

The purpose of a given product can be mapped to the product’s functions. When one maps between functions and components, in most cases, the relationship is a many-to-many, thus making the task complex.

Having identified the five different kinds of product knowledge needed to implement a product configuration system, it seems natural to use this to classify systems with product knowledge. This results in six different types of configuration systems: (i) Systems with knowledge about purpose of the product, (ii) systems with knowledge about function structure, (iii) systems with knowledge about the component structure, (iv) systems with knowledge about the product’s purpose and function structure, and the mapping in-between, (v) systems with knowledge about the function structure and component structure and the mapping in-between, and (vi) systems with all five kinds of product knowledge. This division is depicted in Figure 5-5.

Figure 5-5: Different types of systems with product knowledge
The basis for solving the configuration task is knowledge about the component structure of the product. Indeed, without component knowledge, a product configuration system would not be able to fulfil the configuration task (it could not constitute a solution that contained at least a set of components and a description of the connections between these components). The systems without component knowledge (no. 1, 2, 4) correspond to what Forza and Salvador (2007) call meta-configuration systems. In the PETO project, we have identified many of these meta-configuration systems in engineering companies. This also corresponds with the conclusions of Forza & Salvador (2007).

Although it is debatable whether these meta-configuration systems actually belong to product configuration systems, we have chosen to include the product configuration systems without components knowledge in our typology, despite the fact that they cannot fulfil the configuration task.

Accordingly, we can identify the following types of product configuration systems and classify them according to the knowledge implemented in them: (i) Meta-configuration systems (no. 1, 2, and 4), (ii) structural validators (no. 3), (iii) co-design configuration systems (no. 5), and (iv) automatic configuration systems (no. 6). The systems will be described in the following paragraphs illustrated with the recurring example of a car product configuration system.

**Meta-configuration systems** are particularly useful when one follows a pure customization strategy where meta-configuration systems are used in the preliminary design phase to support sales personnel. We have identified many of these meta-configuration systems in engineering companies in particular, thus supporting the term meta-configuration system as described by Forza & Salvador (2007). In the cases we know from the PETO project, meta-configuration systems are used to support the preliminary design and give rough price estimates or automate parts of the configuration process, see the following references for further descriptions of the PETO project (Edwards & Riis, 2004; Edwards et al., 2005). Without coming to a complete description of the product, as the systems do not contain any knowledge of the product’s component structure. A car meta-configuration system has no knowledge about the components of a car. The meta-configuration system only has knowledge about the functions of the car (e.g. anti-lock brakes, electronic stability program, powerful engine) or about the purpose (e.g. safe, fast, or economic) or about how purpose maps to functions (safe car implies both anti-lock brakes and electronic stability program – fast car implies powerful engine). Therefore, if one is only given the function structure and purpose of the car, it is not possible to produce a detailed configuration of the car. One can only make more or less accurate estimations, and as such, the car meta-configuration fails to solve the configuration task, and needs more assistance to translate purpose- or functional requirements to a description of the component structure of the car (anti-lock brakes from Bosch, electronic stability program from Siemens, tyres from Michelin, 4.2 L V8 engine from Ford etc.).

A **structural validator** contains knowledge about the structural composition of product parts (the products component structure) and the allowed variance so that it can be used to validate product configurations. Similarly, the structural configuration system contains little knowledge about the relation between functional characteristics and product composition. The structural validator provides greater control over the composition of the product parts. This can be useful. For example, it was useful for a company which produced actuators. The company found itself in a situation where the development department spent too much time validating product configurations and too little time developing new products. As the company produced actuators in large quantities, there was an unsatisfied need for consistent product knowledge. The number of orders was high, but not two orders were the same, the firm was essentially producing one-of-a-kind. The processes of
the company were indeed both consistent and explicit, so they supported a configuration-ready conclusion. However, the product knowledge was highly idiosyncratic even though each product design decision was explicit. Initially, this led to a non configuration-ready conclusion. The solution to the highly idiosyncratic product knowledge would normally be to perform a formal review of the product knowledge establishing a common understanding of the product but there was only little interest in doing so. Instead, a structural configuration system was developed to help validate products. The system was a great success and resulted in a very significant raise in product quality.

A car structural validator only has knowledge about the components in the car. The car structural validator can be used to validate a desired solution. Let’s say that the user chooses to match a 4.2L V8 engine from Ford with bodywork intended for economic driving and high mileage, thus configuring a light and soft car. The structural configurator has knowledge about which components can be used together in a given configuration. As the light bodywork is not allowed together with the 4.2L V8 engine from Ford, the user is informed via the structural configurator that the solution is not valid, and the user is asked to make changes to the configuration.

A co-design configuration system is a structural validator with a functional interpretive layer that can transform functional requirements into a structural composition or a particular configuration of the product. However, every so often, customers or sales people do not have a comprehensive structural understanding of the product. If this be the case, it can be difficult to configure a mass customized product by using a structural configuration system. As the customer strive to minimize time and effort, the overwhelming number of possibilities can make the customer relocate the purchase and buy elsewhere. This problem is often referred to as mass confusion (Piller, 2004). Functional configuration systems support users in customizing a given product by capturing the functional requirements to the product and translating them into a particular structural solution, describing the structural specification of the particular product, and thereby reducing the burden of the customer in co-designing his customized products. A car co-design configuration system has knowledge about the function structure and the component structure of the product. Consequently, the car co-design configuration is able to transform functional requirements (anti-lock brakes, air-condition for a mid-range estate car, and powerful engine) to a structural solution (air-condition- and anti-lock brakes from Bosch, and a 4.2L V8 engine from Ford). This makes it possible for a user without detailed knowledge of the components to specify a car from a function structure point of view.

An automatic configuration system is closely related to co-design configuration systems but instead of having to specify all relevant functions and properties, the user must only give the desired purpose of the product as input. The remaining design choices are made by the completely automatic configuration system without interference or guidance by the user. These systems closely resemble AI systems. The user no longer makes decisions in relation to the configuration task at hand.

5.2 Summary

Chapter 5 answers the following research question:

RQ2: How can different types of product configuration systems be distinguished?

By using the typology it is possible to distinguish between different types of configuration systems. The differentiation is based on the product knowledge implemented in the configuration systems. This leads to an identification of four different types of configuration systems. These four types are listed below figure 5-6.
The following types of product configuration systems are identified and it is possible to classify them according to the knowledge implemented in them:

(i) Meta-configuration systems (no. 1, 2, and 4),
(ii) structural validators (no. 3),
(iii) co-design configuration systems (no. 5), and
(iv) automatic configuration systems (no. 6).
6 Prerequisites for Configuration

While configuration systems seem to be the solution to many productivity and customization problems, the empirical reality is that implementation is problematic. In 2005, Associate Professor Kasper Edwards and I published a paper on the subject ‘Configuration Readiness’. The ideas presented in the paper have evolved into the idea of ‘Prerequisites for Configuration’ that is presented in this chapter (see the following papers to identify the progression (Edwards & Ladeby, 2005; Ladeby, Edwards, & Hvam, 2006; Edwards, Ladeby, & Haug, 2007))

The purpose of chapter 6 is to answer the following research question:

RQ3: What are the prerequisites for configuration?

Configuration system implementation projects are often delayed and there are significant problems with configuration systems or perhaps more specifically with the implementation of them. In several implementation projects (Riis, 2003; Hvam, 1999; Hansen, 2003) one can see that implementation is expensive, and that realizing benefits depends on several factors other than the common technical issues.

The PETO project contained interviews in 12 Danish firms who had implemented or who were in the process of implementing configuration systems (Riis, 2003; Edwards et al., 2003; Edwards & Riis, 2004; Edwards & Møldrup, 2004; Edwards & Pedersen, 2004). The PETO project concluded that one of the main cost drivers was specifying the product model i.e. uncovering and understanding the reasons and rules for each and every detailed product choice. 1/3 of the interviewed firms rated specifying the product model as a high cost driver. Upon closer inspection, one can see that the product knowledge in these firms is bound primarily to people. Only little knowledge is available in a formalised, structured, accessible manner. From this, one can infer that knowledge elicitation is a significant distinguishing factor in configuration projects. If the knowledge about the product which is configured and the knowledge about the belonging configuration task are available in an explicit and consistent form, projects seem to be slightly more ready for configuration than in cases where this is not the case. In this chapter we discuss prerequisites for configuring from a knowledge point of view; in other words, we look at the knowledge in the company which is ready to be formalised in a configuration system.

6.1 Knowledge for Configuration Systems

The knowledge required to develop a configuration system can be divided into two: (i) Product knowledge, and (ii) process knowledge.

In chapter 5 we defined five kinds of product knowledge common in configuration processes, and used this to develop a typology of configuration systems. Product knowledge is in its broadest sense the detailed knowledge which a company posses regarding its product(s). Product knowledge is knowledge about a product’s internal properties, such as durability and strength of various components, and external properties such as usage, distribution and production time. Functional properties of the product are also part of this knowledge, e.g. how a particular functionality is constituted by a specific set of parts. See section 4.1 for a more detailed description of product knowledge. Knowledge about a product can be described on the following levels of abstraction (as described in section 4.1):
Process knowledge is knowledge about the sequence of events that happen between a customer requirement and the definition of the component structure, of the given product, which satisfy the requirements. Figure 6-2 depicts the general processes of in companies. Documenting the specifics would require a detailed study of the sequence of events. The specific processes are related to the product in question and different products may follow different processes.

This thesis focuses only on what is defined as the configuration task i.e. the sequence of events between the customer request and the manufacturing planning. The thesis is limited thus because
the configuration task ends with the description of a product, “A product specification”, which is exactly what the total configuration system produces. The product specification is ready for manufacturing planning and subsequent production which requires different processes and systems defined to be outside the scope of the thesis. The detail to which product and process knowledge has to be acquired is determined by the desired scope of the configuration system. For instance, if the goal of the project is to develop a meta-configuration system, the project requires only knowledge about the relationship between i.e. function structure and price. In this case, knowledge about the component structure of the product and how functions are constituted by combining parts is not needed, as the cost structure of a product could be driven by pure market considerations or by the cost relationship between components.

It is obvious that we must make the product and process knowledge explicit and consistent when we implement a configuration system. It is imperative to know both how and why a sales person or a production employee configures products as they do, and also how and why they document the criteria for choosing one component in favour of another. This knowledge is often tacit but in order to develop a configuration system, this knowledge has to be made explicit and consistent. One must group products into different categories and specify the possible variation of components and attributes. As mentioned above, product knowledge can be hard to identify and harvest. In companies where knowledge concerning the process is explicit and consistent, the knowledge is easy to elicit. But in companies where the knowledge about configuration is bound to employees and hence less explicit and consistent, the knowledge is hard to identify and therefore mapping the configuration task is difficult.

When knowledge about the configuration process is not explicit and consistent, the configuration process has often evolved over time to adapt to new and changed products. Sometimes the process has evolved because of personal relationships. Such a configuration process and the inherent product knowledge are very difficult to map and make explicit and consistent as the process is highly idiosyncratic and prone to inconsistency. This might result in the creation of several parallel and competing configuration processes. Given the idiosyncrasies, the results of the competing configuration processes might not be the same although the initial parameters (customer requirements) were. Each person in the process evaluates the customer requirements differently. This subsequently triggers several different structural compositions of the product even though the customer requirements and final functional characteristics of the product are almost identical.

In such a situation, a product configuration system which should represent the only configuration process may be faced with competing processes, resulting in the company offering sub-optimal products. Competing processes also result in inconsistent cost-estimates and increasing cost in post-sale cost calculations. Not having explicit and consistent product and process knowledge related to the configuration process results in two things: (i) Estimated costs of knowledge acquisition are significantly higher than expected, and (ii) the configuration system might not support the dominating configuration process because only a marginal competing configuration process has been documented. Both problems are significant although the effects are different. Cost overruns may result in the configuration system getting axed before implementation. Not supporting the configuration process usually translates into the configuration system not being used and the investment being lost.

As stated before, knowledge elicitation is an important factor when measuring configuration readiness. Thus, the conclusion to the preceding section must be that a prerequisite to successful implementation of configuration systems is that product and process knowledge is explicit and consistent in the company.
The scope and detail of the product and process knowledge is initially determined by the purpose of the configuration system. A meta-configuration system requires far less knowledge than an automatic configuration system.

6.2 Estimating Configuration Readiness

One prerequisite for configuration is explicit and consistent knowledge about the product, and the configuration process which the product belongs to. One must go through three phases when one estimates configuration readiness:

(i) Define configuration scope
(ii) Estimate knowledge
(iii) Estimate readiness

The first step is to define the scope for the configuration system. By this we understand a definition of the configuration complexity in terms of a description of the configuration process environment, and the type of configuration system the company wishes to implement. The type of configuration system determines the amount of detailed knowledge the configuration system must contain. For instance, an automatic configuration system capable of producing production ready specifications must possess knowledge of the individual products down to the last nut and washer.

The second step is to estimate the product and process knowledge to be implemented in the configuration system. Following the decision on the scope for the configuration project, one can use two sets of opposites when one assesses configuration readiness by measuring product and process knowledge: (i) How idiosyncratic vs. consistent the knowledge is and (ii) how tacit vs. explicit the knowledge is.

The third step, to estimate readiness, is achieved by combining the estimates of knowledge into a conclusion. The phrase “configuration readiness” has no precise definition and must be understood as a spectrum ranging from configuration ready to not configuration ready. Not configuration ready companies can expect futile or excessive costs when starting a configuration project, and in the other end of the spectrum we find the companies which are configuration ready. These firms can be expected to develop and implement a configuration system without problems. Thus firms are configuration ready if they do not have to go through a series of comprehensive product, process and organisation development projects before developing and implementing a configuration system.

However, as the customers’ product choice is an exogenous factor the following paragraphs are devoted to explaining how configuration readiness can be estimated. We start with the definition of configuration scope, and follow with descriptions of how one estimates process and product knowledge.

6.3 Definition of Configuration Scope

The first step in our analysis is to understand the scope of the configuration project. By and large, the choice of configuration system type is a strategic decision. However, this decision may indeed be significantly influenced by the estimated benefits and costs of implementing i.e. a meta- or an automatic configuration system. Estimating configuration readiness gives us a hint about the cost of acquiring sufficient product and process knowledge to begin implementing i.e. programming the configuration system. In some cases, because of the tacit nature of the knowledge concerning both process and product, it is better to reduce the scope of the configuration system. For instance, a company which produces one-of-a-kind products with an idiosyncratic specification process where
the knowledge is bound to the employees should consider creating a meta-configuration system rather than an automatic configuration system.

Accordingly, the decision which type of configuration system to is important as it determines the general scope for the configuration project.

6.4 Estimating Knowledge

Following the decision on configuration scope, one can use two sets of opposites when one assesses configuration readiness by measuring product and process knowledge: (i) How idiosyncratic vs. consistent the knowledge is and (ii) how tacit vs. explicit the knowledge is. The tacit/explicit opposite indicates whether product and process decisions are bound to employees or based on known explicit rules and reasons. The idiosyncratic/consistent opposite indicates whether product and process decisions vary according to personal and organisational boundaries. If the knowledge is both consistent and explicit it is ready to be codified, and then formalised in a configuration system.

While we consistently refer to product and process knowledge in this very order, the reality is that the process determines what product knowledge is used when we configure a product. Still, it is primarily the customers’ choice of product which activates a process which in turn determines the product knowledge.

6.4.1 Assessing Process Knowledge

The process knowledge of interest is knowledge about the configuration process. Initially, as described above, we must determine which type of configuration system we wish to pursue as the respective processes may very well differ accordingly. It is important to select the products or product families which are to be documented by a future configuration system.

Regardless of the choice, the essence of estimating configuration readiness is to follow and document the configuration process. One must follow the configuration process of a group of products which have similar customer requirements and documentation. The documentation should include a graphic presentation of the process with details of the people, departments, their choices and how the products evolve. Having done this with a suitable number of products, one can estimate whether the process knowledge is tacit vs. explicit and whether it is idiosyncratic vs. consistent.

Estimating ‘tacit vs. explicit’ is done by comparing the documented process instances. For instance, if two or more instances of the process are completed identically, this marks consistency. Process instances which are not similar indicate idiosyncracy. In theory this estimation looks simple but as we suggest in Edwards et al. (2007), it is complex. Tacit/explicit process knowledge is discovered through interviews where the process choices are questioned. A given process choice can be marked as explicit if the questioned person is capable of explaining the reasons for a given process choice. Process choices where the rationale behind is simply referred to as ‘business as usual’ marks tacit knowledge. An alarm should go off when seemingly identical customer requirements result in different processes without explicit reason. Observe that tacit/explicit process knowledge is defined by the person in question regardless of the number of manuals describing the correct procedure. The process of interest is the actual practice as it unfolds in the company. While manuals exist, their content may be out of date due to a number of reasons such as lack of resources or lack of reflection concerning the real way of doing business.

A simple way of surveying the status of the two sets of opposites is to insert the findings in a simple 2x2 matrix with idiosyncratic/consistent on the X-axis and tacit/implicit on the Y-axis, as
illustrated in Table 6-1. The table illustrates 10 observations with a significant proportion of them being idiosyncratic and tacit

<table>
<thead>
<tr>
<th>Process Knowledge</th>
<th>Idiosyncratic</th>
<th>Consistent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tacit</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>Explicit</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

### 6.4.2 Assessing Product Knowledge

When we map the specification process, the relevant carriers of product knowledge are identified. As with process knowledge each individual product design choice must be documented for a number of similar products. The assessment procedure used for process knowledge is also suited for assessing product knowledge even though the units of analysis are product design choices.

Consistency can be measured by comparing a number of similar customer requirements and their resulting product specifications or quotes. However, the resulting product specification is not sufficient because information systems or supervisors may have changed it to follow company guidelines. Therefore it is imperative to follow the actual process and not rely on end-results. Determining whether the product knowledge is tacit or explicit can once again only be obtained through interviews. The degree to which the employees are able to account for specific rules or principles implies whether the knowledge is tacit or explicit. The stated rules and principles, however, should be compared to the opinion of a well respected employee. The gathered information may be summarised as shown above in Table 6-1

A comparison, as suggested in the previous section, will reveal differences and similarities of the selected instances of the products. However, this only reflects status at a certain time. Thus overall knowledge about product mix and lifetime cannot be obtained, unless the study is done in a prolonged time frame.

Essentially, product knowledge must reflect strategic knowledge which affects the scope and economic properties of the configuration system. This knowledge pertains to the nature of the product mix offered by the company. If the product life is short and both product and process knowledge is tacit and idiosyncratic, one must question the cost and benefit of a configuration system. In particular, the rate of change in products or design rules must be contrasted to the cost of maintaining a configuration system. If the cost is too high, the firm is not configuration ready.

Modularity is not per se a prerequisite for using a configuration system. However, there is a relationship between maintenance cost and modularity. Modularity implies stable relations between product interfaces and this in turn implies explicit knowledge regarding the basic product structure. This knowledge is readily transferable to a configuration system and may serve as a basis where modules may have a high rate of change. Indeed, as only the modules change, the marginal cost of maintaining a configuration system along side developing products is low. Modules also have a positive economic effect on production costs as reuse of modules allows economics of scale.
6.5 Estimating Readiness

Having concluded the estimates of process and product knowledge and having produced two tables similar to Table 6-1 it is possible to make recommendations.

Process knowledge which is both idiosyncratic and tacit is not configuration ready as consistent rules are the basis of any configuration system. A move towards configuration readiness requires at least that the process is consistent. All process changes from idiosyncratic to consistent are essentially organisational changes, and they must be carefully dealt with. If the knowledge is tacit, process choices are often based on historical coincidences or on other reasons long forgotten. Regardless, tacit knowledge makes discussing the process very difficult as there is no established frame of reference. In this situation, one must redefine the process based on the estimate. This allows the redefined process knowledge to be made explicit.

Idiosyncratic and explicit process knowledge indicates different understandings of what triggers one process choice instead of another. If the process knowledge is explicit, it is possible to discuss matters and develop a new process which is based on consensus. Naturally, such new processes should also be explicit and made consistent, resulting in a configuration ready process. The implications are shown in Figure 6-3.

Figure 6-3: Implications and relationships between idiosyncratic/consistent and tacit/explicit process

<table>
<thead>
<tr>
<th>Process Knowledge</th>
<th>Consistent</th>
<th>Idiosyncratic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Explicit</td>
<td>Configuration Ready</td>
<td>Develop new process through consensus</td>
</tr>
<tr>
<td>Tacit</td>
<td>Document process to make explicit</td>
<td>Redefine process</td>
</tr>
</tbody>
</table>

Product knowledge can also be assessed according to the opposites idiosyncratic/consistent and tacit/explicit even though the implications differ to some extent. Product knowledge which is idiosyncratic and tacit is best illustrated by product choices which are based on un-reflected gut feelings and which are not consistent across employees. The same customer requirements result in different product choices depending on random events. In such a situation, the best solution is to make a formal product review resulting in an overview of the product, and a definition of the rules governing different design choices. A formal product review may easily result in the specification process being reviewed and redefined.

Tacit but consistent product knowledge is much easier to deal with and may only require the existing practice to be documented. Still, knowing the rationale for various product decisions is vital for further development of the product and should be gathered over time. Idiosyncratic and
explicit product knowledge allows a deep discussion of the proper way of designing a product given specific customer demands as all knowledge is explicit.

However, the type of production process must be considered before taking drastic measures. If a company typically only sells one-of-a-kind, the idiosyncratic and tacit knowledge perhaps reflects a well trained staff. On the other hand, if the same product is designed in a variety of ways, this indicates inconsistent customer requirement interpretations or erroneous product rule applications. All three scenarios require a product review where design choices are discussed and defined. The implications are shown in Figure 6-4.

Figure 6-4: Implications and relationships between idiosyncratic/consistent and tacit/explicit product knowledge

<table>
<thead>
<tr>
<th>Product Knowledge</th>
<th>Consistent</th>
<th>Idiosyncratic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Explicit</td>
<td>Configuration Ready</td>
<td>Establish product rules through consensus</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Change organisation</td>
</tr>
<tr>
<td>Tacit</td>
<td>Document products to make explicit</td>
<td>Formal product review</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Define product rules</td>
</tr>
</tbody>
</table>

6.6 Summary

The prerequisites for configuration are explicit and consistent product and process knowledge, and the readiness for configuration can be estimated by assessing these two factors. While the framework for assessing whether a company is ready to proceed with a defined configuration scope is established, we cannot predict anything about the organisational change issues that are bound to occur. As soon as the right scope for the configuration project has been established, it is more or less possible to identify any critical bottlenecks in the coming knowledge elicitation process. If the analysis of the organisation has shown that the knowledge concerning both the configuration process and the product being configured to some extent is tacit and/or idiosyncratic it is necessary to take precautions against unwilling experts who possess key knowledge in relation to the configuration system.

The PETO project pointed out that reasons for delayed configuration projects are often found by looking into organisational issues rather than the technical issues concerning the development of product configuration systems. For instance, it is often taken for granted that experts are willing to make an effort in converting their tacit knowledge into explicit knowledge which can then easily be implemented into the product configuration system. However, this is not always the case which is supported by Lightfoot (1999) who specifies a classification of misrepresentation/unwilling experts: 1) Unintentional misrepresentation where the expert omits critical details or fail to elaborate, 2) intentional misrepresentation where experts misrepresent their knowledge hoping to
sabotage the project, and 3) the uncooperative expert who openly refuses to participate in the project.

When you implement a configuration system in an organisation, the configuration system will affect the organisation, and likewise the organisation will affect the configuration system. In Lightfoot (1999) it is discussed how you can motivate unwilling experts. However, we will not go deeper into that discussion in this chapter. All in all, it is very important that the project group addresses this issue and plans how it will handle unwilling experts before the configuration project is initialised.

To sum up, chapter 6 answers the following research question:

**RQ3:** What are the prerequisites for configuration?

The answer is that product configuration requires explicit and consistent knowledge about both the product in question and the configuration process to support it. To estimate configuration readiness, product and process knowledge must be assessed according to two opposites – explicit vs. tacit and consistent vs. idiosyncratic. If the knowledge is both explicit and consistent it is predicted that the company is configuration ready. See Figure 6-5.

**Figure 6-5: Assessing configuration readiness and implications.**
Part III: Configuration in Engineering Companies

“There are only two kinds of theories: Those that are wrong and those that are incomplete.”

Karl Popper
7 Configuration in Engineering Companies

So far, this thesis has been about product configuration in general. It has been necessary to make a rigorous theoretical exposition, to thoroughly define a perception of the subject configuration, as this area of research is often treated in a vague fashion.

In order to avoid saying a little about a lot, it is necessary to delimit the study of engineering companies. My frame of reference (see chapter 4) defines the contextual setting of a product configuration system in a given organisation. What is more, the frame of reference presents the total configuration system that transforms user requirements into a description of a product’s component structure. In an ideal world, it would be possible to understand and analyse the application of product configuration systems in engineering companies by describing each subsystem, the relation amongst them, and how they affect the configuration process. This is, however, beyond the scope of a single Ph.D. study. The goal in the present thesis is to describe which mechanisms can be used when we developing product configuration systems in engineering companies. In order to do so, we have, until now, developed an understanding of the subject of configuration with the aid of:

- A general frame of reference (chapter 4),
- a typology of configuration systems (chapter 5), and
- the prerequisites for configuration (chapter 6).

These three bullet points will be the point of departure from which we will look into motivation and scope of configuration in engineering companies. The general frame of reference is the above-mentioned understanding and definition of the term configuration. The general frame of reference represents my point of view on configuration. The typology shows a theoretical development of a general scheme of classification of configuration systems, and will be used to analyse what kind of configuration systems are developed and implemented in the two case companies. The prerequisites for configuration will be used to analyse if the knowledge in the two case companies is ready for configuration, and what are the main barriers in the knowledge elicitation process. The prerequisites for configuration will also be used to identify general barriers to the development of configuration systems in engineering companies. Are the barriers related to making knowledge explicit or are they related to making knowledge consistent?

In short, this boils down to the following two research questions mentioned in chapter 3:

RQ4: What is the motivation for configuration in engineering companies?

RQ5: What are the barriers for configuration in engineering companies?

In the next two sections (section 7.1 and section 7.2) we will elaborate on the two research questions. Section 7.3 we will reflect on the meta-question using the developed theory from chapters 4, 5, and 6.

Finally section 7.4 is a brief overview of the data collection carried out in this thesis, and a presents a common structure of the case chapters.

7.1 Motivation for Configuration Projects in Engineering Companies

Product configuration systems are often connected to discussions concerning mass customization and personalization of products to the end customer in B2C. In Haug et al. (2007) we reflect on different strategies on the transition toward mass customisation. We conclude that the motives, strategies and incentives are different when engineering companies moves towards mass
customisation than those moving from mass production to mass customisation. Likewise, the motivation for implementing a product configuration system is different when comparing engineering companies and mass producers. For instance, it is obvious that product configuration systems are relevant when companies like Dell are offering an increasing number of options to the customer through their web-based product configuration system. They can offering an increased variety of products, and an increased number of possibilities to the customers – in other words they obtain increased flexibility or customisation as opposed to engineering companies where the motives often are to get more standardisation.

When mass production companies move towards more customisation, the goal is frequently to provide more options for the customer. For this reason, these options are made very visible to the customer. On the other hand, engineering companies that move towards more standardisation focus on optimising internal processes (Hvam et al., 2004; Petersen & Jørgensen, 2005; Hvam, 2006). Since customers of engineering services normally expect a product tailored to their needs rather than a standardised one, using a predefined solution space, where the customisation takes place, is normally not something to advertise with. Equivalently, in some cases, the movement from pure customisation towards more standardisation is supported by a configuration system thus making it possible to produce a quote many times faster than normal. However, presenting a quote so rapidly could be perceived by some customers as lacking in seriousness. In this case, some companies may to some degree pretend that specification tasks take more time than they really do. For these reasons, standardisation may not always be very visible to the customer.

According to Lampel & Mintzberg (1996) the right degree of customisation depends on the kind of industry a company is part of. Lampel & Mintzberg (1996) mention two extremes, Mass Industries (manufacturing standardised goods often of big volume) and Thin Industries (large degree of customisation often with products of low volume). They argue that an important consequence of the shift to what they refer to as “customised standardisation” from companies at both ends of the continuum is that customers loose flexibility in one area and gain flexibility in another area. Thus, they point out an important distinction between mass production and engineering companies that move towards mass customisation. For instance, we see an increase of product variety and a decrease of product variety respectively.

Opposite the mass industries where the task of product configuration system often is to open up the solution space and make it accessible for the customer bringing more flexibility to the customer in a otherwise highly standardised process, product, and transaction strategies, the main task for product configuration systems in thin industries is to close the solution space and consequently a pull to standardise process and product strategies. This is illustrated in Figure 7-1.
Standardisation of specification processes and product knowledge takes place on a high abstraction level, and it provides means to achieve benefits. Turning to literature, Edwards & Riis (2004) have deduced the following benefits from their literature search:

1) “Lower turn-around time, i.e. the time from order confirmation to delivery,
2) Improved quality, i.e. the quality of product specifications,
3) Preserved knowledge, i.e. knowledge is preserved in the configuration system,
4) Using less resources, i.e. fewer resources are used for specifying a product,
5) E-trade, i.e. e-trade is made possible by interfacing with the product configuration system,
6) Optimizing products, i.e. the product configuration system makes it possible to optimize with regard to price, performance, etc.,
7) Making knowledge visible, i.e. knowledge contained in the system is easily available and presented to users,
8) Less routine work, i.e. trivial tasks are performed by the system,
9) B2B networks i.e., the product configuration system allows other companies to interface directly with the product configuration system,
10) Improved certainty of delivery, i.e. detailed knowledge about specifications lead to detailed knowledge about what and when to produce,
11) Focus on standard goods, i.e. a product configuration system can only handle standard goods, in which case everything else is non-standard, and
12) Job training made easier, i.e. examples of different types of product configurations can be illustrated using the product configuration system.”

(Edwards & Riis, 2004, pp.5)

In the PETO project Edwards & Riis explored what the expected and realised benefits of a product configuration system were, and the result from interviews in 12 case studies were, that the top three realised benefits of production configuration systems were:
1) “Improved quality in specifications,
2) Lower turnaround time, and
3) Using less resources.”

(Edwards & Riis, 2004, pp.12)

The companies that participated in the PETO project were two heavy engineering companies, five mass producers, and six batch producers. By focusing on the data from the two engineering companies the four highest scoring realised benefits are, according to Edwards and Riis (2004),:

1) Improved quality in specifications
2) Less routine work
3) Lower turn around time
4) Using less resources

Research question 4 is: “What is the motivation for configuration in engineering companies?”. Through the qualitative study at NNE Pharmaplan and GEA Niro19 this thesis will try to uncover the motivation in engineering companies for starting a configuration project both in terms of what were expected and realised benefits and in terms of whether the companies intended to standardise product and process knowledge.

Logically we expect that the implementation of a configurator in engineering companies is caused by a pull to standardise product and process knowledge. However, if a meta-configurator is implemented, one could expect the company to pursue only standardisation of the product knowledge while letting the process be open, or vice versa. We investigate this by following two separate paths in the next two sections:

- A path exploring the standardisation of process knowledge
- A path exploring the standardisation of product knowledge (in terms of standardisation of specifications)

7.1.1 Standardisation of Process Knowledge

To describe the scope of the planned change in relation to configuration projects in engineering companies we turn to the 1998 paper from Sloan Management Review by Lampel & Mintzberg. The authors start by describing two opposing logics, the logic of aggregation, and the logic of individualization. The following maxims characterize the logic of aggregation (Lampel & Mintzberg, 1996, pp.22): a) reduce the impact of customers’ variability on internal operations, b) do so by identifying general products and customer categories, and then c) simplify and streamline interactions with the customer. The logic of aggregation is often perceived as a central element in the industrial revolution, and it is clearly identified with the Ford model T.

While the logic of aggregation has dominated many industries (i.e. Ford Motor Company), it failed to take over in others. Obvious examples hereof are certain traditional crafts such as personal tailoring, fine jewellery making, fine restaurant cooking, and more recently there has been a general move towards more customisation (as suggested by the growing number of publications in the field of mass customisation20).

19 GEA Niro participated in the PETO project as well.
20 (Pine, 1999; Davis, 1987; Duray et al., 2000; Tseng & Jiao, 2001; Silveira, Borenstein, & Foglitto, 2001; Zipkin, 2001; Salvador, Rungtusanatham, & Forza, 2004; Piller, 2004; Petersen & Jørgensen, 2005; Piller & Kumar, 2006;
Although pure customisation and pure standardisation are perceived as opposing logics, this has not led the emergence of two distinct groups of strategies. In fact, it has led to a continuum of strategies depending on the number of functions that lean to standardisation and those that favour customisation. Lampel & Mintzberg (1996) developed this continuum for a manufacturing company with four stages in its value chain: design, fabrication, assembly, and distribution.

This gives rise to the following five strategies depicted in figure 7-2: (i) Pure standardization, (ii) segmented standardization, (iii) customized standardization, (iv) tailored customization, and (v) pure customization.

Figure 7-2 A Continuum of Strategies (Lampel & Mintzberg, 1996)

As the figure above illustrates, the main focus of the paper of Lampel & Mintzberg is to analyse customisation in manufacturing companies, and therefore the value chain is chosen to give the best description of these. Engineering companies can also be described by using the proposed value chain. For instance, a pharmaceutical facility is designed, modules are fabricated, assembled and finally distributed to the site where the facility is to be erected. Although the model of Lampel & Mintzberg is made with manufacturing in mind, the logic of aggregation and the opposing logic of individualisation still make sense when describing engineering companies. To describe the change in the engineering company, one must look at the value chain for the engineering company and then apply the same logic as described by Lampel & Mintzberg (1996).

In my two case companies, the strategy is best characterised as pure customization (both being engineering companies and one-of-a-kind producers). However, to understand engineering companies it might be helpful to look at the value chain of engineering companies from a ‘logic of individualisation’ and ‘logic of aggregation’ point of view.
According to Construction Industry Institute (1995) the project life cycle can be described as consisting of five phases, see Figure 7-3. The process is not linear, functions can occur concurrently - interaction, feedback, and iteration are inherent within the process (Construction Industry Institute, 1995). The increasing size of the arches illustrates the increasing effort and cost of the project, while the overlap between each phase shows the place where a transition occurs and where decisions are made.

Figure 7-3: Project life cycle diagram (Construction Industry Institute, 1995, pp.7)

A general model of any enterprise or entity life cycle can be found in GERAM (Generalised Enterprise Reference Architecture and Methodology (IFIP-IFAC, 1999)). The life cycle activities include all activities from identification to decommissioning of the entity, and they are illustrated in Figure 7-4. In the GERAM methodology a total number of seven life phases have been identified opposed to the five life phases of the Construction Industry Institute as described above. However, the two models of the life cycle are quite identical in content (with the exception of the decommissioning which is not included in the project life cycle of the Construction Industry Institute).
In this thesis the engineering value chain or project process is defined according to the description of capital engineering projects in Active Workbook (Achieving Competiveness Through Innovation and Value Enhancement Workbook) (Active - Engineering Construction Initiative, 1998). The Active Workbook defines a quite similar structured project process which can be used for all types and sizes of capital engineering projects, see Figure 7-5.
According to AECI (Active - Engineering Construction Initiative, 1998), the key stages of a typical project process are as follows (the following is based on (Active - Engineering Construction Initiative, 1998)):

The **project concept** determines the nature of the project opportunity. The aim of the project concept is to review alternatives and identify potential risks and benefits before defining the project objectives for the project.

The **project definition** stage will test that business objectives are clear, and establish critical success criteria for the project. At the end of this stage, the scope of the project is so well-defined that it satisfies the criteria for authorisation.

After the authorisation of the project the **project execution** stage follows in accordance with the authorised project scope and project strategy. The stages of execution may very well vary with the nature of the project but they will usually include detailed design, procurement, construction, and start up.

**Project handover** marks the completion of the project. At this stage, the project owner checks that the project objectives have been achieved, and formally accepts the project by signing it off as complete.

A continuum of strategies arranged according to the description of the engineering value chain (or project life cycle) could then be illustrated as seen in Figure 7-6.
The general hypothesis in this thesis is that many engineering companies are comparable of following the strategy of pure customisation. The development and implementation of a product configuration system will represent a move towards a more standardised process leading to a standardised concept process or even a standardised project concept and project definition phase. In this thesis, standardisation of the execution phase is not relevant. Engineering companies which are able to standardise their project execution phase are, in my point of view, not engineering companies or one-of-a-kind producers, but, rather have been turned into manufacturing companies producing standardised products.

7.1.2 Standardisation of Product Knowledge

To understand the difference between standardisation of product knowledge in mass producing companies as opposed to engineering companies, it is necessary to understand the difference of the development and specification process that takes place at mass producers versus in engineering companies. A suitable framework for discussing this is the concept of an order specification decoupling line (OSDL). The concept of OSDL is similar to postponement strategies as described in (Rudberg & Wikner, 2004; Pagh J.D. & Cooper, 1998; Olhager, 2003). This concept covers the fundamental separation between 'development' and 'variant specification', and as Hansen (2003) notes:

"The order specification decoupling line (OSDL) is the fundamental 'line' that separates the pre-developed specifications (including predefined standard elements in custom made specifications) from those specifications made during order acquisition or during order fulfilment, i.e. separation of information defined to general markets and information directly created in relation to individual customers."

(Hansen, 2003, pp.144)

The information made explicit prior to order acquisition typically consists of specifications defining materials, product structure, manufacturing processes, test procedures, etc. Rules and
constraints for the product in question can for some products also be made explicit prior to the acquisition of orders.

The information made explicit in the order related variant specification processes consists of partly combinations and modifications (instantiation) of predefined information, partly new information added during the processes. The complexity herein is related to the amount of information that is predefined, and thus the OSDL. This is illustrated in Figure 7-7 and Figure 7-8. Moving from left to right in the two figures is done through an explicit specification of standard parts, standard subassemblies and modules, standard geometries, predefined rules and constraints, document templates, etc.

Figure 7-7: Illustration of the order specification line (Hansen & Hvam, 2004)

The concept of OSDL can be used to define different classes of variant specification systems. Hansen and Hvam (2004) define four generic levels of OSDL: (i) Engineer-to-order, (ii) modify-to-order, (iii) configure-to-order, and (iv) select-to-order, see Figure 7-8:
The four generic levels are not exact definitions. There are examples of companies in between the four levels. For this reason, the classifications should rather be perceived as a spectrum ranging from ETO processes to STO processes. Below, the differences between the four generic levels are described.

Engineering-to-order processes typically take place in engineering companies consisting of skilled engineers/technicians. The process is characterised by complex specification activities, and it can be discussed whether the activities create totally new knowledge and information (not variants). Norms and standards constitute the foundation for the pre-developed specifications which are used to engineer new products. Characteristic of this process is thus the creation of new parts and parts numbers which often can not be predefined in for instance ERP systems, and for which there are no pre-calculated costs. (Hansen & Hvam, 2004)

Modify-to-order processes are somewhat similar to ETO processes even though the OSDL has moved towards the customer, reducing the need for creative engineering skills. The allowed variety is less than found in traditional engineering companies, and the specification task is based on well-defined patterns of product structures. So, a typical solution is based on the use of generic modules and assemblies which can be 'fitted' during the specification process thus making the final customer variant of modules and assemblies. In this way, the variant specification process can define customised products faster and cheaper, and the systems in which this process takes place are similar to ETO systems. Often one will find parametric 3D models used as basis for creating new product variants quickly. (Hansen & Hvam, 2004)
Configure-to-order processes (CTO processes) typically take place in primarily automated systems, wherein part of or all activities in the specification process are supported by expert/configuration systems. In CTO processes the specification task is simplified to combine existing standard parts and modules according to rules and constraints. The OSDL is moved towards the customer through large development efforts. Thus a high degree of specifications are made prior to order. These kinds of specification processes are characterized by speed, low cost and few errors, making them suitable for mass customisation (Hansen & Hvam, 2004). However this requires a high degree of work preparation which can be rather expensive.

Select-to-order processes (STO processes) create new specifications, i.e. invoices with prices and delivery details. The task in STO processes is to transform information of customer needs to a specification of a standard product, and retrieving this information from data storages. The OSDL is moved all the way to the customer thus resulting in little choice regarding variance.

In this thesis, the general hypothesis about product knowledge in engineering companies is that the implementation of a configurator in engineering companies represents a pull to formalise product knowledge through the creation of norms, standards, and generic product structures. Therefore, it represents a pull towards standardisation of product knowledge, which again should lead to standardisation of specification processes.

### 7.2 Understanding Knowledge Elicitation in Engineering Companies

Elicitation of knowledge is central in a configuration project. If the elicitation of knowledge fails, the configuration project will suffer in different ways as explained in chapter 6. A configuration project ends with the sharing of formalised knowledge with the organisation through a product configuration system. Haug (2007) provides a good description of the basic principles of a configuration project. This is depicted in Figure 7-9.

**Figure 7-9: Basic principles of a configuration project (Haug, 2007)**

A simple description of the model above is as follows. A configuration project is initiated in a company. The purpose of the configuration project is to formalise knowledge about a given domain in the company. The knowledge engineer is responsible of developing and implementing a product configuration system that contains knowledge about a given domain. However, the knowledge engineer is not able to accomplish this by himself. He is dependent upon the knowledge of domain experts as the knowledge engineer himself has no detailed knowledge of the domain. The information the domain expert hands over must be correct, and sometimes the domain expert must translate the knowledge into an analysis model in order that the knowledge engineer can use it. In other words, this first vital step is to elicit and capture knowledge about the product and processes of the company and then establish explicit and consistent knowledge.

The second step is to translate the information into an analysis model. The purpose of this is to document the knowledge so it is possible to communicate the knowledge and establish consensus in the organisation about the product model. It is also at this step codification of the knowledge
happens, and the product model is established. The result of this step is a codified model of explicit and consistent knowledge about the product, created so it can be configured later.

When consensus about the analysis model is established, it is sometimes useful to transform the analysis model into a design model which can then be implemented into a configuration system. This step can be called sharing; the explicit knowledge is now shared through a configuration system thus making it accessible to the organisation.

The model of Haug (2007) corresponds to the work by Stower (2004) on making tacit knowledge explicit. He defines three steps in making tacit knowledge formalised:

(i) Elicit pool of explicit knowledge
(ii) Codify explicit knowledge
(iii) Share explicit knowledge (making it accessible and shared throughout the organisation)

The basic principles of a configuration project with the above described steps are illustrated in Figure 7-10.

**Figure 7-10: Formalisation of knowledge**

As it turned out in the VisCon project at NNE Pharmaplan, the figure from Haug (2007) must be augmented. The first step must be described in greater detail with the help of the concept ‘knowledge elicitation’.

From chapter 6 we have two types of knowledge that we should be concerned with when we develop and implement product configuration systems: (i) product knowledge, and (ii) process knowledge. The basic requirement for successfully implementing knowledge in a product configuration system is that the knowledge is explicit and consistent. The process of meeting this requirement is illustrated in Figure 7-11.
In the elicitation process the required knowledge related to the scope of the configuration project should be made consistent and explicit. As it is costly in terms of man-hours to codify knowledge, it is vital that the knowledge elicited is the right knowledge based on consensus in the organisation. Accordingly there are two central processes when eliciting knowledge for configuration:

(i) Making tacit knowledge explicit, and
(ii) Establishing consensus about knowledge so the foundation of the configuration system is consistent knowledge and not idiosyncratic knowledge.

In engineering companies, the knowledge engineer is dependent upon the domain expert to help him formalise the knowledge. As the knowledge engineer does not have sufficient domain knowledge to develop the product model that forms the basis of the configuration system, he receives resources in the shape of billable hours so he can compensate the domain expert for performing the task of making the knowledge explicit and codified. To obtain the knowledge an agreement (formal or informal) is settled between the knowledge engineer and the domain expert. The problem is that the knowledge engineer does not know enough about the domain to make him capable of checking whether the domain expert has satisfied the agreement.

The purpose of research question 5 is to describe barriers to the knowledge elicitation.

### 7.3 Understanding Configuration Projects

In chapter 4 I put forward the ‘total configuration system’ as understanding of the frame where configuration takes place. The total configuration system is depicted in Figure 7-12.
Although the figure above describes how products are being configured, not how configuration systems are being developed, the figure is useful if we want to understand the configuration project in engineering companies. Likewise in the total configuration system where the configuration process is affected by different operators, development and maintenance of configuration systems are also affected by different operators. In chapter 4 we saw three operators of the total configuration system: proposed users, organisation and product configuration system. When looking at the development and implementation of product configuration systems as a technical process we can now identify the following operators: Users, knowledge engineers, domain experts, and other IT systems.

Integration to other IT systems is a delicate issue and a difficult task. However, it is merely a technical issue, and therefore, it is not included in the analytical model. Users, domain experts and knowledge engineers are often employed in the same organisation. In some cases they are not, however. For instance, in companies which produce consumer goods such as Dell computers, users do not have any affiliation with the organisation other than being customers. In other cases users might be part of the organisation that develops the configuration system, but they are located in another subsidiary or department than the developing organisation. Consequently, they might belong to a different organisational culture.

Comparing the analytical model presented in Figure 7-13 below with the basic principles by Haug (2007) in Figure 7-9 reveals a significant difference. In the analytical model proposed in the present Ph.D, the user is an operator who affects the development and implementation of a configuration project. Contrary to this, the user is not represented at all in the basic principles of a configuration project. The basic principles of a configuration project focus on representation of industrial knowledge thus failing to consider the user as an important factor in that given context. The user must be included into the analysis because he is an important part. Indeed, it is almost impossible to develop a successful configuration system without involving the user in the project.

The knowledge engineers play a key role in the configuration project as they elicit knowledge from the domain experts to formalise it into a configuration system. Sometimes knowledge
engineers are hired from external companies to carry out the development and implementation of the configuration system.

As the domain experts have extensive knowledge about the company’s product and business processes and consequently represent the employees, they are most often employed in the company that owns the configuration project. However, sometimes, a vendor to the company possesses important knowledge about a subpart or a component of the product which is vital to the configuration project. In such cases, domain experts might belong to several different companies.

The analytical model for the configuration project can be seen in Figure 7-13.

Figure 7-13: Analytical model

There are several procedures for developing product configuration systems. The one which is most featured in this Ph.D. is from the Technical University of Denmark. It is most comprehensively described in Riis (2003) and most recently described in Hvam et al. (2008). A lesson from Hubka & Eder (1988) point out that the technical process cannot be designed, and equivalently, it is difficult to control the development of product configuration systems 100%. Even so, as Dwight D. Eisenhower notes: "In preparing for battle I have always found that plans are useless, but planning is indispensable." As it is necessary to plan the development of a product configuration system, and to carry out the planning of the project, the procedure for development of product configuration systems is as good as any other procedure for developing IT-systems. The present Ph.D. will not focus on the process of developing and maintaining product configuration systems nor treat it intensively in the analysis of the engineering companies. This Ph.D. focuses on the interplay between the three operators: Users, knowledge engineers, and domain experts.

As we saw in chapter 6, the prerequisites for configuration were consistent and explicit knowledge, and knowledge engineers have to elicit the needed knowledge from relevant domain experts in the organisation. The domain experts are those employees from the company who have excessive knowledge about the products of the company. The cooperation between the three operators (domain experts, users, and knowledge engineers), is crucial for the project. If they cannot cooperate, the project will be more costly or delayed. How the communication evolves among the user, the knowledge engineer, and the domain experts depends on the type of organisation which the project is carried out in.
As described in section 4.5.5, there are different kinds of organisation structures. Mintzberg (1980) has identified five ideal types or configurations: (i) The simple structure, (ii) the machine bureaucracy, (iii) the professional bureaucracy, (iv) the divisionalised form, and (v) the adhocracy. Each of the ideal structures corresponds to a dominant pull from different parts of the organisation.

In this thesis which focuses on engineering companies, two of the five ideal types deserve special attention. As the present thesis focuses on engineering companies, the operating adhocracy and the professional bureaucracy must be given extra thought, as we assume that these two kinds of companies are dominant in the engineering trade.

Figure 7-14: Professional bureaucracy (Mintzberg, 1980, pp.334)

Professional bureaucracies (depicted in Figure 7-14) often appear where the environment is both stable and complex. Professional bureaucracies are bureaucratic in nature but without being centralised. The dominating coordinating mechanism is standardisation of skills which allows the employees in the operating core to work relatively freely of the administrative hierarchy and of other colleagues. The autonomy in the operating core is made possible by the predetermined behaviour from the standardised skills. The key part of the professional bureaucracy is its operating core where much of both informal and formal power of the organisation rest. Managers of the middle line must be professionals themselves, and they must maintain the support of the professional operators, in order to have power in the organisation. The technostructure is minimal in this organisation because the complex work of the operating professionals cannot easily be formalised, neither can its outputs be standardised by action planning and performance control systems. The support staff is, however, highly elaborated but mostly they carry out simple, routine work and back-up the high-priced professionals in general. In the support staff of these organisations, there is no democracy, only the oligarchy of the professionals. (Mintzberg, 1980; Mintzberg, 1993)

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21 Highly trained specialists or professionals
22 Which Mintzberg refers to as the pigeonholing process
The operating adhocracy often appears where the environment is both dynamic and complex. In the operating adhocracy, the innovation is carried out directly on behalf of the clients. The operating adhocracy hires and gives power to professionals who are highly knowledgeable and skilled. The specialists are grouped in functional units for hiring, professional communication, training, etc. but deployed in project teams to do their work. In the Operating Adhocracy, the administrative and operating work tends to blend into one single effort. In other words, ad hoc project work does not allow a sharp differentiation of the planning and design of the work from its actual execution. Both requires specialised knowledge and are thus carried out on a project-by-project basis. As a consequence, the middle line managers and support staff often blend together with the operating core in the project teams. While professional bureaucracies try to pigeonhole client problems into known contingencies onto which they can apply a standard program of standardised skills, the operating adhocracy engages in creative efforts to find a novel solution. Because these organisations seek to innovate, their specialists must coordinate informally by adjusting mutually in organically structured project teams. (Mintzberg, 1980; Mintzberg, 1993)

The operating adhocracy has a lot in common with the professional bureaucracy. In effect, to every professional bureaucracy an operating adhocracy corresponds which does similar work but with a broader orientation. For the engineering company that seeks to match each client problem with the most relevant standard skills within its given catalogue, there is company that treats that problem as a unique challenge requiring a creative solution. The former, because of its standardisation, can allow its professional operators to work on their own; the latter, in order to achieve innovation, must group its professionals in multidisciplinary teams in order to encourage mutual adjustment. The missions are the same but the outputs and the structures that produce them are different.

The next two sections deal with issues with implementing configuration systems in professional bureaucracies and operating adhocracies, respectively.
7.3.1 Issues with the Professional Bureaucracy

When trying to implement product configuration systems in professional bureaucracies there are predictable issues. Usually, technical systems in professional bureaucracies are neither highly regulative and sophisticated nor automated. Their knowledge base is sophisticated but the set of instruments that is used to apply the knowledge base is not. The environment of a professional bureaucracy is complex yet stable. The operating core of a professional bureaucracy is dominated by professionals who use procedures that are difficult to master but well-defined. The procedures are difficult to learn and can only be learned in formal training programs but they are sufficiently defined to become standardised. (Mintzberg, 1993)

The professionals in the operating core resist rationalisation and the division of their skills into simply executed steps. The procedure makes the professionals’ skills programmable by the technostructure and consequently it destroys the basis of their autonomy. (Mintzberg, 1993)

Changes come slowly and painfully after much political intrigue and shrewd manoeuvring by the professional and administrative entrepreneurs. Rather, change seeps in by the slow process of changing the professionals changing who can enter the profession, what they learn in its professional schools (norms as well as skills and knowledge), and thereafter how willing they are to upgrade their skills. (Mintzberg, 1993)

No two professionals are alike or equally skilled. This gives rise to issues with coordination, and standardisation of work processes. The work is complex work and has ill-defined outputs. Consequently, outputs from this process are ineffective. Indeed, it is difficult to formalise knowledge into a product configuration system as one of the main tasks is to create consensus among the professionals. The fact is that complex work cannot be effectively performed unless it comes under the control of the operator who does it. (Mintzberg, 1993)

Taking the description of the professional bureaucracy into consideration the following issues can be expected when trying to develop and implement a product configuration system in a professional bureaucracy:

- Development and implementation is slow and painful
- Employees resist standardised solutions and consequently formalisation of knowledge
- It is difficult to establish consensus regarding the standardised solutions.

7.3.2 Issues with the Operating Adhocracy

As with its bigger sister the professional bureaucracy, there are predictable issues when trying to implement configuration systems in an operating adhocracy. The operating adhocracy is positioned in an environment that is both complex and dynamic. The operating adhocracy can never be sure where its next projects will come from. A downturn in the economy or the loss of a major contract can close the company down literally overnight. (Mintzberg, 1993)

As with professional bureaucracies, operating adhocracies tend to have simple, non-regulating, and non-automated technical systems. What drives the company is to solve the complex problems of its clients. It exits to innovate for itself in its own industry. No organisation structure is better suited to solve ill-defined, complex and ill-structured problems but the operating adhocracy is not competent when performing ordinary things – it is designed for the extraordinary. (Mintzberg, 1993)
The adhocracy is what Woodward (1965) calls a custom producer, unable to standardise and consequently, unable to be efficient. The inefficiency is rooted in two problems: (i) High costs of communication, and (ii) unbalanced workloads. (Mintzberg, 1993)

The operating adhocracy is primarily driven by projects where specialists from different professions must work together in multidisciplinary teams and reach a common understanding of the project and the client’s needs. Due to the organic structure of this organisation coupled with its ambiguities and independencies, the operating adhocracy emerges as the most politicised type of organisation structure, and the political game is played with few rules. Faced with a decision in the operating adhocracy, everybody gets into the act, and it takes a lot of time when managers, specialists and others who have an opinion have to be consulted in the decision process. The problem is defined and redefined, alliances build and fall around proposed solutions, and finally, everybody settles down to hard bargaining about a favoured solution. (Mintzberg, 1993)

As mentioned earlier, another root of inefficiency is the unbalanced workload. As the organisation came into being to solve problems imaginatively, not to apply standards indiscriminately, it is almost impossible to kept high-priced specialist busy on a steady basis. For this reason, it is difficult to forecast future workloads and, consequently, it is difficult to find free resources to internal optimisation projects. (Mintzberg, 1993)

Taking the description of the operating adhocracy into consideration the following issues can be expected when trying to develop and implement a product configuration system in an operating adhocracy:

- It is difficult to free resources to a configuration project
- A slow and painful process precedes agreement on a favoured solution
- It is difficult to standardise and thus formalise knowledge as the structure relies of mutual adjustment rather than standardisation of skills as coordinating mechanism.

### 7.4 Data Collection

Data was collected from the following two case companies in the winter of 2007 and spring of 2008:

(i) NNE Pharmaplan A/S

(ii) GEA Niro A/S

All interviews were taped and transcribed and are not freely obtainable due to promised anonymity to the interviewees. Both companies are considered belonging to engineering companies. On some points they are similar, and on others they are dissimilar. The following table will highlight differences and similarities.

<table>
<thead>
<tr>
<th></th>
<th>NNE Pharmaplan</th>
<th>GEA Niro</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Configuration Expertise</strong></td>
<td>NNE Pharmaplan started their project in 2005</td>
<td>GEA Niro started their configuration project in 2001</td>
</tr>
<tr>
<td><strong>Product vs. Process Stability Matrix</strong></td>
<td>NNE Pharmaplan is characterised by dynamic product and process.</td>
<td>GEA Niro is characterised by a stable product and dynamic processes.</td>
</tr>
<tr>
<td><strong>Workforce</strong></td>
<td>The workforce of both companies can be characterised as consisting of highly specialised employees or specialists.</td>
<td>Closed</td>
</tr>
<tr>
<td><strong>Design space // Solution Space</strong></td>
<td>Open</td>
<td>Closed</td>
</tr>
</tbody>
</table>
7.4.1 Structure of Interviews

The interviews were carried out as semi-structured interviews. The interview guide is in Danish, as the interviews were carried out in Danish. An interview guide was made for each case. The guides are similar in content, though they have some case specific differences. The particular interview guide for each case can be found in the appendices.

Each interview was divided into four themes which were given a quarter of an hour each. The interviewer used the rules of semi-structured interviews as taught by Professor Helena Hurme in the ‘Thematic Interview Course’ at Åbo Akademi, Vasa, Finland. The thematic interview is described in (Hirsjärvi & Hurme, 1980) (in Finnish). There does not exist any literature in English that describes the thematic interview, therefore a brief description of the thematic interview will be given in the next paragraph.

The thematic interview is an interactive situation that is planned in advance and initiated and controlled by the researcher. It is the role of the researcher to motivate the interviewee and keep up the motivation of the interviewee. The researcher knows his role, but the interviewee has to learn it during the interview. It is called the ‘Thematic Interview’ because it focuses on certain themes which are discussed, and instead of using specific questions, certain themes are treated. The themes represents specified sub-concepts of the theoretical concepts upon which the research treats, and the interview situation, the themes are presented and specified through questions to the interviewee. This to a large extent frees the interview from the viewpoint of the researcher and gives voice to the interviewees, although the interview is directed at the subjective experiences of the interviewees to situations, which the researcher has analysed in advance. The phases of a thematic interview can be described as (although the phases do not always come in this order):

- Choice of themes and writing the research plan
- Creating the thematic guide
- Interviewing
- Transcribing the interviews
- Analysing the results
- Reporting

I made my choice off themes based on the reflections presented in this chapter. Then the the thematic guide was made, and this can be seen in Figure 7-16. Finally the thematic theme guide was adapted to each particular case. The particular interview guide for each case can be found in the appendices.
The first theme was always ‘Ritual Sounds’. ‘Ritual Sounds’ refer to the time devoted to establish a secure relationship with the interviewee. Up to 15 minutes was set aside to this theme. However, as soon as the interviewee was accustomed to being taped, and understood the agenda of the interview, the formal interview was started. After a trusting environment had been established with the interviewee, the three themes were brought to attention to the interviewee. The sequence in which the themes were presented to the interviewee was not always the same. The sequence varied according to the natural flow of the conversation.

The purpose of the motivation theme was to identify the scope of the configuration project as well as the type of configuration system which was implemented. The purpose of the development theme was to investigate the process of formalising knowledge in engineering companies, and to see if problems could be coupled with missing prerequisites for configuration. Finally, the purpose of the use theme was to identify how well the planned change was implemented and sustained.

7.4.2 Structure of Case Chapters

To present the two cases in a similar way, the two cases will be described and analysed in two chapters of the same structure. The composition of the two chapters consists of two parts. First, we have a descriptive part, which is mainly put together from statements of the interviewees, where they describe the configuration project. Second, we have an analysis of the case where the case is analysed with the purpose of answering research question 4, research question 5, and the meta-question in relation to the case. The structure is:
- Description of Case
  - Configuration in Case
  - Development and Implementation
  - Operation and Maintenance
- Analysis of Case
  - The Motivation for the Configuration Project
  - Barriers for the Configuration Project
  - Understanding Configuration in Case

### 7.5 Summary

Before we embark on the description of the cases in chapters 8 and 9, we this chapter has reflected on the following two research questions:

- **RQ4**: What is the motivation for configuration in engineering companies?
- **RQ5**: What are the barriers for configuration in engineering companies?

RQ4 makes us understand the motivation for configuration in engineering companies in terms of standardisation while RQ5 makes us understand barriers for configuration in engineering companies in terms of formalising knowledge by making it explicit and consistent.

The meta-question of this Ph.D. is: “How are configuration projects carried out in engineering companies?” In order to answer the meta-question and to understand configuration projects in engineering companies, the following analytical model can be used:

**Figure 7-17: Analytical model for understanding configuration projects in engineering companies**

In the chapter we have also seen a description of the data collection carried out in the project, and a presentation of the structure of the interviews carried out as well as the structure of the following case chapters.
8 Case: GEA Niro

GEA Niro A/S is a Danish company that has been a part of the German GEA Group since 1993. GEA Niro specializes in the development, design and engineering of liquid- and powder processing equipment for the manufacture of products in powder, granular or agglomerate form. The GEA Group is a world leader in the areas of process engineering, process equipment and plant engineering.

Spray dryers and coolers, fluid bed systems, freeze drying systems, solid/liquid extractors, evaporators, membrane filtration systems, agglomerators, and granulators feature in a comprehensive delivery programme marketed world-wide through an extensive network of Niro and GEA companies and representatives.

The original A/S Niro Atomizer was founded in 1933, and quickly became a world leader in industrial drying, with spray drying, freeze drying, and fluid bed processing as core technologies. In the 1990’s GEA Niro dropped "Atomizer" from the company name and in 1993, the Niro Group was acquired by the German GEA Group and began to co-operate closely with other GEA companies specializing in process technology and engineering.

A growing importance of controlling feed quality prior to drying brought GEA Niro into the concentration business and falling film evaporators became part of the scope of supply, primarily within the dairy industry. This involvement in pre-treatment has since grown to include extraction and membrane filtration. The start of this period saw the two-stage drying concept introduced to the dairy industry. Spray drying technology was also applied to air pollution control in 1978.

In 1989 the need to further develop particulate processing techniques led to GEA Niro upgrading its fluid bed technology and introducing new equipment for blending, coating, pelletising, and de-dusting (to produce powdered, agglomerated or granular products of specific properties). During the 1990’s GEA Niro formed the GEA Niro Pharma Systems business unit in order to strengthen the presence of the Powder Technology Division in the pharmaceutical market.

In 2002, GEA Niro A/S acquired the activities of the Atlas Food Division from Atlas-Stord Denmark A/S, specializing in the design and supply of freeze drying systems for food applications and vacuum systems for deodorizing edible oil.

The daily operations of GEA Niro A/S is controlled through four main divisions: Chemical, Food & Dairy, Pharmaceutical and After Sales. GEA Niro also has special activities within environmental engineering where the core technologies of GEA Niro are used in air pollution control and waste management.

8.1 Description of Case: GEA Niro

Data consists of four interviews at GEA Niro. Each interview was of 1 - 1½ hours’ length, and they were semi-structured in the same way as the interviews at NNE Pharmaplan. At GEA Niro the following four persons were interviewed:

- A user from the operating core
- A domain expert, and project owner from the operating core
- A manager from Middle line management

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23 Taken from the official webpage of Niro: www.niro.dk
8.1.1 Configuration at GEA Niro

The configuration project at GEA Niro was initiated around the year 2000 with the commencement of an industrial Ph.D. project. The first year was used on figuring out what the goals for the project should be, and what approach should be used.

Configuration at GEA Niro has until recently been limited to the dairy division. Recently, GEA Niro has worked on introducing the configuration mind set to other divisions. The configuration system covers 50% of the total orders which go through the sales department for dairy products.

Manager: (Appendix B: GEA Niro, 2008, pp.41) The system has been in operation since the end of 2004. Knowledge engineer: (Appendix B: GEA Niro, 2008, pp.59)

The configuration system is primarily used as a screening mechanism or an alignment of expectations with the customer in the early sales process. User: (Appendix B: GEA Niro, 2008, pp.10) The process is described as consisting of the following steps.

1. The customer contacts GEA Niro to get a quotation on a facility.
2. The preliminary quote is calculated in the configurator. It is an 8 hour process.
3. If the quote is acceptable for the client he often sets up a sales meeting with sales representatives from GEA Niro, and perhaps asks for modifications.
4. The modifications are then made at hand, and a detailed quotation is presented for the customer.
5. A contract is signed with the customer, and the engineering phase starts, which lasts up to two years.

The configurator is used to screen the incoming serious customer requests from the frivolous requests so that no unnecessary time is spent on frivolous requests. User: (Appendix B: GEA Niro, 2008, pp.10)

The configurator is primarily used in the sales phase, see Figure 8-1.
When the contract is signed, the order is transferred to the project department, where they start from scratch. The only thing which is re-used from the quotation is the standardised concepts. Domain expert: (Appendix B: GEA Niro, 2008, pp.32) The configurator is used for the first quotation given to the customer which is an estimate that is 80% correct.

“What you get is a draft... 80/20 of a project as we say”

Domain expert: (Appendix B: GEA Niro, 2008, pp.32)

Eventhough the configurator at GEA Niro is highly advanced and technical capable of making detailed specifications, it has not yet replaced the engineer. Often, the sales person has to tweak the result of the configurator or suggest additional equipment. For instance if the calculations indicate a noise level which is too high. User: (Appendix B: GEA Niro, 2008, pp. 8ff)

“All things being equal, I don’t believe you can hire a secretary to use the system - not yet. It requires more. Secondly, you have to evaluate in some way.”

User: (Appendix B: GEA Niro, 2008, pp.9)

Consequently, the configurator is a support tool for the sales personnel. It does not guarantee a correct calculated solution as, from time to time, it makes errors. The configurator occasionally makes miscalculations. For this reason, a process technologist always evaluates the calculation. This is done subsequent to the configuration. The process technologist is given the calculation, and
gives it a glance – ‘does it seem reasonable’? The sales person is responsible for the price and the text part. The process technologists are responsible for the technical data. Manager: (Appendix B: GEA Niro, 2008, pp.47)

The configuration system at GEA Niro is complex and many resources have been used in for development. The ambition has also been high from start. Nevertheless, the output of the configuration system is still merely a draft, and the final specification of the technical system is not configured. As a consequence, the configurator must be characterised as a meta-configurator.

On the other hand, the configurator resembles a co-design configuration system as the configurator at GEA Niro is able to transform functional requirements to a structural solution, which is a complex interplay between two distinct systems (Knowledge engineer: (Appendix B: GEA Niro, 2008, pp.65)): (i) The configurator at GEA Niro, and (ii) a process simulation tool called Sim Cal, which is integrated into the configurator.

Figure 8-2: Configuration process at GEA Niro

![Flow chart for GEA Niro](image)

“It (Sim Cal) is the brain behind. It is really Sim Cal that gets you from function to structure. It is its task - together with the configurator... It is interplay...”

Knowledge engineer: (Appendix B: GEA Niro, 2008, pp.65)

As Figure 8-2 indicates, the interplay between the two systems is as follows. The user inputs functional requirements in the configurator and the configurator calculates main parameters for the system. The main parameters are transferred to Sim Cal, and Sim Cal calculates the dimensions of the structural solution based on a simulation of the process. The results are then compared with lists of standard components in the configurator. The configurator has rules on how the nearest bigger or smaller sizes of the main components is selected. When the main standard components have been chosen, the solution is sent back to Sim Cal, and a new process simulation is run. If the solution is
valid, and the solution lives up to the functional requirements, a quotation can be printed and used in the customer dialogue. Knowledge engineer: (Appendix B: GEA Niro, 2008, pp.65)

The output of the configurator at GEA Niro is not a complete solution with the component structure; nevertheless, it is an accurate estimate. When the customer has accepted the price, the engineering phase starts, and the solution is often engineered to order. The standard concepts survive beyond the sales phase, nothing else. Following the definitions given in chapter 4 and 5, the configurator developed and implemented in GEA Niro is a meta-configurator that maps functional requirements to a structural solution based on standard concepts and components.

8.1.2 Development and Implementation

The configuration project at GEA Niro began in 2002. The first model was released by the end of 2003. This was a shear test model. A year later (at the end of 2004) the next version of the model was released, and during 2005 the configuration system was placed on the agenda of the sales people of GEA Niro.

The structure of the knowledge model is based on a modular breakdown of a spray drying facility into sub systems or standard concepts. The work on standard concepts started in 1988 and forms the foundation for the configuration system. Domain expert: (Appendix B: GEA Niro, 2008, pp.26)

Getting the sales people to use the system has been difficult. The six years from 2002 to now have been necessary to convince the users to trust and use the configuration system. Knowledge engineer: (Appendix B: GEA Niro, 2008, pp.59) First when they had received answers on why it was developed, and they could see that something reasonable was behind they began to trust the output, and consequently they began to use the system. Knowledge engineer: (Appendix B: GEA Niro, 2008, pp.59)

All told, the implementation process has been long, and especially anchoring the configuration system in the users has been a slow process.

“I believe that they have to spend a year or two - maybe up to three years to be accustomed to it. Because in a typical engineering company systems like these are not pushed from the top. At least not at GEA Niro.”

Knowledge engineer: (Appendix B: GEA Niro, 2008, pp.59)

One of the reasons for the slow implementation process is that the management has not made it obligatory to use the system, and the users have had alternatives to the configurator. All along, the specialists have had alternatives to the configuration. They have had a person sitting next to them that could make quotations when they did not bother to use the configurator. Knowledge engineer: (Appendix B: GEA Niro, 2008, pp.59)

“Not until this man is shut down is it possible to say: now it is only the configurator. Or you could say that this guy should only deal with facilities that cannot be run through the configurator - that is where they are at today. Today it is the configurator first and Johannes second. Before it was Johannes first, then the configurator if Johannes was not available.”

Knowledge engineer: (Appendix B: GEA Niro, 2008, pp.59)

From the start of the project a key domain expert was assigned as resource to the project. The domain expert did not only have the theoretical knowledge, he had the practical knowledge as well,
and, furthermore, he had much knowledge from previously produced facilities. Knowledge engineer: (Appendix B: GEA Niro, 2008, pp.55)

“Although he is retired, he still works two days a week. He is too valuable for them to let go. It is he who possesses all their experiences on how to cobble together a spray dryer for milk.”

Knowledge engineer: (Appendix B: GEA Niro, 2008, pp.55)

8.1.3 Operation

Internal data from GEA Niro shows that the configuration system is used in 50% of the first time quotations that is sent to customers. However, GEA Niro does not keep track of how much of the output from the configuration system is used, and how much is carried out the traditional way, the system only registers that the system has been used. Manager: (Appendix B: GEA Niro, 2008, pp.40)

There have been some resistance against the configuration system but as the system gets better by every release, the resistance is shrinking. Traditionally a sales person has had a support base of calculators, correspondents, process engineers and support staff that all got together and made a mini project. So the sales person has handed out tasks and then he has joined the ends as project manager on the quotation project. That scenario has changed. The sales person now works behind a computer screen. He presses some keys, and then he gets the whole quotation served on a plate and sends it to the customer. Surely this is a great change, and some have gone through this transformation easier than others. Manager: (Appendix B: GEA Niro, 2008, pp.39)

Some of the sales people saw it as an advantage because they had more time to sell, and therefore, they could actually make more sales, because all the paperwork was done relatively easily. It boosted their sales opportunities, and hence the interest in it. Others from the other end of the spectrum have seen themselves as going from a high-tech process-seller to a refrigerator salesman. Manager: (Appendix B: GEA Niro, 2008, pp.39)

The only way to motivate the change of the users’ habits and work processes has been to make the configurator fit their needs or make sure that the configurator procedure benefits them:

“The only way to change that [their work process] is, when they can see with their own eyes, that it is ingenious to use the configurator... When they in some way or another benefit from using the configurator. If not, forget it.”

Knowledge engineer: (Appendix B: GEA Niro, 2008, pp.62)

The system is continuously being improved. However, as it has become highly complex, it is not easy to maintain. This is the weakness of formalised systems. If one is dealing with complex systems, with many concepts, rules, attributes, etc., starting of on the wrong modular structure will bury you in work. When the system is in operation and an error is discovered where a logical consequence is that the level of modularisation of the knowledge base has to be changed, the knowledge engineering team has to use a month or two to re-model the knowledge base. This has often been difficult to explain to the users, and they have difficulty seeing the necessity. They are reporting errors, they report improvements which they would like to have done, and nothing happens for two months. Knowledge engineer: (Appendix B: GEA Niro, 2008, pp.63) On top of this, the configuration system is built as sequences of rules, and one does not have to change much before it affect other rules. It is not always possible to figure out all consequences, and it is not always possible to test 100% for consequences.
"It seems like there is a tendency towards... when we identify an error, and say this one we have to correct... But then it is as if you unfortunately introduce a new error."

User: (Appendix B: GEA Niro, 2008, pp.9)

The configuration system does not guarantee error free quotations; it is the sales people’s responsibility to proofread and check whether there are any errors in the document. Manager: (Appendix B: GEA Niro, 2008, pp.43)

8.2 Analysis of Case: GEA Niro

The configuration project at GEA Niro has been underway for many years, and, no doubt, a lot of money has been spent on the project. According to the knowledge engineer, the process they have gone through from 2002 and the subsequent six years has been necessary. Knowledge engineer: (Appendix B: GEA Niro, 2008, pp.59) Taking into consideration that the development of standard concepts has taken almost 20 years, it is clear that the standardisation of knowledge and the formalisation of knowledge in GEA Niro has not been an easy process.

As described in section 8.1.2, it does not seem to have been the conversion of tacit knowledge to explicit knowledge that has caused big problems in the knowledge elicitation process. Engineers in GEA Niro are generally open to sharing their knowledge. The reason is that Niro is a project based organisation, and the employees are accustomed to knowledge sharing on a daily basis as part of participating in typical engineering projects. As a consequence, sharing of knowledge and getting support to convert otherwise tacit knowledge to explicit knowledge is not a problem for the domain expert.

However, as the knowledge engineer from GEA Niro explained, you need to be able to ask the right questions. Thus, the knowledge engineer has to have some basic knowledge of the domain so he is able to ask interesting questions to the domain expert.

"Again, it is perhaps the downside of having to work with engineers, because engineers... it must be interesting for them. If it is not interesting, or if you can not ask interesting questions, they may well start to ignore you a little."

Knowledge engineer: (Appendix B: GEA Niro, 2008, pp.56)

8.2.1 The Motivation for the Configuration Project

One of the most important reasons for starting the configuration project at GEA Niro was preserving knowledge. Losing knowledge was feared for two reasons. Firstly, an important knowledge based system in GEA Niro had been implemented on an old UNIX server which was outdated, and it had become difficult to get spare parts to the hardware. The system was crucial in getting price calculations done in time. Domain expert: (Appendix B: GEA Niro, 2008, pp.20)

"We could no longer get spare parts to the hardware. It was like sailing towards an iceberg - like Titanic."

Domain expert: (Appendix B: GEA Niro, 2008, pp.20-21)

Secondly, the freeze dryer systems were getting more and more complex with more automation, more and larger subsystems. For this reason, it became increasingly difficult for new sales representatives to sell the systems. It was only the experienced employees who could do it. The experienced employees were approaching retirement. The experienced process technologists also faced retirement. They were all facing retirement, and would to leaving the company at more or less
the same time, so this constituted another reason. Domain expert: (Appendix B: GEA Niro, 2008, pp.21)

“We have to write their knowledge down somewhere so when they leave the company, we know where to look up the knowledge. So… knowledge management.”

Domain expert: (Appendix B: GEA Niro, 2008, pp.21)

As the projects and products became more and more complex, and the sales representatives no longer could cope with the complexity, another reason for making a configuration system was that a configuration system would result in fewer errors. When GEA Niro started up an engineering project, a lot of money was reserved to contingency or warrantee costs. By reducing the number of errors in an engineering project, GEA Niro would be able to reduce the contingency and warrantee costs. Domain expert: (Appendix B: GEA Niro, 2008, pp.21)

All in all, it was obvious that something had to be done to retain the knowledge in GEA Niro. It took a new employee up to five years to become efficient as a sales representative. The first year he was a cost. The second year he was a \( \frac{3}{4} \) cost. It was expensive to train new employees. Domain expert: (Appendix B: GEA Niro, 2008, pp.22) So old employees were leaving, and new ones took five years to train. It further complicated the case that the knowledge of the employees on their way to retirement was not consolidated anywhere. Knowledge engineer (Appendix B: GEA Niro, 2008, pp.55)

To make the knowledge acquired and consolidated into one system, so that the knowledge could be shared with the sales people, was thus a primary motivational factor. In that way, it would be possible to get less experienced sales people to sell facilities. Knowledge engineer: (Appendix B: GEA Niro, 2008, pp.55)

“If he is able to look up knowledge in a system, then it will be faster to get to the right answer.”

Domain expert: (Appendix B: GEA Niro, 2008, pp.22)

The last main reason which supported the project was: The hitrate had been significantly lowered. This was not due to more customers or more competition. The big food companies had sites spread across the world. Arla alone had 39 facilities in Scandinavia. Every year around the time for the yearly budget for next fiscal year, a message came out to the site and production managers to report in numbers and possible investment. Nearly every site manager or production manager wanted a new facility and called Niro to get a quotation to use for his budget. That is the reason why the hit rate was low. Domain expert: (Appendix B: GEA Niro, 2008, pp.21)

“When I began in the company 30 years ago, we made nine quotes to get a single order. Every ninth was a hit. It has been rising and rising ever since, and now we probably get up to 40-50 before we get an order.”

Domain expert: (Appendix B: GEA Niro, 2008, pp.21)

**Standardisation of Knowledge**

Standardisation of knowledge can be identified on two levels in the GEA Niro case. Firstly, the process of making quotations has become more standardised and formalised. Secondly, product knowledge has become more standardised as well.

Although standard concepts have been on the way in GEA Niro since 1988, it is not until the recent five years that they have been used as a standard in GEA Niro. Knowledge engineer:
Part of the reason is that it takes a long time to reach consensus amongst specialists. It does not take long to make the standard concepts but it takes a very long time to reach consensus among specialist so that they begin to use the standard concepts. Domain expert (Appendix B: GEA Niro, 2008, pp.27)

“Five different people, five different opinions.”

Domain expert: (Appendix B: GEA Niro, 2008, pp.27)

The standard concepts have been on their way for a long time. It has been a long process, and with the configurator it became possible to make it a standard in GEA Niro. Before, GEA Niro always designed solutions that were specific for the customer. Now, there is a tendency towards basing it all on the same standardised basis. The feeding section now is based on the standard concepts, and in 90 % of the cases the standard concepts are good enough. User: (Appendix B: GEA Niro, 2008, pp.14)

“This is precisely what we talked about before with engineering hours which are expensive... therefore we can not afford to sit for several weeks and find out what the feeding section should look like... Not saying, if the customer only wants one tank it should be possible as well.”

User: (Appendix B: GEA Niro, 2008, pp.14)

According to the sales people, standardisation has made it difficult to customise facilities to the customers. Although it is possible to choose between different concepts and options in the configurator, it is not always possible to get to a satisfying result. Frequently, when you try to tailor the facility for the customer, the configurator is no longer up to the challenge, and it is difficult to carry out the customisation. User: (Appendix B: GEA Niro, 2008, pp.13) In similar fashion, the configuration process has been formalised in connection with the configuration project. A workflow has been implemented in the configurator. The user has to answer questions in a given sequence, and experience shows that it is important to answer questions in the right sequence. Asked about how locked the process is, the user replies:

“I feel it is quite locked. I would say... to ensure things not going haywire, then I have said: ‘Start from A and work your way through.’ It has been a little dangerous otherwise. It is as if you preferably have to take the ‘right way’ through.”

User: (Appendix B: GEA Niro, 2008, pp.14)

Say, compared to the control towers in CPH airport, the process is still relatively flexible but the process knowledge has been formalised in some way. The user is now restricted to use standard concepts with some options and variability. It is still possible to give textual inputs, and add additional prices, which is possible in a more open solution space, but it is not allowed to deviate from the standard concepts to a larger extent, and the users have to pleed well before any deviation is allowed. Some users feel it is terrible, and their typical argument is that the facilities become too expensive if the sales people are not allowed to tweak the solutions. Manager: (Appendix B: GEA Niro, 2008, pp.44)

In conclusion, the motivational factors for the configuration project were:

- Preservation of knowledge
- Consolidation of knowledge
- Reduction of error
• Reduction in resources spent on answering requests with decreasing hitrate

The configuration has standardised both product as well as process knowledge in GEA Niro by narrowing the solution space, by introducing standard concepts, and by proposing standardised components on the basis of functional requirements.

8.2.2 Barriers for the Configuration Project

Two important processes that could be barriers to the knowledge elicitation process were identified in section 7.2:

(i) The process of making tacit knowledge explicit.
(ii) The process of establishing consensus about knowledge

In the following two sections these two processes at GEA Niro will be analysed.

Explicitness

Converting tacit knowledge to explicit knowledge went well in the GEA Niro project. It did not seem to be a problem. The engineers gladly shared their knowledge.

“It went well [converting tacit knowledge]. Again, because the employees who possessed the knowledge... there was not one of those who had anything to lose. They were on the road to retirement age; they knew well what they were worth... So they were free to tell us how to do things. They were just happy that they were asked.”

Knowledge engineer: (Appendix B: GEA Niro, 2008, pp.55)

The reason for this can be found in the nature of the GEA Niro business. GEA Niro is a typical project organisation where sharing of knowledge is required in order to complete projects. In this type of business where there is a tradition of working with projects, you are forced to share your knowledge. Perhaps a project has ten employees involved and if you do not share your knowledge with the others, the project will most likely fail. Knowledge engineer: (Appendix B: GEA Niro, 2008, pp.55)

As the old saying goes: ‘It takes one to know one’. This seems to be the biggest challenge in the engineering project. You have to be able to understand the domain experts, and if you to not possess some basic knowledge about the domain of the experts, they lose interest in you. It seems as if this is the downside of having to work with engineers in a company like GEA Niro. The project has to be interesting for them, and if not or if you can not ask interesting questions, they may well start to ignore you a bit. Knowledge engineer: (Appendix B: GEA Niro, 2008, pp.56) Consequently, it is vital that the knowledge engineer has basic knowledge of the domain. If the knowledge engineer do not have some basic knowledge of the domain, it is difficult to keep discussions on track.

“If there are two experts who sit next to you [to support you], then suddenly they begin to speak almost too technical, and if you can not keep up with [them] and understand just a fraction of it, you are lost and then they lose interest. So it has helped greatly that we understand what a process plant is. One can ask [questions], and sometimes they are stupid questions, but you can ask for something they care about. This is an important parameter.”

Knowledge engineer: (Appendix B: GEA Niro, 2008, pp.56)

Consistency

While converting tacit knowledge to explicit knowledge did not seem to be a barrier to the knowledge elicitation in the GEA Niro configuration project, the establishing of consensus or
consistent knowledge represented a huge challenge. The trouble arose when they tried to establish consensus amongst the domain expert to propose standard solutions for functional requirements. This was not easy. This is closely related to making product knowledge consistent. Creating consistency amongst domain experts is difficult.

Very independent people, experts, work in Niro. Each has his own set of experiences. Perhaps one works at ten different sites in South America, another at ten different plants in Asia. One is working with milk; another is working with coffee. These people might have very different approaches to their work due to the knowledge they have obtained in their work life. Some of them prefer to sell low tech plants; others prefer to sell grand projects. These people have had to sit down and cut some of the edges; agree on some models they could all vouch for. Obviously, this has to be a long process. Knowledge engineer: (Appendix B: GEA Niro, 2008, pp.57)

An illustrative example of how long it takes to reach consensus is the development of standard concepts. The development of standard concepts was more than 20 years underway. After the implementation of the configurator, a separate concept-application to the configurator was developed. This exposed the standard concepts in the company. Not until now have the standard concepts become standard in the company. Actually, today, if a facility is designed, it is most likely designed and specified according to the standard concepts. Knowledge engineer: (Appendix B: GEA Niro, 2008, pp.60)

“You have to go to a design review, and if the supervisor, or one of the project engineers, has modified the concept, he is taken up to the blackboard, and then he has to explain why it is better than the standard concept.”

Knowledge engineer: (Appendix B: GEA Niro, 2008, pp.60)

“This is new. Earlier it was every man for himself. Come up with your own suggestions, just design your own system... if you want to be green - it's fine with me... and the development [of reaching consensus] might have happened anyway, but with the configurator, it has been pushed forward at lightning speed at GEA Niro”

Knowledge engineer: (Appendix B: GEA Niro, 2008, pp.60)

As a matter of fact, it seems that experience is an important factor when one establishes consensus about standard concepts in engineering companies.

“I've been here for a long time, and the reason why I get [my] concepts accepted is probably that I have grey hair.”

Domain expert: (Appendix B: GEA Niro, 2008, pp. 27)

Even though some experts did not agree with the work of the configuration team or with the standard concepts, they accepted the new ideas because “he has been there for a while”, and “he probably knows what he is doing.” Not only because of the grey hair but because it was an employee from the company (who was not young), coming with all the new smart ideas, and after all he was as thrilled as the young ones were. Domain expert: (Appendix B: GEA Niro, 2008, pp. 27)

The difficulty of reaching consensus between domain experts suggests to me that the model of the knowledge elicitation process illustrated in Figure 8-3 is too simplified.
The establishment of consensus must per definition involve more than one domain expert. So the conception of consistent knowledge mostly refers to establishing consensus among the domain experts. With numerous domain experts the knowledge elicitation process could be characterised as illustrated in Figure 8-4:

**Figure 8-4: The knowledge elicitation process (revised)**

When consensus among the domain experts has been established, it is possible for the knowledge engineer to elicit the knowledge. This should result in consistent and explicit knowledge. It can be very difficult for the knowledge engineer to mediate and facilitate the establishing of consensus. Often, the world is not black or white, and personal preferences can be the reason for not reaching consensus.

### 8.2.3 Understanding the Configuration Project at GEA Niro

The configuration system has been used to standardise both the early sales process and the product knowledge. Standardisation of the process has been necessary as it has become more and
more difficult to distinguish frivolous requests from serious requests. In the last decade, the hit rate has decreased, and Niro must answer more requests with a quotation before they get an order. As a consequence, it has been necessary to reduce the manpower needed for producing the first quotation material to the customer. The implementation of a configuration system has been chosen as a solution, and the early sales process has become more standardised. However, the whole truth is more complicated. The sales people still have alternatives as the old business process is still alive. The configurator is used for most quotations but there is now data on how much of the final quotation material which comes from the configurator, and how much is from manual work.

Standardisation of the product has lead to a closed and smaller solution space thanks to the implemented standard concepts. Earlier it was everybody for himself, now all have to comply with the standard concepts or argue for any deviation. The standard concepts have been developed since the late eighties, and not until recently with the implementation of the standard concepts in the configurator have they been widely accepted in GEA Niro.

In relation to the formalisation of product knowledge, preservation of knowledge has been a motivation for the configuration project due to the following issues:

- Old IT –systems
- Old employees
- Increasingly complex systems, hence, complex knowledge.

Elicitation of tacit knowledge and the conversion into explicit knowledge have not been a big challenge for the knowledge engineers at GEA Niro. The domain experts at GEA Niro willingly share their knowledge. However, to get the engineers to share their knowledge, it helps if the knowledge engineer is able to ask interesting questions. With such a complex domain as the domain of GEA Niro, this is of course a challenge for the knowledge engineers. On the other hand, this is probably true for most knowledge elicitation tasks. If you can not ask interesting questions, people probably lose interest in you.

If the conversion of tacit knowledge into explicit knowledge was relatively unproblematic, the establishing of consensus about standardised solutions, on the other hand, has been problematic. In GEA Niro it has taken about 20 years to develop and implement standard concepts. The standard concepts are now integrated in the configurator and they are widely accepted in the organisation. GEA Niro has used a lot of resources on the configuration project. Indeed, establishing the configurator took 6 years, and making the standard concepts took 20 years of development. How come this advancement has been so slow?

In chapter 7 we saw an analytical model to analyse configuration projects in engineering companies. The analytical model for the configuration project at GEA Niro can be seen in Figure 8-5.
In order to understand why it is difficult to establish consensus and consistent knowledge regarding the products in GEA Niro, we have to understand the interaction between the users, knowledge engineers, and domain experts. We must take the type of organisation that GEA Niro is into consideration. The description and preliminary analysis of the case of GEA Niro show that GEA Niro is best characterised as a professional bureaucracy. The environment of GEA Niro can best be described as complex and stable – complex enough to require extensive training to know how to choose the relevant procedure but stable enough to enable these skills to become standardised and well defined.

According to section 7.3.1, the following issues are expected in a configuration project in a professional bureaucracy: Development and implementation is slow and painful; resistance towards standardised solutions and consequently to formalisation of knowledge is present; and it is difficult to establish consensus regarding standardised solutions. All three issues can be observed in the GEA Niro case.

The development and implementation of the configuration system has evolved slowly at GEA Niro, and many resources have been used in the configuration project. Establishing standard concepts has taken two decades, and not until recently have they been generally accepted in GEA Niro. We see two origins to the slow development process:

(i) The domain experts have found it difficult to reach consensus

(ii) The users have refused to have their work process standardised

These observations are in line with Mintzberg’s ‘Structures in Fives’ (Mintzberg, 1993).

The most difficult part is establishing consensus among the agents/domain experts, while the process of getting the domain experts to share their knowledge is relatively uncomplicated. This is illustrated in Figure 8-6.
Usually it would be the task of the knowledge engineer to facilitate the establishing of consensus among the domain experts but due to information asymmetry, it is difficult in this case. The elicitation of knowledge from the domain experts by the knowledge engineers can be described as a principal-agent problem with multiple agents. The principal-agent problem (or agency dilemma) is found in most employer/employee relationships, and deals with the difficulties that arise under conditions of incomplete or asymmetric information when a principal hires an agent. In this case, the knowledge engineer hires multiple domain experts to help him describe the product knowledge necessary for the scope of the configuration system.

The problem arises for the knowledge engineer when the domain experts do not agree upon a favourable solution. It is difficult for the knowledge engineer to settle discussions as he does not have the domain knowledge. He has to trust that the domain experts are interested in defining a solution to the problem that they can agree upon. But what if the domain experts do not want to reach consensus?

We know from the description of the professional bureaucracy in ‘Structures in Fives’ that any standardisation of work processes here will be difficult if not futile.

The users of the configurator as well as the domain experts at GEA can be considered professionals from the operating core. They all carry out specialised jobs that require years of formal training. The professionals in the operating core in theory resist rationalisation and thus division of their skills into simply executed steps. This is also the case at GEA Niro. Opponents show opposition in a subtle way – not by being unwilling when sharing their knowledge but instead by obstructing the establishing of consensus and thereby making it impossible to make the knowledge consistent and formalised in a configuration system. Another explanation to the difficulties with reaching consensus in GEA Niro is that no two domain experts are alike or equally skilled. This also gives rise to issues with establishing consensus.
The configuration system is a threat to the professionals; it makes the professionals’ knowledge programmable by the technostructure and consequently it destroys the basis of their autonomy. As a consequence, changes in GEA Niro have come slowly and painfully after much political intrigue and shrewd manoeuvring by the knowledge engineers. As mentioned before, change can seep in by the slow process of changing the professionals and this is also evident in the GEA Niro case.

8.3 Summary

GEA Niro has standardised both product and processes in the sales phase. However, the engineering phase is until now left untouched. The work that has been carried out at GEA Niro has resulted in a more standardised sales process. The sales process has been formalised in the sense that the configuration system should be used to produce the initial quotation material at GEA Niro. Equivalently, the product has been standardised as well.

The saying ‘everybody for himself’ now no longer seems to do GEA Niro justice. The configurator selects standard concepts on the basis of the functional requirements given to the configurator. After the first process simulation, the configurator then selects standard sizes of components. This has lead to better reuse and more economy of scale regarding the manufacturing of components, i.e. lesser errors. The configurator must have given a range of benefits further down the value chain of GEA Niro as well. This has however not been the motivation for GEA Niro, and these benefits are difficult to measure.

The standardisation of product knowledge has resulted in a closed solution space, and it has become more closed than before the configuration system was implemented. It is, however, possible for the users to give textual input and to make notes about possible customisations ordered by the user.

Earlier, it was everybody for himself. If you had a personal preference regarding the solutions you calculated for the customers, you could implement it without resistance. Now you have to argue and explain why you have deviated from the standard concepts. So the solution space measured in product variance has become more closed. Functional requirements now point to specific standard concepts and process and instrumentation diagrams.

The configurator is developed to support the sales process of spray dryers. It has a very narrow focus compared to configurators in other engineering companies. As GEA Niro has developed a closed solution space, and has a stable product, it is able to develop an advanced configurator. However, the configurator only supports the early sales phase of the GEA Niro business process, and it will probably be difficult to extend the scope of the configurator to cover more of the business process. This is primarily due to the resistance to standardise the work process by the operating core of GEA Niro. It makes it difficult to formalise more knowledge. The question is whether GEA Niro has reached the limits of the configurator, not because of technical issues but due to organisational issues.
9 Case: NNE Pharmaplan

With more than 80 years of experience, the engineering company NNE Pharmaplan is a leading supplier of systems, consultancy and engineering services to the international pharmaceutical and biotechnological industry. NNE Pharmaplan competencies span all technical disciplines applying to engineering, construction, validation, start-up and optimisation, and reconstruction of facilities for product development and production plants, pilot plants and laboratories within the pharmaceutical and biotechnological field.

NNE Pharmaplan executes projects by applying modular engineering principles. By breaking a plant down into modules that can be constructed and tested off-site, NNE Pharmaplan gets around some of the time-related constraints arising at a construction site. These constraints can be site conditions, qualified building resources, problems with conducting several tests at one time as a result of inadequate supplies, test personnel or QA resources, or organisational and logistics related complexity at the construction site. The main elements in modular engineering are:

- Modular process design that addresses all project phases and validation and operation of the plant
- Modular building engineering using intensive and flexible off-site construction resources
- A set of project execution tools which support the fast track engineering activities and use modular principles adapted to the specific project.

With the use of fast track engineering and modular principles, NNE Pharmaplan is in a position to construct a pharmaceutical plant in record time.

When NNE acquired the German engineering company Pharmaplan in the winter of 2006 (the deal was completed on the 31st of March, 2007) the world’s largest resource pool of expertise in the pharma and biotech industries was created. NNE Pharmaplan is an engineering and consultancy company with an exclusive focus on pharmaceutical and biotechnological industries employing more than 1,500 employees distributed in more than 21 offices around the world. In the following a few key milestones of the history of NNE Pharmaplan will be presented.

NNE A/S was separated from Novo Nordisk A/S in 1991 and turned into an independent subsidiary. Until 1991 NNE had been a technical department of Novo Nordisk A/S. At the time the total number of employees was around 130. Only two years later, in 1993, the number of employees had doubled. At the turn of the millennium the number of employees has passed 1,000 making NNE a significant player in the engineering and consultancy business of pharma and biotech companies. In 2002 NNE finished a new complete biotechnological plant for production of the haemophilia medicine FVII (NovoSeven®) for Novo Nordisk A/S. This was a fast track engineering project. The 14,000 m2 facility was built in only 18 months and the plant is considered a milestone for NNE and indeed the whole pharmaceutical industry regarding the innovative use of modular engineering. In 2003 NNE completed the world biggest insulin bulk plant of 32,000 m2 in record time. The facility is designed and built using modular engineering techniques. A year later NNE handed over a 7,000 m2 biopharmaceutical plant which was constructed in only 14½ months. In 2005, the NovoSeven® facility won the inaugural Facility of the year award. In the winter of 2006, NNE announced the acquisition of the German based company Pharmaplan GmbH.

The information for this section is based on the official webpage of NNE Pharmaplan A/S: www.nne.biz.
9.1 Description of Case: NNE Pharmaplan

As this thesis has been produced partly at NNE Pharmaplan, the case is described thoroughly. The author of this thesis has occupied the position of project manager of the visual configuration project in the company. The work as project manager has mainly been located in two departments: The Methods and Systems Department (from 2004 – 2007), which was NNE Pharmaplan’s cross disciplinary work method department, and the Conceptual Design department (from 2007 to primo 2009), which works with carrying out conceptual designs for NNE Pharmaplan’s customers. Four years of work experience has been documented in several notebooks which contain new insights, general notes and observations.

A visual configuration project at NNE Pharmaplan originates from ideas from this Ph.D. study. Extracting and implementing a major part of the knowledge in the visual configurator became a considerable part of my work at NNE Pharmaplan. To test the models and conclusions of this Ph.D., 5 interviews were conducted in Danish. The interviews were taped but due to promised anonymity to the interviewees, the interviews are not available.

I interviewed employees from different parts of the organisation (described below with the use of ‘Structures in Fives’ definitions (Mintzberg, 1980; Mintzberg, 1993)):

- Project sponsor from the strategic apex
- Domain expert A, engineering manager from the technostructure
- Domain expert B from the operating core
- User and former project manager of VisCon from the operating core
- Manager from middle line management

References to interviews are made in the following way: Project sponsor: (Appendix A: NNE Pharmaplan, 2008, pp.8)

9.1.1 Configuration at NNE Pharmaplan

The case of visual configuration at NNE Pharmaplan is well-described in several conference proceedings, and at several occasions it has been presented to the community related to product configuration in Denmark. Ladeby et al. (2007) contains a good description of the ideas and the motivation behind the configuration project. A similar description with a slightly different focus is found in Larsen et al. (2006). The product configuration project was a natural successor to the modular engineering research project carried out at NNE Pharmaplan in the period from February 1997 to August 2000. A detailed description of the modular engineering project can be found in Miller (2001).

Dalux Config has 50 registered users who have received formal training in the use of the program. Dalux Config is used in Sweden, Denmark, Germany, France, Switzerland, and US. In May 2008 it was decided to upgrade the software to version 3, and the upgrading process formally ended in July 2008.

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25 This section is based on my own experience. I was one of the driving forces in the VisCon project in the early project phases, and I left the project after it was launched to operation. From May 2008 to January 2009 I was the project manager for the VisCon project.

26 The software developed at NNE Pharmaplan in the visual configuration project is called Dalux Config.
In short, the scope of the visual configuration project at NNE Pharmaplan (VisCon) was to formalise product knowledge, and then to create a customer-focused front end engineering tool which could be used to involve the customer in the early phases of an engineering project. The process of finding out how to apply the VisCon tool to a given project was left open and up to the user. In this way, the user could adapt his use process to the task at hand. The formalised knowledge in VisCon was codified according to modular engineering principles which were developed as part of a preceding industrial PhD project.


Figure 9-1 illustrates the six engineering activities in relation to the overall view of the engineering activities. In the figure, the six main engineering phases are described and related to front end definition, execution and operation. As Figure 9-1 indicates, the visual configuration project primarily had Conceptual Design as primary focus.

Figure 9-1: Engineering activities in engineering companies

When the initial sales process is finished, the conceptual design phase commences. The purpose of making a conceptual design is to clarify the project’s conditions and superior goals and scope. The conceptual design phase ensures that all relevant alternatives are examined, and it makes sure that an estimation of time and price is made within ±30% certainty.

The aim of the visual configuration project at NNE Pharmaplan was to support the conceptual design phase. The conceptual design phase has a significant influence on the course of the engineering phases to come. At NNE Pharmaplan it is estimated that as much as 80-90 percent of the total cost of a facility project is confined to the conceptual design phase, see Figure 9-2.
The key activities in the conceptualizing phase at NNE Pharmaplan are:

- Calculation of product capacity
- Establishing of area need and area concepts
- Establishing of process and utility concepts
- Layout of the facility

These activities form the foundation of a proposal for the facility. The proposal is delivered to the customer in a conceptual design report. The proposal includes price estimation on the total costs of the facility with a 20-30 percent certainty.

A preliminary study showed that a good configuration tool for NNE Pharmaplan should at least support the following decisions, which the specialists at NNE Pharmaplan often found hard to communicate to customers:

- Area needs for various equipment,
- Site evaluation and expansion typologies,
- Plant layouts, and
- Flow of materials and personnel.
The product knowledge supposed to go into the visual configuration systems was in the beginning limited to geometrical knowledge (scale elements relatively to capacity), and price knowledge which calculated price in relation to capacity. Max 7 attributes were made visible to the user at any given time. The idea was that the level of detail in VisCon should match the rough calculations carried out in the conceptual design phase. The primary focus in the conceptual design phase was to select solution concepts and not to design or engineer detailed solutions.

The engineering services at NNE Pharmaplan are modularised according to the principles of modular engineering. Modular engineering aims at decomposing equipment and buildings into self-contained functional units with standardised interfaces and interaction, where interchangeable modules is a principle for creation of variety

VisCon is a meta-configuration system. It is not possible to configure a structural solution of a module let alone a whole facility with this system. VisCon operates with key attributes that have an impact on the size of a module. Originally, the visual configuration system at NNE Pharmaplan also had price calculation data but this was ditched as it proved almost impossible to maintain and develop. Furthermore, it was difficult for the user to interpret the calculations as the context (i.e. country, degree of automation, design principle etc.) was vaguely stated.

9.1.2 Development and Implementation

The VisCon project started out in September 2004 with a pilot project carried out together with a Danish Software house that could deliver a 3D configurator. The project ended as the team decided that the software could not fulfil the expectations to a dynamical user interface. However the pilot project highlighted interesting aspects and cleared the way for configuration in the early stages of a facility project at NNE Pharmaplan. The conclusion from the pilot project was that a visual configurator could support the conceptual design phase.

In April 2005 a new pilot project was started with another software vendor (Dalux). The challenging task from top management was that within a month the visual configuration team should be able to present a mock-up and configurable model of the NovoSeven facility at the InterPhex conference. If the team could do that, the project would continue. As the team succeeded, the result was that the VisCon project was initiated. The project was formed as a strategic cooperation between Dalux and NNE Pharmaplan, and subsequently, Dalux Config was co-developed between NNE Pharmaplan and Dalux. Dalux would at the end of the project obtain the legal rights associated with the source code, while NNE Pharmaplan afterwards would become a regular customer to Dalux.

In May 2005 I was transferred to the Conceptual Design Department, and took a one-year leave of absence from my PhD-study to focus on the development and implementation of the visual configurator at NNE Pharmaplan. I worked as a knowledge engineer and was responsible for collecting and formalising knowledge.

During the summer of 2005, the first prototype was launched to the users. This prototype was called Dalux Config 1, and after the launch the team immediately began developing the next version of the software so that it was possible to collect and integrate new user requirements into Dalux Config 2. The process was dynamic; indeed it could be compared to the extreme programming methodology. Although the software was not finished or ready for use, the team was using it, and gave feedback to the developers while handling the contact to appointed users as well. This gave the project an ultra short development cycle and it lead to the launch of Dalux Config 2 in January 2006. A year from ignition of the VisCon project, in April 2006, the project was officially transferred into operation.
A modular engineering project had been carried out at NNE Pharmaplan prior to the start of the configuration project. As it was the general belief that the modular structure formed a solid foundation for configuration, it was decided to base the configuration project on the master principles listed below:

- Define the production process by its (chemical/physical) unit operations
- Organise the plant in "stand-alone" functional Process Modules encapsulating the unit operations
- Ensure simple and standardised interfaces

A module fulfils the following rules (see Figure 9-3 for illustration). The "product" changes status (physically, chemically, concentration, purity, mixture of ingredients, accumulation, etc.) during passage of the module. A module spans all the necessary equipment, which autonomously carries out a process operation. A module has one input and/or output per media (product, process support, utility). A module is decoupled by simple, well defined and standardised interfaces to other modules. Removing the module removes the functionality, but leaves the remaining modules (functions) intact and operational. A module makes 'Single source' responsibility during design, construction and qualification possible.

Figure 9-3: Process module definition

The modular engineering approach and the principles behind are useful when the complexity of a technical system rises. The very idea of defining a module so that it has as simple an interface as possible to other modules is useful. Modular engineering is a structured approach for enabling these simple interfaces and boundaries to other modules and it enables decoupling. In this way, the modules can be engineered as packages and ultimately they can be tested off site without other modules present. User: (Appendix A: NNE Pharmaplan, 2008, pp.43)

“These principles are plain common sense, and have been driven by the modular engineering approach.”

User: (Appendix A: NNE Pharmaplan, 2008, pp.43)

When a conceptual engineer creates floor layouts, a lot of knowledge can be reused. Even the simple task of loading an old project and reusing some of the concepts may be a substantial advantage and timesaver compared to starting from scratch each time. In the configuration system it is easy to open up several designs and copy and paste between these. By reusing knowledge in this way, many design tasks can be simplified at an early stage.
Each piece of equipment implemented to the configurator has a number of variables or attributes. The variables are values that are used to describe the class. Typical parameters are names that identify the class and parameters like width and height that defines the visual properties of the class. The kinds of data on the class can be of many different types, e.g. text strings and numbers. These values can have two kinds of rules attached to them: (i) Calculation, and (ii) logic. This approach is described in the following.

Often some kind of calculation between the variables is necessary. A simple example is to have three variables named diameter, height and volume. Calculating the variable volume can be a simple function of the two other parameters which is easily described in a spread sheet. Often it turns out that the calculations become more complicated than this example, but they are still easily described by using spread sheets. The team chose to make it possible to link variables from the component to spread sheets since (i) a spread sheet is a powerful tool for this type of knowledge, and (ii) spread sheets are the preferred tool of engineers when they face a calculation problem. Simple calculation knowledge (multiplications, subtractions, additions, etc.) is often described directly in a C# rule builder.

Some types of knowledge are hard to describe in spread sheets. A typical scenario is that a product is available in several sizes (e.g. small, normal and large) and only the smaller sizes have a specific feature available (e.g. cooling). Describing this in a spread sheet quickly ends up being rather complicated using ‘if’ or ‘case’ statements. Nevertheless, experienced spread sheet programmers tend to implement such applications even though they become very hard to maintain. In particular, this is true when the product sheet becomes more complicated than the example above. A better way to describe this type of knowledge is by using truth tables or other types of logic. Table 9-1 depicts an example of a truth table:

Table 9-1: A truth table

<table>
<thead>
<tr>
<th>Size</th>
<th>Cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>small, normal</td>
<td>True</td>
</tr>
<tr>
<td>Large</td>
<td>False</td>
</tr>
</tbody>
</table>

To write this example by using if-statements in C# code may be simple, but add a few extra parameters and values and it will become very complicated. Entering this kind of product knowledge by utilizing truth tables ensures a valid solution. It is also possible to define truth tables in VisCon.

9.1.3 Operation and Maintenance

As we recall, the vision for the VisCon project was to formalise product knowledge while keeping it open to how the user wishes to use it. In the development process it became obvious that the principles from modular engineering were not strong enough to facilitate reuse of knowledge, and furthermore it was difficult to implement a satisfactory price calculation algorithm. Consequently VisCon became a different system in the use phase than intended.

“I believe it has become a tool that we more use to illustrate something for the customer than a sales tool used together with the customer.”

User: (Appendix A: NNE Pharmaplan, 2008, pp.42)

To a question on what the team did not achieve, the manager has the following answer:
“Two major things. First, not being able to implement it in the work process... but, actually, we did take that out of the scope early in the project... Another thing we had was enabling a cheap conceptual design. We have proved that this was possible but we have not done it completely on bigger projects.”

Manager: (Appendix A: NNE Pharmaplan, 2008, pp.34)

The users primarily used the tool to illustrate decisions made or they used the tool for the final layout. However, the tool was intended to help develop scopes and layouts by involving the customer in the early phases of a project and not only to illustrate and visualise progress made in-between meetings. The reason that this did not happen was not that the functionality of VisCon was inadequate. Some users had used the tool together with the customer and got good feedback on the work sessions. The functionality to use VisCon on workshops together with the customer was implemented. However, it was only tested in a few cases. User: (Appendix A: NNE Pharmaplan, 2008, pp.42) Primarily, the reason was that the VisCon tool was not stable enough. It would suddenly stop responding or shut down which was not a big problem when working at the office, but it was a big issue when the tool was used in a workshop together with the customer. Secondly, VisCon was not flexible enough. It was difficult for the user to figure out why one was not allowed to give a certain value as input to a given module. A lot of the restrictions on the modules were due to the validity of price calculations. It turned out that the price calculations implemented in the system constituted more of a disadvantage than an advantage. It stifled the system. Thirdly, the price calculation did not take the context into account. For instance, it could not take into consideration that it was more expensive to construct a facility in Denmark than in China. As a consequence, the price calculations were not used as it was difficult for the user to figure out the premise for the calculations. Besides, it turned out that the price calculation knowledge was difficult to elicit and maintain.

In the conceptual design department, price estimates on the fill & finish part of the facility were pretty accurate. It was possible to calculate a fairly accurate price in a matter of hours. It was not possible to calculate an equivalently accurate price for an API-facility even though it took three weeks. User: (Appendix A: NNE Pharmaplan, 2008, pp.41) The VisCon team believed it would be possible to implement price calculation, if the modular engineering principles could be used as a way to attack the process. User: (Appendix A: NNE Pharmaplan, 2008, pp.41)

Another issue with the price estimates was that they were fixed according to single projects. Actually, in order to avoid price calculations on the basis of extremes, price calculations should really have been based on average projects. The biggest problem with price calculations was, and still is, that they change over time. It was optimistic to believe that it could be possible to estimate a price of a facility together with the customer in a two hour session. The problem with giving the customer an early quick estimate is that the customer always remembers this first estimate no matter how many times you adjust the estimate either upwards or downwards. Domain expert B: (Appendix A: NNE Pharmaplan, 2008, pp.57)

In NNE Pharmaplan there was no consistent price structure. The structure changed from project to project, and depended on who calculated the price. For instance, when prices were collected from other colleagues, it was different what was included in the price, and what was not. This made it difficult to develop and maintain models. The prices were extruded from very different projects, projects of different sizes, qualities, and with different courses of events. If a project had been really terrible, then it had probably a relatively high engineering cost. Domain expert B (Appendix A: NNE Pharmaplan, 2008, pp.57)
“The whole time I had doubts in the back of my mind – the price calculation I made on the tank storage module does it contain the same as when we made the price calculations on the HPLC module? Were the same activities included?”

Domain expert B: (Appendix A: NNE Pharmaplan, 2008, pp.57)

In the beginning, the adoption of the system by the users was very positive. The use of the system was not forced upon them – they could choose whether they wanted to use the system or not. This laissez-faire approach had the effect that the configuration system was not used in every project, and when it was finally used, it was used retrospectively to illustrate the work carried out. Apparently, the project had all requisites but one: Change management. Manager: (Appendix A: NNE Pharmaplan, 2008, pp.31)

Although the project did not succeed in integrating the configuration system in the business process of NNE Pharmaplan, the project did not face resistance towards the change or encountered premeditated forces that tried to maintain status quo.

“I believe it is human nature... it can be a little unwilling to change. A lot of it [resistance] is simply caused by... lack of knowledge is not the right word... by unawareness regarding what is common practice, and what are the benefits to the company by doing what we want them to do.”

Domain expert A: (Appendix A: NNE Pharmaplan, 2008, pp.21)

A peculiar thing was that although most super users were located in Denmark and the project was located in Denmark, the majority of the use of the configuration system happened outside Denmark. There are several interpretations of this. The most plausible explanation is that in Denmark there were several known alternative ways to create 3D models, and in the subsidiaries there were no alternatives. Suddenly, the subsidiaries were in a position where they themselves could make advanced 3D models by using the configuration system.

The implementation of the configuration system had one effect that was significant. It helped spread the basic concepts of modular engineering. When you used the system, it was obvious what a module was, and what it contained.

“It has created some concepts, so we at least have some notions of some basic concepts for process modules - but to formalise basic concepts... that has not happened. I think that is an incredibly difficult process.”

User: (Appendix A: NNE Pharmaplan, 2008, pp.43)

As mentioned before the means to achieve the benefits was to standardise/formalise product knowledge while keeping an open process regarding how the system was used. It was the intention that VisCon should be founded heavily on the principles of modular engineering. The VisCon project soon ran into problems:

“Everybody that participated in the modular engineering project had this naïve conception that you in the future would be able to copy from project to project. But we quickly had to realise that modular engineering does not mean that the modules are alike. We engineer modules from case to case. As a consequence, they are not very generic.”

Domain expert B: (Appendix A: NNE Pharmaplan, 2008, pp.54)
Typically, a module emerged as an element or a representation of some equipment needed for a given project and later it was transformed into a configurable module either configurable in relation to capacity or configurable in relation to both capacity and price. The modules implemented in the VisCon were classified in three groups.

- Modules configurable in relation to price and capacity.
- Modules configurable in relation to capacity
- Modules not configurable.

With the upgrade to version 3 of Dalux Config, the last bit of modular engineering was removed from the VisCon project. It turned out that the modules in VisCon was not generic enough to enable reuse across projects. In this way, it became difficult to carry out price calculations on the projects, and it became difficult to estimate the right scaling of equipment. This, together with the fact that VisCon was most often used to illustrating purposes, lead to a redesign of the knowledge base. The knowledge base now consists of single pieces of equipment categorised according to chemical unit operations. Modular engineering has taken the form of reuse of work procedures which put people on the right track with their assignment fast. Actual reuse of modules does not belong in the engineering world. Domain expert B: (Appendix A: NNE Pharmaplan, 2008, pp. 54)

As already mentioned, the price calculations have been skipped, and this has lead to the new release of the improved VisCon which is based on Dalux Config 3 (released July 2008). The newer version of VisCon provides better and faster visualisation on the basis of less knowledge implemented into the system. The modules and equipment are categorised according to chemical unit processes, and the price calculation has been permanently removed.

With the new version of VisCon the emphasis is on quick visualisation, quick support, and quick updating of the knowledge base. The knowledge base has been remodelled to become even more decoupled, and this allows for quicker modifications of existing equipment and quicker addition of missing equipment. In this way, VisCon is now primarily an intelligent 3D visualisation system:

“Our visual configuration tool will primarily be used to determine what the scope is in a way so the customer feels – ‘this is useful decision support’”

Project sponsor: (Appendix A: NNE Pharmaplan, 2008, pp.10)

After two years of operation (2006-2008), the focus of the visual configuration project has shifted. Conceptual design is a two way process, a design process as well as a draft for a decision. Both processes are equally important, and as mentioned before, they are quite controversial among engineers and specialists at NNE Pharmaplan. Project sponsor: (Appendix A: NNE Pharmaplan, 2008, pp.10). VisCon now primarily aims at supporting the drafting or conceptualisation process, not the design or engineering process.

In other words, NNE Pharmaplan has forfeited formalising product knowledge in the way it was originally intended, and price calculations are no longer part of the scope. Likewise, the ambitions concerning the re-use of knowledge are scaled down. The explanation is two-fold.

(i) It proved harder to obtain re-use of modules from other projects.

(ii) The design space or solution space of NNE Pharmaplan is enormous.
NNE Pharmaplan has not achieved great re-use in connection with the development and implementation of VisCon. The only form of re-use VisCon facilitates is that the equipment implemented in VisCon can be used again and again. However, there is only geometrical knowledge in the model, so VisCon is only a very advanced 3D drawing tool. The re-use of larger parts of knowledge from project to project has not been obtained. Initially, the vision was to define generic standard modules which could be reused from project to project. However, it turned out that the projects were not very copy friendly, they had their own life. Domain expert B: (Appendix A: NNE Pharmaplan, 2008, pp.54)

The solution space of NNE Pharmaplan is extensive compared to e.g. GEA Niro’s. No doubt, Gea Niro produces many variants of spray dryers. If GEA Niro makes a quotation with their configurator, it is always a quotation on a spray dryer. The configurator makes quotations for something that GEA Niro’s own production can manufacture afterwards. In the case of NNE Pharmaplan there is no production.

“The scope is infinitely open. It ranges from: Everything has to be bought in disposable plastic so it is possible to throw out, to: Everything has to be welded together in stainless steel with equipment in everywhere.”

Project sponsor: (Appendix A: NNE Pharmaplan, 2008, pp.10)

9.2 Analysis of Case: NNE Pharmaplan

To understand the motivation at the beginning of the VisCon project, it is necessary to understand the development that NNE Pharmaplan went through in the years from 1989 to 2005. This development can be aligned to the development that Starbucks went through from being a local coffee bar to a global coffee company. In 1989 NNE Pharmaplan was known for its in-depth understanding of Novo Nordisk, and its processes. NNE Pharmaplan only worked for Novo Nordisk, and it only worked with what was relevant for them. All work and knowledge was customised to this single customer. In 1991 NNE Pharmaplan became an independent company, and should have started acquiring external customers but it was not until almost ten years later in 1999 that NNE Pharmaplan seriously pursued working for other customers.

“In 1991 there was only a single customer – Novo Nordisk. In 2007 and onwards 2/3 of NNE Pharmaplan’s turnover will come from external customers. It is a significant change for us to start to adapt and interface with so many new customers.”

Domain expert A: (Appendix A: NNE Pharmaplan, 2008, pp.19)

Let us take a step back. In 1999 it became obvious that other customers had other needs and a different way of working. Realising this and aiming to fulfil other customers’ needs initiated a development which was important for the VisCon project. Project sponsor: (Appendix A: NNE Pharmaplan, 2008, pp.7-8).

“In 1989 we became aware that it was necessary to develop business processes and bureaucratise what was before agreements between employees.”

Project sponsor: (Appendix A: NNE Pharmaplan, 2008, pp.8)

So the task in the nineties was to learn to work on commercial terms and conditions. In the period from 2000 to 2005, NNE Pharmaplan began to work for more and more customers, and it became apparent that if the company should differentiate itself as a company with a high cost level due to its location in Denmark, then it had to be able to carry out projects faster than its competitors,
This led to the goal of being able to engineer facilities in less than 12 months, i.e. it led to modular engineering. In 2005 the focus shifted from speed to understanding the customer’s context, - the company should be at ease with and understand the challenges of the now very diverse customers. Project sponsor: (Appendix A: NNE Pharmaplan, 2008, pp.8-9)

There is much tacit knowledge in our customers, and as a consequence, the next step in our modularisation effort is aimed at [improving] the initial contact with the customer

Project sponsor: (Appendix A: NNE Pharmaplan, 2008, pp.9)

At that time, NNE Pharmaplan was challenged on its ability to understand assignments, and much time could be spent before NNE Pharmaplan and a given customer was apparently on the same page. Project sponsor: (Appendix A: NNE Pharmaplan, 2008, pp.9)

“In the CD phase it is very easy to talk at cross-purposes. We have numerous times experienced that where the customer talks about a 50 MDKK investment, we hear everything he says, and automatically think of an investment of 250 MDKK. This will turn out into a conflict at some time - simply because the mental images of the investment are not aligned. Therefore, it is necessary to establish some common images of the scope of the investment at the beginning of the project.”

User: (Appendix A: NNE Pharmaplan, 2008, pp.40)

The development of NNE Pharmaplan can be described in terms of three big changes. These changes call for new ways to organise work and how NNE Pharmaplan executes projects. Domain expert A: (Appendix A: NNE Pharmaplan, 2008, pp.18)

(i) Size of company - NNE Pharmaplan has more or less ten-doubled in numbers of employees since 1989, and it is now a global company with both national and internal customers and projects.

(ii) Project types - the total investment cost has become bigger, and the projects are finished faster, and at the same time the customers demand low risks.

(iii) Customer types - "2/3 of NNE Pharmaplan’s turnover originates from outside Novo Nordisk.

To sum up, NNE Pharmaplan has gone from working for a single internal customer to working with a single external customer (still being Novo Nordisk) which was beginning to be a global company, and then finally NNE Pharmaplan has turned into a global company with many diverse customers. In the company the development has gone from an internal focus to an external focus. They are beginning to acquire more and more impulses from outside the company, thinking globally, and finally adapting to the different needs of very diverse customers which all want a quick and efficient solution. This development has paved the way for the tool VisCon. In other words, it led to the decision of starting a project of making a tool that supports visual decisions in cooperation with the customer. A customer should not wait for weeks before he sees drawings and illustrations of what has been agreed upon. Instead the specification is produced while the two parties sit together in a room. The VisCon tool was born to solve the issue of becoming customer focused, flexible and visual at the early stages of an engineering project. Project sponsor: (Appendix A: NNE Pharmaplan, 2008, pp.9)
9.2.1 The Motivation for the Configuration Project

NNE Pharmaplan had a problem with its work methods. The traditional work methods of NNE Pharmaplan’s architects were often outshined by the work methods of competitors. This made NNE Pharmaplan look old-fashioned and inefficient. The reason was that some of the architects in NNE Pharmaplan used the same work methods that they had used when they worked for Novo Nordisk. They applied traditional work methods (sketches and so on), and when they had developed plans and scenarios, they went through them with the people at Novo Nordisk: they made notes, and then they had to go home and make the corresponding corrections to the proposed solutions and plans. When they returned later on with the adjusted plans and solutions, they discovered consultants from a competitor, and afterwards they heard that the competitor could create and present one scenario after the other by using a simple Microsoft based IT-tool, indeed they did it together with the client. The competitors were able to make a lot of progression in a simple afternoon session while NNE Pharmaplan had to plan week long sessions to reach the same result. Domain expert A: (Appendix A: NNE Pharmaplan, 2008, pp.23)

The money for the VisCon project was driven by the sales process. In NNE Pharmaplan the sales process is perceived a bit broader than in other companies. In NNE Pharmaplan the sales process typically also encompass the work carried out when making a conceptual design for the customer. A conceptual design is typically ½ % of the total investment in a new facility, sometimes even less. If the conceptual design is carried out to a satisfactory level for the customer, the possibility rises of the customer coming back and asking for a basic design, and then a detailed design. It is in the later design phases that the business is for NNE Pharmaplan. In this way, making a good CD is often a sales process in itself. User: (Appendix A: NNE Pharmaplan, 2008, pp.42)

“It was a big motivational factor for us that we could get a tool that could enable us to make better conceptual designs. In many years we have been oriented towards communication as graphical as possible. In other words using as little text as possible, and as many illustrations as possible – because the customers are often better at understanding illustrations.”

User: (Appendix A: NNE Pharmaplan, 2008, pp.42)

In other words, the VisCon system was meant to be a visual sales support tool, a presentation tool or more simply, a tool to impress the customers of NNE Pharmaplan. Project sponsor: (Appendix A: NNE Pharmaplan, 2008, pp.14)

“It had something to do with that we had to go out and market ourselves. That was the idea from the beginning, and why we got funded in the first place. It [VisCon] was supposed be used as a part of the sales process.”

User: (Appendix A: NNE Pharmaplan, 2008, pp.40)

The aim was to be able to quickly configure a facility in the conceptual design phase by involving the customer in a series of workshops, and afterwards, the project was handed over to the traditional conceptual methods: To quickly visualise for a customer how his facility would look like or could look like. This was vital as many of NNE Pharmaplan’s customers, or the people that NNE Pharmaplan had the opening dialogue with, did not have a good visual understanding of what a given facility would look like. From that angle, VisCon was a tool to impress the customers– it did not necessarily illustrate 100 % correctly but it could open doors regarding the customer. Domain expert B: (Appendix A: NNE Pharmaplan, 2008, pp.54)
The tool clarified the scope but it did not necessarily organise the work to come. Project sponsor: (Appendix A: NNE Pharmaplan, 2008, pp.10) The tool aimed at a delicate balance between configuring a good enough solution but without using more manpower than could be forfeited if the customer did not wish to continue the project. One must not waste too much work on the solution. A controversial point of view in the conceptual design phase was that a conceptual design constitutes a basis for two things. It both forms a basis for making a decision and it forms a basis for the following design work in the next phases. Project sponsor: (Appendix A: NNE Pharmaplan, 2008, pp.10):

“With that [the duality of the conceptual design] in mind, I think, that we have made a reasonable compromise with VisCon.”

Project sponsor: (Appendix A: NNE Pharmaplan, 2008, pp.10)

One of the biggest challenges in making a conceptual design for a new customer is to get a shared image of the project. Images are easier to understand than clear text. Research proves that if information is presented orally, people remember about 10% tested 72 hours after exposure. That figure goes up to 65% if you add a picture. Apparently one of the reasons that text is less efficient than pictures is that the brain sees words as lots of tiny pictures. Data clearly shows that a word is unreadable unless the brain can separately identify simple features in the letters. (Medina, 2008)

The challenge of creating a common image and perception of the project was particularly difficult, if NNE Pharmaplan was not familiar with the customer, and had not executed projects with the customer before. Presenting diagrams, technical drawings, sectional views, plan drawings, and other technical specifications to the customer did not help. If the customer was not accustomed to thinking in that language and working with that kind of design documentation, he could not imagine what the plant would look like. Domain expert A: (Appendix A: NNE Pharmaplan, 2008, pp.24)

A customer typically knows his own production facilities. At home, he might already have something almost similar to what he wants. Often, it turns out that the layout must be rearranged, and the end result turns out to be a different product. Nevertheless, the customer has some images of a running production facility in his mind, and ideas about what the new project should be able to do. In this case, it is a question of retrieving the technical specifications which constitute the foundation for translating the project into specific images - images which the customer can relate to his daily execution of production and work flows. This is a relatively abstract exercise. It includes involvement of many different disciplines. For instance, equipment cannot be placed in front of doors and windows. There is relevant input from a lot of different disciplines – logistics, capacity analysis, process analysis, building design, mechanical design, space management, and others. The more information you are able to visualise and put into a configurator early in the process the better. It is easier to give an estimate on something that looks approximately like the end product. It might not end up looking like that, but at least there is something to work with. Domain expert A: (Appendix A: NNE Pharmaplan, 2008, pp.24)

“Starting to close discussion one after another, so you haven’t everything open for discussion, but you can quickly zoom in on where we have the challenges in a given project. Known stuff as making cold water, hot water, and WFI systems and stuff like that... it is rarely those things you are focusing on. Then you can make decisions, allocate areas and volumes for it, and then zoom in on the primary workflows around the process, and pick the equipment.”

Another driver for this project was a fixed price competition where you lock the price before starting the work. NNE Pharmaplan had not really applied this strategy before. As company, NNE Pharmaplan had been accustomed to using time and material to make a price. Manager: (Appendix A: NNE Pharmaplan, 2008, pp.33).

“There is never a fixed market price for a conceptual design, and we have always had an inclination to come to heel, and work by hourly rate for new customers.”

Manager: (Appendix A: NNE Pharmaplan, 2008, pp.33)

Although new customers often prefer a fixed price on conceptual design, they still ask what the hourly rate is, and there a lot of the motivation is lost. So the concept of producing multiple scenarios for a fixed price and using the money saved by the configurator seems too visionary here


**Standardisation of Knowledge**

The aim for VisCon was to formalise knowledge about the relation between capacity and price. Furthermore, the aim was to boost the modular engineering approach by moving the structural decomposition of a facility into modules into the early stages of the conceptual design phase of the engineering project. This was important since the structure of the facility was already defined in the CD phase of a project, and consequently, a big share of the total investment cost was disposed here. In other words, as the foundation of the project was made in the conceptual phase, it was important to make the right decisions in that phase. The foundation was of course adjusted as the project progressed if the scope is changed or adjusted. Domain expert A: (Appendix A: NNE Pharmaplan, 2008, pp.20)

Furthermore, a strong motivation for the VisCon project was to crystallise product knowledge. The foundation for this was already made in the preceding PhD project about modular engineering. There were several aims. One was to crystallise some of the work that was made during the modular engineering project in relation to better practices and technology groups. Another was to implement what was already developed regarding modular engineering, to get the knowledge synthesised and accessible in the front-end of the projects of NNE Pharmaplan. Domain expert A: (Appendix A: NNE Pharmaplan, 2008, pp.23)

VisCon was intended to be a meta-configuration system, and the result is also best described as a low level meta-configuration system - at least compared to the very complex meta-configurator at GEA Niro. The configuration system at NNE Pharmaplan does not contain knowledge about unit processes, components, and functionality. Nor does VisCon prevent engineers from making the wrong decisions. VisCon is merely made to support the communication with the customer. The visual configuration tool is meant to show the scope for a facility project so that the customer feels well supported and is given a good basis for the decision to proceed or not.

A decisive difference between Viscon and other tools in the engineering world is that VisCon is intended for conceptual design. VisCon clarifies the scope but it does not necessarily organise the work to come. Project sponsor: (Appendix A: NNE Pharmaplan, 2008, pp.10) That is why it is not crucial if a certain process is formalised and implemented in VisCon. If the scope is fixed, there can be different ways to reach the final result, if it is decided to proceed. Project sponsor: (Appendix A: NNE Pharmaplan, 2008, pp.10)

VisCon also supports formalisation at NNE Pharmaplan. It provides the engineers in the conceptual design phase with a tool to illustrate the scope of a new facility in a quick fashion by using a database of known elements and modules but there are no procedures on how you should
use the system. In this way VisCon contributes to formalising knowledge regarding NNE Products while keeping a non-formalised process concerning how it is used.

“I agree with you in, that it is contributing to formalising our product knowledge, but keeping an open process concerning how we use it - [it is] less locked than others.”

Project sponsor: (Appendix A: NNE Pharmaplan, 2008, pp.9)

Skilled process engineers must operate the tool in the front line, and interface with the customers’ process engineers. The tool provides the engineers with the possibility to meet the customer prepared with a lot of extra experience in their pockets, and with quick access to knowledge concerning for instance how much space is needed, the dimensions of the equipment, what it costs. In that way the engineers can create different scenarios on an informal basis. Domain expert A: (Appendix A: NNE Pharmaplan, 2008, pp.25) Thus, the engineers at NNE Pharmaplan can quickly create several scenarios. Domain expert A: (Appendix A: NNE Pharmaplan, 2008, pp.25) This point is also supported by a specialist, who frames it in the following way:

“It is necessary to have a big driver’s license to drive VisCon as it is now... or else there should have been more development on [it] - an expert system where you got more information about the modules, and the contexts they can be used in. In that way, you could have had pre-configured configurations that you could have chosen amongst.”


A more sophisticated configuration system would require that we put more knowledge on functional and component structures of each module into VisCon. Instead of configuring a bioreactor solution, you would choose among different types of reactors, and configure the bioreactor according to your current context. However, although with some extra effort it would be possible to reach that level of detail, we decided to keep a high abstraction level, as the project sponsor below very nicely frames it with reference to Clausewitz (1873).

“We definitely belong to the latter, where the soldiers have to think, and take responsibility.”

Project sponsor: (Appendix A: NNE Pharmaplan, 2008, pp.12)

The project sponsor refers to countries where soldiers do not act autonomously and have to follow the chain of command versus those countries where soldiers can act as self-contained units.

In general, VisCon supported the standardisation of process knowledge. It has already been observed that we intended to keep the process of using the system as open as possible. Of course the flexibility of the work processes was limited due to the product knowledge implemented in the system. For instance, if the correct modules were not implemented, the system would not be fit for use in the given context. However, a CD which is produced at NNE Pharmaplan’s office in France will look different than a CD made in Denmark. User: (Appendix A: NNE Pharmaplan, 2008, pp.51)

“It will never pay to standardise the process because the important thing is to, each and every time, consider and optimize from your current situation, and that limits standardisation.”

User: (Appendix A: NNE Pharmaplan, 2008, pp.51)

In conclusion, the expected benefits of the VisCon project were:

- A visual sales tool.
• A fixed price competition.
• A tool for calculating prices

The realised benefit of the VisCon project was:

• A visual sales tool which improved communication with customers

In order to be fast and agile when making scopes with a customer and in order to create a shared image fast with the customer, NNE Pharmaplan chose to standardise product knowledge. How the configuration system should be applied, and the business process was left open however.

9.2.2 Barriers for the Configuration Project

Two important processes that could be barriers to the knowledge elicitation process were identified in section 7.2:

(i) Making tacit knowledge explicit.
(ii) Establishing consensus about knowledge.

In the following two sections these two processes at NNE Pharmaplan will be analysed.

Explicitness

Normally, making tacit knowledge explicit is difficult. An obvious explanation is that engineers try to protect their knowledge, because they feel that knowledge is power. This is described in Lightfoot (1999), who calls them the unwilling experts. However, at NNE Pharmaplan this did not seem to be the case:

“From time to time the story about specialists that try to protect their jobs by not sharing their knowledge is brought up. I at least got a couple of observations that dismissed this.”

Project sponsor: (Appendix A: NNE Pharmaplan, 2008, pp.13)

The author of this thesis was knowledge engineer on the VisCon project and both guided the development of the configuration system in the right direction and implemented knowledge into the knowledge base. A large team of specialists and domain experts supported me when I elicited knowledge.

Naturally, some experts did not like the project, thought it was a waste of time, or they could not see advantages and benefits. Nevertheless, they never tried to derail the configuration project by not cooperating and not sharing their knowledge. Most of the time, the hardest problem was to gain access to the experts because they were busy. It would take time to get to them. As long as you were able to ask the right questions which were intriguing or interesting for the experts, they were usually willing to help. If you are a knowledge engineer in a company like NNE Pharmaplan, it definitely helps if you have some basic technical understanding, and if you are able to ask interesting ‘what if’ questions. As was the case with the knowledge engineers of GEA Niro, putting tacit knowledge into words was not a problem.27

Consistency

Creating consist knowledge was a challenge in the configuration project at NNE Pharmaplan. Often there were various suggestions to how a specific module should be standardised, and all of

27 This is based on my own observations
the suggestions were equally true. When the team implemented a new process module to the knowledge base, we often met different opinions and views on how it should be done in terms of attributes, rules, etc.

Knowledge engineers without domain knowledge find it difficult to settle such discussions, and then translate the knowledge into an analysis model. In this case, instead of trying to make standardised solutions, we implemented all the variants we could identify into the configurator. We started by implementing a single solution. When a user then suddenly requested a different solution to the chemical unit operation, we implemented that as well, and the knowledge base grew. The users of VisCon now had two solutions to choose from for that given chemical unit operation.

Instead of narrowing down the solution space of NNE Pharmaplan, it was kept open. Of course this required that it was possible to create consensus on the specific modules. This was never a problem, however, as the visual configurator worked at a very high level of abstraction thus making it difficult to identify details that you could disagree upon.

There is nothing in the NNE Pharmaplan case which contradicts the observations in the GEA Niro case. Accordingly, the following model still stands.

**Figure 9-4: Knowledge elicitation at GEA Niro**

In the VisCon project, we did not start the fight of establishing consensus regarding standardised solutions. We simply did not need to. However, the issues described at the GEA Niro case would most likely apply if we had had to. If we had faced the problem of establishing consensus around standardised solutions, Figure 9-4 would no doubt be an accurate description of the situation at NNE Pharmaplan. Like at GEA Niro, the specialists at NNE Pharmaplan had very different backgrounds and opinions about what a standardised solution should look like and how it should act. As we did not try to establish consensus and consistency, the knowledge elicitation process at NNE Pharmaplan can best be characterised as illustrated in Figure 9-5.
9.2.3 Understanding the Configuration Project at NNE Pharmaplan

NNE Pharmaplan set out with three goals: to make a visual sales tool that could involve the customer; to enable easier price calculation of API facilities; and, in the long run, to enable NNE Pharmaplan to compete with fixed prices on conceptual designs of API facilities. However, NNE Pharmaplan only realised the first goal. This is not due to lack of ambition, it is more the other way around. Focus on delivering customer-oriented or even customer-centric engineering services is very ambitious. Making this configuration project was a big step toward delivering engineering services in a new way:

“It is really our industry’s first step toward something which could become user-driven innovation. I would not go as far as saying it already is user-driven innovation, but at least there is a common platform that enables user-driven innovation. Until now we have called it a dynamic interactive customized design tool. The outcome is so realistic that the customer is able to affect the design, so it feels right.”

Project sponsor: (Appendix A: NNE Pharmaplan, 2008, pp.15)

The configurator of NNE Pharmaplan was developed to support visual communication with the customer. Therefore the configurator does not have advanced and detailed knowledge about concepts and components. The visual configurator has knowledge about the size of the module in relation to the capacity. The configurator at NNE Pharmaplan has no detailed knowledge on the product structure, nor has it detailed knowledge on the function structure of the product. Thus it is a meta-configuration system or even a low-level meta-configuration system.

Furthermore, another goal was to implement price calculations into the configurator as well. This would be adding a layer of knowledge, and the knowledge pool would become more detailed. As a consequence, the product knowledge implemented in the system would have to become more
specific and formalised. Consequently, the price calculation data stiffened the configuration system, and made it inflexible.

The solution space of NNE Pharmaplan is much larger than the solution space of GEA Niro. The scope is vast. It is, however, restricted to the pharmaceutical, the biotechnological and life science equipment. A big difference from GEA Niro is that NNE Pharmaplan does not have a regular production or manufacturing line to consider. NNE Pharmaplan is a pure custom producer - an engineering firm that manufactures design specifications, and supervises the construction on the site. When a facility has been constructed, NNE Pharmaplan is responsible for getting the facility validated and putting it into operation.

If NNE Pharmaplan wishes to develop a more advanced configurator which can give more specific outputs, the scope for the configurator must be narrowed down. If NNE Pharmaplan has the ambition of producing quotation material like GEA Niro, the scope of the configurator must be narrowed down to a specific type of pharmaceutical or biotechnological facility, or even better to specific process modules.

Some process modules are more stable over a period of time than others. For example, take the Purified Water Module which is implemented in VisCon and illustrated in the Figure 9-6.

**Figure 9-6: Purified water module**

The purified water module is normally a black utility module, and it is not critical to the manufacturing of the active pharmaceutical ingredient (API). The module is a relatively stable product which NNE Pharmaplan often buys as an off-the-shelf module from an external supplier. The task at hand at NNE Pharmaplan is to determine the needed capacity and the distribution of clean steam to the facility. When that has been carried out, the only remaining task is to select the right model from a trusted supplier. As the module is relatively stable, it is possible to add more knowledge to the module than compared to other not so stable or custom built modules. In this way it is possible to develop a more advanced configurator.
The motivation for the configuration project at NNE Pharmaplan was to formalise product knowledge while keeping an open process concerning the use of the configuration system. In NNE was never the ambition to formalise the engineering process. The tool was kept as flexible as possible. There is no reference to a formalised procedure that describes the use, nor is such a procedure implemented in the system. So the scope for the project was to make a system that could support decisions in the early engineering phase without necessarily being an organising tool for the later engineering phases.

The elicitation of knowledge in the VisCon project was disturbed by the process of making knowledge consistent. Getting the domain experts to share their tacit knowledge was not a problem. However, getting the domain experts to reach consensus about the looks and description of a given module proved to be more difficult. In NNE Pharmaplan the solution was to implement different solutions rather than to try and settle the discussion. This resulted in many variants, but it also strengthened the visualisation possibilities as more equipment was implemented in the configurator.

In chapter 7 we saw an analytical model of configuration projects in engineering companies. The analytical model for the configuration project at NNE Pharmaplan can be seen in Figure 9-7.

Figure 9-7: Analytical model for understanding the configuration project at NNE Pharmaplan

In order to understand why it was difficult to implement more formalised knowledge into the configuration system, and thus why price calculation and modularisation had to be skipped, we must understand what kind of organisation NNE Pharmaplan is. In section 7.4, NNE Pharmaplan was described as an operating adhocracy. That is, however, not the whole truth. In fact, NNE Pharmaplan is an operating adhocracy which is becoming a professional bureaucracy because the company is trying to seek out a more stable environment and focus its engineering services. Furthermore, because of the increasing size of NNE Pharmaplan, it has been necessary to create more formalised structures in the departments of accounting, finance, procurement, and engineering services. However, the primary coordinating mechanism at NNE Pharmaplan is still mutual adjustment. This suggests that it is an operating adhocracy. The best description of the organisational structure at NNE Pharmaplan is made by using the operating adhocracy. The environment of NNE Pharmaplan can best be described as being both complex and dynamic, which, according to Mintzberg (1993), calls for an organic and decentralised structure.
According to section 7.3.2, the following issues are expected in a configuration project in an operating adhocracy: Difficulty to free resources to a configuration project; a slow and painful road to agreement on favoured solutions; and, finally, difficulty in standardising and thus formalising knowledge as the structure relies on mutual adjustment rather than standardisation of skills as coordinating mechanism. All three issues can be observed in the NNE Pharmaplan case.

At times, it has been very difficult to free resources for the VisCon project. Internal projects in NNE Pharmaplan have to compete with paying projects of clients. As a consequence, to make them attractive, internal projects are funded with money to pay the employees the external fees. In this way, the employee can contribute to the project and still reach the level of invoicing he has to. At the end of the day, if both an external project and an internal project lack resources, the external project has a higher priority. In NNE Pharmaplan we encountered this issue when acquiring data for the price calculation, which was the task that took the best part of our time. It manifested itself in longer lead times for the contribution and more postponements due to more important tasks. It should be noted that the VisCon project took place at a very busy time for NNE Pharmaplan. They took in many new clients, new subsidiaries and they acquired Pharmaplan. Naturally, during such a period, it is more difficult to get confrontation time with the specialists.

According to section 7.3.2 it should be a slow and painful process to agree on a favoured and standardised solution. However, we bypassed this problem in the VisCon project by not trying to formalise standardised solutions. Instead, we implemented all the different solutions that we could identify. If a solution was requested multiple times, we made the solution more intelligent by adding scaling according to capacity or price calculation.

However, some observations confirm that we encountered difficulties when we tried to reach consensus regarding approaches and standardised solutions. During the three years which the project lasted, NNE Pharmaplan’s Method and Systems department was responsible for the development and implementation of cross disciplinary methods and tools in the organisation. A standardised solution often involves different technical disciplines and compromise on some areas for the sake of the greater whole (the question of a local/global optimisation). The department had only a small voice in the rest of the organisation and they were often accused of being too theoretical. Thus, the work of the department was not recognised. It was very difficult to reach consensus on new approaches and methods, and for that reason, the department slowly deteriorated.

Luckily, the VisCon project did not encounter this problem. The project had a narrow scope of users (we focused on the CD department), and furthermore, eventually, we created a very low level meta-configuration system, thus escaping the need to establish consensus regarding the knowledge implemented in the system.

The operating adhocracy is one of the most politicised types of organisation described by Mintzberg (1993). The organisation is organic and decentralised where the preferred coordinating mechanism is mutual adjustment, and the operating adhocracy gives power to experts whose knowledge has been highly developed through training programs. Whereas the professionals in GEA Niro can operate on their own, the specialists at NNE Pharmaplan combine their efforts in cross disciplinary teams to solve the needs of a specific client. This should give rise to difficulties when one tries to formalise standardised solutions. Like in the professional bureaucracy, the professionals in an operating adhocracy resist rationalisation and the division of their work into simply executed steps. For this reason, decision processes are long with several meetings due to the politicised nature of the professional adhocracy. Again the VisCon project avoided this by using a ‘don’t ask’ approach. Decisions were simply made without attempting to reach consensus. On the
other hand, this was only possible because of the simple and uncomplex nature of the knowledge implemented into the system.

As with GEA Niro, getting the domain experts to share their knowledge was relatively uncomplicated, and as we didn’t try to reach consensus and establish consistent knowledge, the knowledge elicitation process was as illustrated in Figure 9-8.

Figure 9-8: The knowledge elicitation process at NNE Pharmaplan

9.3 Summary

NNE Pharmaplan has developed a low level meta-configurator. They have chosen to leave the application of the configurator open to the users while only formalising product knowledge to a low degree. The work at NNE Pharmaplan has lead to a possible new business process that involves the customer in the conceptual design by utilising configurable 3D graphics. Until now the users of the system have not adopted the configurator on its premises. Instead, they use the configurator to illustrate scenarios rather than to co-develop the scenarios together with the customer as originally intended.

The solution space of NNE Pharmaplan is much larger than the solution space of GEA Niro. As a consequence, it has not been possible to develop as advanced a configurator as the one developed at GEA Niro. Consequently, NNE Pharmaplan has chosen to facilitate an open solutions space by making it easy to implement new modules. This is possible because they have implemented a low degree of knowledge on each module. This allows the catalogue of equipment to grow rapidly and thereby in time it will provide great flexibility for the staff of users. As a result, the configuration team has diminished resources spent on establishing consensus. Everybody can implement their special variant.

If the NNE Pharmaplan wanted to extend the scope of the configurator either by implementing more knowledge on each piece of equipment or by covering larger parts of the conceptual design process, two big challenges would lie ahead: (i) The knowledge at NNE Pharmaplan is not consistent, and it would be difficult to reach consensus among the specialists in the operating core.
(ii) The solution scope has to be closed and reduced or else it would be very ambitious to implement and maintain the vast amount of knowledge concerned.
Part IV: Discussion and Conclusion

“All generalizations are dangerous, even this one”

Alexandre Dumas fils
10 Discussion

This chapter consists of a discussion of the thesis, which is divided into four sections: (i) Discussing the main elements, (ii) Discussing research questions and results, (iii) What should in hindsight have been different, and (iv) Contributions to configuration research.

10.1 Discussing Main Elements

This thesis has four elements: (i) Literature, (ii) methodology, (iii) theoretical work, and (iv) empirical work. In the following section, strengths and weaknesses of these four elements will be discussed.

10.1.1 Literature

Almost all researchers begin by looking into existing literature with the purpose of forming a basic understanding of a given research area and its related problems. The literature presented in chapter 2 shows important contributions to configuration literature and together with the summaries of the literature from different research communities in section 1.2 this forms the theoretical foundation for this project. From this foundation, the thesis has evolved.

Initially, the perspective was on the different research groups. The most active research groups within the field of product configuration in relation to this project were identified and a description of their work can be found in section 1.2. The four groups were: (i) The Technical University of Denmark, (ii) Helsinki University of Technology, (iii) Forza and Salvador, and (iv) The University of Klagenfurt.

Citations in these papers guided the selection of publications to form the literature review in chapter 2. Much literature has been omitted in this thesis either because it was outside the scope of the project or because it would take up too much space.

Reading literature has been a continuing activity which ended at the end of summer 2008. Literature published later than the summer of 2008 has generally not been incorporated. However, there are exceptions to the rule.

Retrospectively, it would have been desirable to look further into the literature of knowledge management, especially literature which focused on formalisation of knowledge, and knowledge elicitation. This was evident when the empirical work was collected and the literature search had formally ended. Such literature would have strengthened the understanding of barriers to developing configuration systems and, moreover, the model for configuration readiness would probably have improved by such a study.

However, the involvement of Mitzberg’s ‘Structure in Fives’ to understand organisation structures turned out to be very rewarding and central to the answering of research question 4 and research question 5. Also the use of Hubka and Eder’s ‘Theory of Technical Systems’ turned out to be very rewarding in respect to establish a clarity of concepts, and being able to answer research question 1, research question 2, and research question 3.

10.1.2 Methodology

The scientific point of view in this thesis is described in chapter 3. According to Fuglsang & Olsen (2004), there are three lines of scientific theories: Demarcationisms, scientific realism, and complex realism. The methodological considerations were initiated with reflections on which of the three lines of scientific theories were suitable for understanding how configuration projects are
carried out in engineering companies. I do believe that there is a there is an independent natural and social reality to be studied. We might not be able to understand or observe it fully, but the reality is independent, and mechanisms, causal potentials and tendencies can be used to explain models in configuration research. This is in opposition to the methodology of complex realism such as social constructivism. For this reason, this line of theory is ruled out, although one must recognise the importance of looking into the influence of social factors eminent in complex realism. The use of tools, explanation models, and the creation of new knowledge depends on the context in which they are applied. This is in opposition to demarcationism and positivistic notions. Correspondingly, the research of this thesis has been conducted from a critical realist perspective which lies in the area of scientific realism. As it turns out, the methodological approach in this thesis fits well into the frame of critical realism.

According to critical realism it is not possible to establish absolute truths. All knowledge is fallible even when an independent reality exists. This shines through in the way the conclusions are formulated, and accordingly, this thesis has as overall goal of understanding and establishing good reasons to believe. Indeed, an important contribution to the research area which this thesis gives is the establishment of a coherent framework of clarified concepts which can be used to understand configuration, different kinds of configuration systems, and prerequisites for configuration. Indeed, this is well aligned with critical realism.

Retrospectively, using different research methods as advocated by critical realism could have strengthened this thesis. Semi-structured interviews are the empirical basis of this thesis, and the validity of my conclusions could have been strengthened by including other research methods such as quantitative data collected through questionnaires. Qualitative research often aims at understanding underlying reasons and motivations, thus providing insights into the setting of a problem, and generating ideas. If the timeframe had not prevented it, supporting the conclusions of this thesis with quantitative research would probably have been rewarding.

10.1.3 Theoretical Work

The theoretical work has evolved through an iterative, dialectical process of reading literature, writing, reviewing, and discussing matters with Jørgen Lindgaard Pedersen, my supervisor, and other fellow researchers.28

The purpose of my theoretical work is twofold: (i) To establish a clear frame of reference for configuration, configuration systems, products and other related terms, and (ii) to explain observations that are made in the case studies of engineering companies. Chapter 4 establishes a frame of reference and the definitions in that chapter are used to understand how configuration systems differ (chapter 5), what the prerequisites for configuring are (chapter 6), and, finally, preliminary thoughts on what configuration in engineering companies is (chapter 7).

The frame of reference in chapter 4 is constructed around definitions of the following key concepts: Product, product model, configuration system, configuration process, and configuration. The key concepts are theoretically defined by the use of relevant literature. The definitions are connected in a model of the total configuration system which is based on Hubka & Eder’s (1988) theory of technical systems. This theory is a total concept theory for engineering design, and the strict definitions and rigorous approach of Hubka & Eder are inspiring. However, this basis of the frame of reference has shaped the frame. Had other theories been used as a basis, the frame of

28 In this connection I would like to express gratitude to Kasper Edwards, Anders Haug, and Gudmundur Oddsson.
reference would have most likely looked different even though the key concepts would in all likelihood have been defined in a similar fashion.

The typology developed in chapter 5 is based on Hubka & Eder’s (1988) description of a product but it also corresponds with the frame of reference in chapter 4. The way a product is described is in line with the engineering design research community and design science’s most acknowledged theories. This definition forms the basis for much research carried out in the area of engineering design. It seemed natural to continue on this path by establishing the frame of reference. Hubka and Eder identify different abstraction levels in order to describe a product. The abstraction levels are adapted to identify different types of configuration systems. Before this, the abstraction levels are mapped to other research to check whether they form an appropriate description for the purpose of describing different types of configuration systems. Had I chosen a different approach, either to subdivide configuration systems by using e.g. the process as distinguishing factor; or by using another way of describing the product, the typology would have looked differently. However, the theoretical work of chapter 4 and 5 would then be disconnected.

How can configuration readiness be estimated? This question triggered the creation of a model for prerequisites for configuration (chapter 6). It quickly became evident that this question is central, when companies consider the possibilities of product configuration. The prerequisites for configuration have been developed by retrospective analysis of case material from the PETO project. Accordingly, the model is not tested empirically.

Chapters 4, 5, and 6 forms the theoretical foundation for the two case studies of engineering companies carried out in this thesis which is described in detail in chapter 7. First, possible motivational factors for implementing configuration systems in engineering companies are identified. Secondly, possible barriers for implementing configuration systems in engineering companies are discussed. Finally, a model for understanding the development and implementation of configuration systems in engineering companies is presented as a synthesis of the theoretical work. The interaction between three important actors in configuration projects is described with the aid of Mintzberg’s (1993) ‘Structures in Fives’.

The question arises: Do the models capture all the necessary elements? The models are logically consistent and contribute to an understanding of configuration projects in engineering companies on the premises of the chosen theories. Even though the choice of theories is estimation, it constitutes a logical and consistent foundation to analyse configuration projects in engineering companies. Of course, as the models are sensitive to the choice of theories, the models as well as other result in the empirical study would have been different if the choice of theories was different. In similar fashion the choice of theories would have been different if the meta-question or the subject was different. The model does not capture technological difficulties in building a knowledge based system, nor does it capture psychological aspects of the interpersonal relations between users, knowledge engineers, and domain experts. Furthermore, there is no economical evaluation of projects in engineering companies. The study does not show when benefits surpass the costs.

10.1.4 Empirical Work

The empirical sources used in this project are primarily interviews and observations. Only the interviews have been systematically documented. The noting down relevant observations and new insights at NNE Pharmaplan has been done thoroughly but in a fairly unstructured manner. However, some of these observations have given rise to ideas and thus facilitated the development of the models presented in this thesis.
Nine interviews with employees from two engineering companies were conducted during the winter of '07/'08. The interviews were semi-structured (thematic interviews) and followed the interview guide presented in section 7.4.1. The interviews all lasted approximately an hour, and covered different phases of the configuration project in the company: (i) Vision, (ii) development, and (iii) operation. All interviews were transcribed for later analysis.

The models from chapter 4, 5, and 7 served as my frame of reference during the interviews and the analysis of the transcriptions. Being too prepared and focused on the ‘frame of reference’ can result in overlooking and not picking up other relevant and interesting topics. This must be an area of focus. However, the obvious advantage being well prepared is the possibility of going into detail in certain topics, as this makes the interviewer better prepared and able to pick up interesting topics during the interview.

The interviewees had different backgrounds (educationally), different positions in the company (operating core, technostructure, middle layer, strategic apex), and different roles in the configuration project (project manager, domain expert, user, knowledge engineer). This gave the broadest possible view on the configuration projects in the two cases with the possibility of analysing the cases from different points of views. The question is whether more empirical evidence should have been collected, and whether this would have changed the conclusion.

The number of interviews is fairly low, and so is the number of case companies. As far as covering different layers and project roles in each case company, the interviews carried out are sufficient. More interviews could have strengthened the thesis as they would possibly have given a more thorough picture of the case companies, however.

In the same way, introducing more case companies would have strengthened the validity of the conclusions of this thesis. That is, if they had conformed to the conclusion. However, the timeframe limited the number of case companies.

Another way of strengthening the validity of the conclusions could be triangulation, i.e. to support qualitative interviews with quantitative data such as questionnaires. Qualitative research often aims at understanding underlying reasons and motivations, provide insights into the setting of a problem, and generate ideas for later quantitative research. If it had been possible it would have been interesting to support the conclusions of the thesis with quantitative research. This however was not possible in the timeframe of this project.

The interviews created the foundation of answering the meta-question of this thesis: “How are configuration projects carried out in engineering companies?” The interviews were the key instigators which pushed the project forward providing new insights into motivations and barriers for configuration projects in engineering companies.

10.2 Discussing Research Questions and Results

This thesis set out to answer the somewhat complex meta-question: “How are configuration projects carried out in engineering companies?” The question was motivated by the observation that engineering companies showed an interest in developing and implementing product configuration systems which, however, in theory, better fit the more standardised worlds of manufacturing. The meta-question then leads to the following five research question:

**RQ1:** How can the concepts of a product configuration be understood?

**RQ2:** How can different types of product configuration systems be distinguished?

**RQ3:** What are the prerequisites for configuration?

**RQ4:** What is the motivation for configuration in engineering companies?
RQ5: What are the barriers for configuration in engineering companies?

The meta-question will be discussed in section 10.2.6.

10.2.1 Research Question 1

“How can the concepts of a product configuration be understood?”

This question has been answered by the establishing of a frame of reference of product configuration in chapter 4. The frame of reference together with the definition of key concepts is the foundation for understanding product configuration systems. The conclusion of chapter 4 is that the interaction between product configuration systems, and their environment, and the configuration process can be illustrated as in Figure 10-1.

Figure 10-1: Total product configuration system

The total configuration system describes the operators of the total configuration system as all the sums of operators: ΣUsers, Product configuration system, and ΣActive environments. Active environments can be other IT-systems or environments such as an organisation. Above the active environment is illustrated as the organisation. All operators in the total configuration system have an effect on the configuration process. The model of the total configuration system is solely a theoretical work. The illustration of the total configuration system is heavily inspired by the ‘The Theory of Technical Systems’ by Hubka and Eder (1988).

The framework of configuration offers the following definitions of basic concepts to describe a configuration system in a company.
• **Technical systems** are objects, products, things, machines, implements, technical objects, etc. which are made by humans to fulfil a specific need.

• **A product model is an abstract** representation or description, describing (a) the structure of P and (b) facts, object, concepts and properties that are relevant in any life cycle phase of P. P can be a single product or a family of products. A product is a thing, a substance or a service produced by a natural or artificial process.

• **A product configurator** is a software-based expert system that supports the user in the creation of product specifications by restricting how predefined entities (physical or non-physical) and their properties (fixed or variable) may be combined

• **Configuration process**: To combine predefined entities (physical or non-physical) and define their variable properties, while obeying constraints and legal interface combinations in a way that satisfies given requirements.

• **A configuration is the output** of the configuration process, e.g. a description of the component structure of the product and any connections between the components in the set or a description of inconsistencies in the requirements.

An interesting implication of this model is that it is not possible to look at the development of a product configuration system as being a merely a technical development project. The configuration process can not be designed, it can only be supported. Thus, starting a configuration project by redesigning the process, and modelling the as-if and to-be state of the configuration process does not per se lead to a successful configuration project.

The work made in creating the frame of reference is purely theoretical. It is based upon acknowledged papers and books from the configuration and design science community. The framework presents coherent definitions on key concepts related to configuration, and it offers an explanation of how the key concepts interrelate.

The purpose of the frame of reference is not to establish the best available description of configuration related terms nor is it to give the best or most acknowledged definitions. The purpose is to make the meaning of key terms clear, and to make it explicit how configuration systems and their connection to the process and other systems are perceived in this thesis. Research in configuration has suffered from ambiguous definitions and concepts. The frame of reference has been my way of avoiding the pitfall of ambiguity. In that way it has been possible to use the terms consistently throughout this thesis, and hopefully it has constituted a good foundation for the generated models.

10.2.2 Research Question 2

"How can different types of product configuration systems be distinguished?"

This research question was answered in chapter 5. It is possible to distinguish configuration systems through the typology developed in that chapter. To sum up, four types of configuration systems were identified in the typology: (a) Structural validators, (b) co-design configuration systems, (c) automatic configuration systems, and (d) meta-configuration systems.

The typology was based on the product knowledge that is contained in the configuration system. Other factors could have been chosen to distinguish different types of configuration systems, e.g. the configurations systems could be distinguished by the type of business process or configuration process they support for instance. a sales configurator supports the sales process, or the customisation scope of organisation determines what kind of configuration system is suitable (this has amongst others been suggested by (Forza & Salvador, 2007)). Another method for distinguishing configuration system would be to base it on the type of knowledge-based system or
reasoning methods they use. However, at the given moment it made most sense to base the typology upon the product knowledge contained in the configuration system (see discussion in chapter 5).

Interestingly, the typology easily lends itself to normative suggestions regarding: (i) Implementation related issues, and (ii) use related issues. This is illustrated in Figure 10-2.

Figure 10-2: Implementation and use related issues.

It seems obvious that while it is relatively easy to design and implement a product configuration system which belongs to the lower part of the figure and which contains only performance, functional, or component knowledge, the complexity rises when mapping between the different kinds of knowledge is included. The reason might be that relations between e.g. functions and components are not one-to-one, but rather one-to-many or many-to-many. This results in a higher workload when implementing a product configuration system, and the reason why configuration projects fail or are delayed might be that some of the many-to-many relations have not been resolved, thus making the mapping between i.e. components and functionality complex and difficult to model.

When using a product configuration system, it is evident that the higher workload in the implementation phase pays off. By delegating a higher effort in the design and implementation phases of the product configuration system, it is possible to reduce the burden of choice on the users via fewer decision variables. This should lead to less confusion for the user (Franke & Piller, 2003; Salvador & Forza, 2004b).

Another interesting aspect of the typology is the lack of empirical proof of completely automatic configuration systems. While it is possible to identify product configuration systems in
the other categories, it is difficult to identify any projects that fit the definition of automatic configuration systems. One might suspect that the concept is a purely theoretical construct. However, the reason why we have not yet seen a completely automatic configuration system in operation is probably the high workload connected with the design and implementation of this category of product configuration systems.

In order to develop completely automatic configuration systems, the company must possess a high degree of configuration readiness i.e. formalised knowledge about the product and the process. Likewise, it facilitates the maintenance of the configurator, if there are one-to-one links between the purpose, function structure, and component structure. In most Danish companies, this would require an extensive product review.

10.2.3 Research Question 3

“What are the prerequisites for configuration?”

Interestingly, the framework for assessing process and product knowledge easily lends itself to normative appraisals regarding a configuration project. The goal is to end up with explicit and consistent knowledge concerning the product which is being configured and the configuration process it supports. Configuration ready knowledge is knowledge which is ready to be formalised; knowledge which is explicit and consistent. If product knowledge is idiosyncratic and explicit, we assume that the employees deliver the best possible product match to the customer. If the process knowledge is configuration ready implementing a structural configuration system is best. The structural configuration system provides better control over the composition of the product parts. In the same vein, the structural configuration system contains less knowledge about the relation between functional characteristics and product composition.

For instance, a company producing actuators found themselves in a situation where the development department spent too much time validating product configurations and too little time developing new products. The processes of the company were indeed both consistent and explicit leading to a configuration ready conclusion. However, the product knowledge was highly idiosyncratic although each product design decision was explicit. Initially, this led to a not configuration ready conclusion with little interest in doing formal reviews. The firm produces actuators in large quantities and subsequently wished for consistent product knowledge. However, it turned out that although the numbers were high, not two orders were the same, and the firm was thus essentially producing one of a kind. Consequently, a structural configuration system was developed to help validate products. The system was a great success and lead to a very significant rise in product quality.

The model seems logical and reasonable, and the distinction between process and product knowledge is sound. However, tacit knowledge does not seem to pose a problem in engineering companies where domain experts willingly help knowledge engineers to make knowledge explicit. So the tacit/explicit distinction does not have any implication in the cases presented in this thesis. Hence, tacit knowledge does not seem to be a large barrier for the development and implementation of product configuration systems in engineering companies. However, it must be easier to establish consensus about a company’s products, and create consistent knowledge, if explicit knowledge exists.

It is mainly product knowledge which is implemented in the configurator while the use process is partly the interaction between the actors of the total configuration system (i.e. a series of defined steps you have to go through in the configurator and the configuration process defined in the organisation). In the case of NNE Pharmaplan, it was decided to keep the use process of the system...
open, and in GEA Niro the use-process of the system was kept well defined and closed. In the former case, getting the users to use the system was difficult, whereas in the latter, there was a competing business processes.

If one follows the definition of the configuration process in this thesis, one cannot design or control the configuration process, as it would require users of the configuration system to act like machines, and this is not possible. You would have a better chance of controlling the employees in the operating core with a clear line of command, and a vertical centralised structure, such as is present in the machine bureaucracy. In a machine bureaucracy, the work of the operation core is highly rationalised, repetitive work requiring a minimum of skills, and the coordinating mechanism is standardisation of work processes. In professional bureaucracies and operating adhocracies this is not the case. For this reason, change management becomes particularly important and should be carried out from the very start of the configuration project.

The model of prerequisites for configuring helps you find out what change management tasks you face in a configuration project. If the process is highly formalised, as would be the case in most machine bureaucracies, your change management task is simple. If the process is explicit and idiosyncratic, the change management task is somewhat more complex, as you must establish consensus about a new configuration process. However, since the process is explicit, this should be a simple negotiation. In operating adhocracies and professional bureaucracies, however, it would require many meetings to obtain agreement on a favourable configuration process. Likewise, if the configuration process is tacit and consistent, the change management task is more complex than if the configuration process has already been formalised. If the configuration process is tacit and consistent, the employees would find it difficult to explain how they actually carry out configuration but they would already configure products in the same way each time, so this process would merely have to be described. If the configuration process is tacit and inconsistent, as encountered in the GEA Niro and NNE Pharmaplan, you have the most complex change management task. Professionals in such an operating core are highly autonomous and the task at hand is complex and cannot easily be broken down into a series of standardised steps. The work process depends on the task at hand, the needs of the client, and on the professionals assigned to the task. Not two professionals are alike, and each professional choose to solve the task as he thinks best given the particular task description. If he was faced with other client needs he might choose differently. Professionals in such companies resist standardisation of their work process thus making the change management task complex and hard.

10.2.4 Research Question 4

"What is the motivation for configuration in engineering companies?"

It is difficult to find a plain answer to research question 4, as the configuration projects of the two case companies has turned out to be very different from each other. Although both configurators which have been developed are meta-configurators, they are different in scope and complexity. For instance, while rules between modules have been avoided in NNE Pharmaplan, rules between standard concepts exist in the GEA Niro project. This indicates a more complex configurator at GEA Niro compared to the configurator at NNE Pharmaplan. The time and resources spent are also very different. GEA Niro started the project in 2001, and has used many resources to develop and maintain the system. The system at NNE Pharmaplan was developed in little over a year, and the resources needed to maintain the system are petite. The configuration system at NNE Pharmaplan runs with no formal budget, and the system evolves on a project driven basis.
GEA Niro had four motivational aspects for their configuration project: Preservation of knowledge; consolidation of knowledge; reduction of errors; and as the hit rate had been decreasing, more requests had to be answered. From a standardisation/customisation point of view, GEA Niro approached this by reducing the solution space of the selected product by defining standard concepts prior to implementing a configurator. This necessitated a formalisation of the process as well.

NNE Pharmaplan also had several ambitious motivational aspects at the beginning of the project: A wish to create a visual sales tool; enabling fixed prices competition (comparable to creating lower turn around time thus using less resources); tool to make price calculation easier and better (comparable to creating a lower turn around time, improved accuracy/quality by using less resources). NNE Pharmaplan fulfilled the first goal while the others were dropped in the course of time. From a standardisation/customisation point of view the motivation was to formalise the product knowledge of the modular engineering projects, while leaving the process open. Formalising product knowledge was abandoned as the solution space was big, and there was no intention of narrowing the solution space. Instead, a strategy of moving towards customer-oriented conceptual design was followed. For instance, one aim was to involve the customer in the scoping of a project through visually oriented workshops.

On a high abstraction level there are similarities between the two companies. The expected benefit of both projects was to standardise knowledge about the products in the company. In GEA Niro the knowledge was standardised to a greater detail than in NNE Pharmaplan. While GEA Niro succeeded in formalising product knowledge, formalising knowledge was abolished in NNE Pharmaplan’s most recent upgrade of the visual configuration system. From a standardisation/customisation point of view the motivation in both companies was to standardise knowledge. In NNE Pharmaplan this was dropped in the early phases of the project, while GEA Niro succeeded through the implementation of standard concepts.

It is difficult to generalize about motivation for configuration in engineering companies, as the two cases differed too much.

10.2.5 Research Question 5

“What are the barriers for configuration in engineering companies?”

With the use of configuration readiness and Haug’s (2007) model for development of configuration project, two key processes were found which are used to formalise knowledge for configuration systems. The two processes are identified in section 7.2. The two processes were:

(i) Making tacit knowledge explicit, and
(ii) Establishing consensus about knowledge, so the foundation for the configuration system is based on consistent and not idiosyncratic knowledge.

The two case studies shed light on whether these processes can be barriers to making knowledge formalised in engineering companies. The research question primarily focuses on the two first steps in the knowledge formalisation process described by Stover (2004).

The purpose of a configuration project in a company is to formalise knowledge about a given domain in the company. The knowledge engineer is responsible of developing and implementing a product configuration system that contains knowledge about a given domain as a mean to the purpose. However, the knowledge engineer is not able to accomplish this by himself. He depends on the knowledge of domain experts, as the knowledge engineer himself has no detailed knowledge of the domain. The knowledge engineer must get correct information from the domain expert, and
sometimes he is even dependent on the help of the domain expert to translate the knowledge into an analysis model. This is the first vital step - to elicit and capture knowledge about the product and processes of the company and make it explicit and consistent. The second step is to translate the information into an analysis model. The purpose of this step is to document the product model (codified knowledge) which forms the basis of the configuration system. Sometimes it is useful to transform the analysis model into a design model which can then be implemented into a configuration system as described in (Riis, 2003). Finally, the configuration system is developed and implemented. This final step is called sharing – the knowledge is now shared with, i.e. distributed to, the whole organisation through a configuration system thus transforming the explicit and consistent knowledge into shared knowledge.

The basic principles of a configuration project with the above described steps are illustrated in Figure 10-3.

Figure 10-3: Formalisation of knowledge

The simplified illustration from Haug’s (2007) thesis (see Figure 7-9) did not fully cover the problems of the VisCon project at NNE Pharmaplan. At NNE Pharmaplan, there were often various suggestions as to how a specific module should be standardised, and all of the suggestions were often equally true. As a knowledge engineer (without any domain knowledge), I found it difficult to settle discussions about modules.

In relation to engineering companies, the knowledge engineer is dependent on the domain expert to help him formalise the knowledge. As the knowledge engineer has not got sufficient domain knowledge to develop the product model of the configuration systems, he gets resources in shape of billable hours so that he can compensate the domain expert for performing the task of making the knowledge explicit and codified. The knowledge engineer is then able to translate and share the knowledge via a configurator. In order to obtain the knowledge, an agreement (formal or informal) is settled between the knowledge engineer and the domain expert. The problem is that due to information/knowledge asymmetry regarding the domain, the knowledge engineer do not know whether the domain expert has satisfied the agreement.

The two case studies proved to my surprise that converting the tacit knowledge to explicit knowledge in the knowledge elicitation process had been uncomplicated. The predominant picture of the domain experts from the two case companies was that they happily shared their knowledge, and did not mind getting involved in the configuration project. Of course, there were exceptions - a few viciously unwilling experts participated in the VisCon project at NNE Pharmaplan. The
prevailing observations are, however, that domain experts happily share knowledge, and this point is confirmed in the interviews.

A knowledge engineer from GEA Niro provided the interesting observation that this was not remarkable as the domain experts were used to share their knowledge on a daily basis when they carried out engineering projects. That might be the explanation for this observation.

What turned out to be a more difficult task was making the knowledge consistent. Making the knowledge explicit does not guarantee consistency alone. It is necessary to create consensus in the organisation about the product knowledge that forms the basis for implementation of the configuration system, and to create consensus about how the system is applied in the configuration process. In this thesis, in answering research question 5, the focus was on product knowledge, as it was mainly elicitation of knowledge in relation to the configuration system which was investigated in the interviews.

Both case studies revealed that the toughest barrier to developing product configuration systems in engineering companies concerns establishing consensus among the domain experts about the proposed standardised solutions.

On the basis of the case studies, the idealised process which is described in Figure 10-3 has turned out to be too simplified. A more suitable figure showing the involvement of the domain experts is shown in Figure 10-4.

Figure 10-4: Revised knowledge elicitation process

One of the obvious theories that describe information asymmetry is the principal-agent problem. The principal-agent problem treats the difficulties that arise under conditions of incomplete and asymmetric information when a principal hires an agent for a task. In this case the principal is the knowledge engineer and the agent is the domain expert. Still, most literature about the principal-agent problem deals with one agent and one principal. In the two case companies there were multiple agents and only one principal. Further investigation into the problem of the
knowledge elicitation process, was limited by issues of time. The conclusion must be this is an interesting area for future research.

10.2.6 Meta-question

A synthesis of the discussion above should answer the meta-question: "How are configuration projects carried out in engineering companies?" The research questions form a basis for understanding configuration in engineering companies. The sequence in which the five research questions are listed is not random. The sequence forms a research path towards understanding configuration projects in engineering companies – a path towards answering the meta-question. In similar fashion, the research questions form a set of lenses through which one can understand configuration in general and specifically in engineering companies. The answer of the meta-question should go further than the sum of the five research questions, and it should contribute to a better understanding of the motivation for and barriers against configuration projects in engineering companies.

All in all the answer to the research question is: The motivation for the configuration project is standardisation. Configuration projects are typically carried out to support the early phases of the engineering process. The aim of the projects is to standardise by offering fewer options to the customer rather than offering more options to the customers as usually is the case in mass customisation cases.

As most engineering companies are professional bureaucracies or operating adhocracies, resistance can be expected. In professional bureaucracies and operating adhocracies the operating core is normally against any kind of rationalisation of their work. The resistance would take the shape of unwillingness among the members of the operation core. They would be unwilling to reach consensus about formalised concepts or solutions. The resistance would less likely take the shape of these members professionally trying to protect their knowledge. A further challenge is that the configuration process is tacit and idiosyncratic. This burdens the change management aspect of configuration projects in engineering companies.

Although engineering companies are expected to be characterised by tacit knowledge, and it was expected that tacit knowledge should pose a problem, this turned out not be the case, neither in GEA Niro nor in NNE Pharmaplan.

10.3 What Should, in Hindsight, Have Been Different?

The present project was completed in little over four years, and much has been learned in the process. Were I to carry out a similar project today, it would have been done differently. In this section the changes to the project are outlined with the gained experience from this project in mind.

At the beginning, this project was outlined as a project that should focus on the modelling of knowledge in relation to visual configuration in engineering companies. However, as the project started and the work began at NNE Pharmaplan, it quickly became evident that the modelling of knowledge was not a big challenge in relation to the development of the visual configuration system. Indeed, tools such as the product family master plan were sufficient for the modelling of knowledge for visual configuration.

Consequently, the focus of the project changed into how and why configuration systems were applied in engineering companies. Product configuration systems had in the last ten years been applied to the more project oriented engineering companies. Often, at conferences, it would be difficult to determine why the examples presented belonged to product configuration, and why a wide variety of projects were presented as configuration projects.
The ambiguity of definitions in the configuration world underlined the need to create precise definitions of key concepts. Accordingly, much energy was put into understanding the key concepts and establishing the frame of reference before the other models could be developed. A project of today would not have to waste time on establishing such a frame of reference.

In the later phases of this project, it has been difficult to formulate problems encountered during the development of the visual configuration system at NNE Pharmaplan. Experiences and observations were registered in several notebooks. The notes made in the notebooks were not as helpful as they could have been, as it was difficult to search and extract knowledge and interesting observations from the notebooks. Using a formalised tool\(^{29}\) to handle qualitative data and in this way using a more formalised way of taking notes would have been beneficial, as it had made it possible to search the data, and work with the observations to formulate hypotheses for the case studies.

10.4 Contribution to Product Configuration Research

There are two separate contributions of research in the present thesis. Primarily, there is a general contribution to the theory about configuration in terms of the answers to research questions 1, 2, and 3:

- **RQ1:** How can the concepts of a product configuration be understood?
- **RQ2:** How can different types of product configuration systems be distinguished?
- **RQ3:** What are the prerequisites for configuration?

Answering these questions have created the frame of reference and belonging coherent models that make it possible to distinguish different types of configuration systems from each other. Furthermore it has made it possible to assess configuration readiness. This is a novel and theoretical contribution to the configuration community. The reference model, typology, and assessment of configuration readiness have all been presented to peers of the community on conferences with good feedback.

Secondly, answering research questions 4 and 5 has yielded specific observations related to configuration in engineering companies. The research questions are:

- **RQ4:** What is the motivation for configuration in engineering companies?
- **RQ5:** What are the barriers for configuration in engineering companies?

The contribution has been the analysis of what the motivation is in engineering companies prior to the start of a configuration project. Furthermore, a contribution is the description of the barriers to formalising knowledge in engineering companies. It was expected that the main barrier to formalising knowledge in engineering companies was making tacit knowledge explicit due to the high degree of tacit knowledge which is profound to the engineering world. This turned out not to be the case, and this is also the conclusion in the Ph.D. thesis of Anders Haug (2007). Accordingly this has turned out not to be a novel contribution.

However, the novel contribution of this thesis is to pinpoint why it is difficult and time consuming to develop product configuration systems in engineering companies. It turns out it is challenging to establish consensus and consistent knowledge in professional bureaucracies and operating adhocracies.

\(^{29}\) NVivo, Journler, Microsoft OneNote, etc.
10.4.1 Contributions to Literature

During the study I have also contributed to the configuration literature. Below is a list of the literature. Many of the publications have been made in a joint effort with associate professor Kasper Edwards (Technical University of Denmark), Bent Dalgaard Larsen (CEO of Dalux), now assistant professor Anders Haug (University of Southern Denmark), and Professor Lars Hvam. (Thank you for inspiring talks, and discussions.) The list of contributions is divided into:

- Journal contributions
- Conference contributions

Journal Contributions


Conference Contributions

10.5 Are the Results Idiosyncratic or General?

Again it is necessary to divide the discussion in two: One regarding the theoretical contributions and one regarding the study of engineering companies. The models in this thesis (from chapters 4, 5, and 6) have been discussed and presented to fellow researchers on conferences in full papers with peer review. The conference papers have generally received good feedback and suggestions for improvements. The models from research questions 1, 2, and 3 are thought to be general and it is the intention that they can be applied to any company which works with product configuration systems.

However, the models lack empirical validation. Empirical validation of the theoretical contributions has never been the aim for this thesis. The models are theoretical constructs and have been a means to create structure in the product configuration research literature. In this way, they have been beacons, stationary points of reference, which have made it possible to analyse and understand configuration in engineering companies. The models represent a specific view of the configuration world, and therefore it is necessary to understand the models before jumping to the conclusions on configuration in the engineering companies. Without the models, the complexity of the configuration world would have made the empirical work of this thesis difficult.

I hope others will find the framework, the typology and the model for describing prerequisites for configuring useful in their future research.

The empirical studies are less capable of providing generalisations. It is always difficult to draw general conclusions from qualitative research. Indeed, as neither the motives for implementing a configuration system were particularly alike in the two companies nor the scope of the two development projects were, it has even been difficult to compare the two projects.

It is clear, that the scope of the configuration project at GEA Niro is more ambitious than the scope at NNE Pharmaplan. The costs and resources used for the projects are also dissimilar. However, in both case companies, it has been the wish to standardise more rather than to customise more. This has turned out to be too ambitious in the NNE Pharmaplan case, but in GEA Niro the goal has been reached. When a mass producer implements a product configuration system, the motivation is usually to allow more customization. It seems, however, that the goal in engineering companies is the opposite.

All in all, it appears that the theoretical models can be applied in general. However, nothing general can be said about the motivation for starting a configuration project in an engineering company - yet. The cases indicate that a barrier for the knowledge elicitation phase in configuration projects in engineering companies are the establishing of on standardised solutions. Converting tacit knowledge into explicit knowledge was expected to be a great challenge, as much of the knowledge in engineering companies is not particularly well documented. However, the opposite was the case. This seems to be an interesting conclusion. For all that, it is difficult to say whether it is a general feature or just a coincidence in these two cases.
10.6 Summary

This chapter has discussed the main elements of the present thesis. First, the main elements of the thesis were discussed. The main elements were a discussion of literature, a methodology, theoretical work, and empirical work. Secondly, the research questions and the meta-question have been discussed one by one. Thirdly, the lessons learned and the things that should have been done differently have been discussed.

At the end of the chapter, the contributions to product configuration research are presented and related to the community, and, finally, the generalisability of the results has been discussed.
11 Conclusion

The present thesis has had the primary aim of understanding configuration in engineering companies by answering the meta-question: “How are configuration projects carried out in engineering companies?” The increasing use of product configuration systems in engineering companies has motivated this question.

11.1 Overview

Chapter 1 gives an introduction to product configuration in engineering companies, and presents the field of research related to product configuration systems by identifying important research groups. These are: (i) The Technical University of Denmark, (ii) The Helsinki University of Technology, (iii) Forza and Salvador, and (iv) The University of Klagenfurt. Finally, chapter 1 presents the aim and structure of this thesis.

Chapter 2 presents a survey of the literature of product configuration systems. The history of research in product configuration systems are presented through three themes: (i) The Rise and Fall of R1, (ii) Definition of Configuration and the Configuration Task, and (iii) Product Configuration Systems – a new Kind of Expert Systems. Finally, the progression of product configuration systems as research area is discussed.

Research questions and methodology are laid out in chapter 3. The chapter starts out by discussing the scientific standpoint of the research. Then the research questions are developed by an investigation into shortcomings and strengths of the contributions presented in chapter 2. Following this analysis the research questions are developed. The meta-question is divided into the following five research questions.

RQ1: How can the concepts of a product configuration be understood?
RQ2: How can different types of product configuration systems be distinguished?
RQ3: What are the prerequisites for configuration?
RQ4: What is the motivation for configuration in engineering companies?
RQ5: What are the barriers for configuration in engineering companies?

By answering the five research questions, it is possible to answer the meta-question. Research questions number one, two and three aim at understanding general traits of configuration, and constitute stationary points of reference when we try to understand configuration in engineering companies by establishing clarity about key concepts. The contributions from research questions 1 through 3 are theoretical constructs, and build on a deductive logic. The fourth research question focus on understanding what the motivation has been for the engineering companies to pursue a product configuration system. The fifth research question aims at understanding possible barriers for configuration in engineering companies based on two important processes in configuration: Making tacit knowledge explicit, and establishing consensus about knowledge.

Chapter 4 answers research question number one by developing a frame of reference that highlights the organisation’s role in the configuration process. The frame of reference contains definitions of key concepts of configuration. A consequence of the model is that one must develop three systems to change the configuration process if a product configuration system is applied in a company. Naturally you have to develop the configuration system itself. Next you have to develop your organisation or at least carry out some kind of change management. Finally, you have to develop or train the users. An interesting observation from the theory of technical systems is that you cannot design how the human system applies the technical system. You can only design the
technical system not the technical process. Of course you can do your best in guiding and training the human system but at the end of the day, you cannot be sure that the human system acts as intended or trained. Consequently, it is supposed that the implementation of configuration systems requires as strong a focus on training of users, and change management as on the technical side of developing the product configuration system itself.

The fifth chapter answers research question number two by developing a typology for distinguishing different types of configuration systems. The distinguishing factor is what kind of product knowledge the configuration system contains. Product knowledge is described according to theory from design science; more specifically from the theory of technical systems. Four different types of configuration systems are defined in the typology: (a) Structural validators, (b) co-design configuration systems, (c) automatic configuration systems, and (d) meta-configuration systems.

Chapter 6 answers research question number three. To answer research question number three a model for assessing configuration readiness is developed. The onset of the model is that two types of knowledge are necessary for the development and implementation of product configuration systems: (i) Knowledge about the product to be configured, and (ii) knowledge about the process which the configuration system should effect. After having identified the two types of knowledge necessary for a configuration project, the focus turns to what state the knowledge is in. The knowledge is assessed in two dimensions: Explicit vs. tacit, and idiosyncratic vs. consistent. Knowledge should be both explicit and consistent before it is configuration ready, otherwise the knowledge is not configuration ready. Configuration knowledge which is not ready does not indicate that it is impossible to develop and implement a product configuration system. Rather the term not configuration ready indicates that the knowledge elicitation will be harder than in a similar company with configuration ready knowledge.

The seventh chapter is an introduction to the empirical work carried out in this thesis. It starts out by discussing possible motivational factors for starting configuration projects in engineering companies. Two main effects are identified: (i) Standardisation of process knowledge, and (ii) standardisation of product knowledge. Afterwards, barriers to knowledge elicitation in engineering companies are pointed out. Then the structures for the following case chapters are given. The case chapters are divided into a descriptive part which provides the reader with information about the given configuration project, and an analytical part which consists of an analysis regarding research questions 4 and 5. Finally the method of collecting data in the two case companies is described.

Chapters 8 and 9 contain a description of the GEA Niro case and the NNE Pharmaplan case.

In the tenth chapter the results are discussed. Chapter 10 starts out with a discussion of the main elements of this thesis: (i) Literature, (ii) Methodology, (iii) Theoretical Work, and (iv) Empirical Work. Then the results of each research question are discussed. The discussion then turns to what should have been made differently. Finally, the contributions of the present Ph.D. are discussed, and whether the results are idiosyncratic or general.

11.2 Results

The results of this thesis answer the meta-question: How are configuration projects carried out in engineering companies? The answer of the meta-question is subdivided into five research questions. Consequently, these research questions are answered first.

11.2.1 Research Question 1

“How can the concepts of a product configuration be understood?”
Due to ambiguities in configuration research it has been necessary to create a frame of reference which would constitute the basic point of view which underlies this Ph.D. In chapter 4 the frame of reference of product configuration has been developed. The frame of reference accounts for a specific view on configuration, and it is built on established theory from the research community of product configuration.

Research question number one was posed as the first question in order to establish clear definitions that would permeate the rest of the thesis and by the same token, prepare for the development of the following models and the subsequent, empirical study of engineering companies. The most important definitions in the framework of configuration are the basic concepts which are necessary to describe a configuration system in an organisation. These concepts are:

- **Technical systems** are objects, products, things, machines, implements, technical objects, etc. which are made by humans to fulfil a specific need.
- A **product model** is an abstract representation or description, describing (a) the structure of P and (b) facts, object, concepts and properties that are relevant in any life cycle phase of P. P can be a single product or a family of products. A product is a thing, a substance or a service produced by a natural or artificial process.
- A **product configurator** is a software-based expert system that supports the user in the creation of product specifications by restricting how predefined entities (physical or non-physical) and their properties (fixed or variable) may be combined.
- **Configuration process**: To combine predefined entities (physical or non-physical) and define their variable properties, while obeying constraints and legal interface combinations in a way that satisfies given requirements.
- A **configuration** is the output of the configuration process, e.g. a description of the component structure of the product and any connections between the components in the set or a description of inconsistencies in the requirements.

It is not enough merely to understand the configuration system in order to understand how a given product is configured. Other actors or operators than the configuration system affect the configuration process. This is explored in the model of the total configuration system, see Figure 11-1.

**Figure 11-1: Total configuration system**
The illustration of the total configuration system is a specific view on the configuration of a given product. An incomplete description of a product’s components structure is input to the total configuration system, and the output of the total configuration system is a complete specification of the product’s component structure. The series of steps carried out in between are called ‘configuration process’ or just ‘configuring’. Three important operators that affect the configuration process were identified: Users, product configuration system, and organisation. The total configuration system, together with the definition of key concepts, comprises the frame of reference of this thesis.

11.2.2 Research Question 2

“How can different types of product configuration systems be distinguished?”

This question has been answered in chapter 5 where a typology is presented. Configuration systems are distinguished by the product knowledge contained in them. The research question is theoretical in nature and has the purpose of identifying which different types of configuration projects there are in order to describe what kinds of configuration systems are implemented in engineering companies.

The typology is founded on knowledge of the product being configured. Product knowledge can be described on three different abstraction levels: The level of purpose, the level of function structure, and the level of component structure. Looking at these levels makes it possible to identify different kinds of configuration systems based upon the product knowledge they contain.

Figure 11-2: Types of product configuration systems

By using Figure 11-2, four types of configuration systems can be identified: (3) Structural validators, (5) co-design configuration systems, (6) automatic configuration systems, and (1, 2, 4) meta-configuration systems.

According to the definition of configuration systems above, the output of a configuration system is a description of the component structure of the product. Because of this, all systems that do not contain knowledge about the product’s component structure are put in the category of meta-configuration systems. Systems which contain only knowledge of the component structure cannot transform functional requirements to a structural solution. Instead, they are only able to validate a structural solution. For this reason, these systems are called structural validators. Co-design configuration systems assist the users in transforming a description of the products function structure to a description of the products components structure. This is a complex task that requires
mapping of the function structure to the component structure. Finally, the automatic configuration systems assist the user in getting from a description of purpose to a description of function structure and further on to a description of the component structure. Apparently, there are no evident examples of this kind of automatic configuration system. Nevertheless, should one be created, it would be particularly complex and resource demanding, as the knowledge base would contain knowledge, rules, and descriptions of the product on all three abstraction levels. In that case, the challenge would probably be to keep every relation between any of the three abstraction levels as concrete as possible by using one-to-one mapping of elements in the knowledge base.

11.2.3 Research Question 3

“What are the prerequisites for configuration?”

To understand motivations for and especially barriers against configuration systems in engineering companies it is necessary to understand what the prerequisites for configuration are. In chapter 6 a model for estimating configuration readiness has been developed. The model is based on theoretical considerations of what must be the prerequisites for configuration. The knowledge required to develop a configuration system can be divided into two: Product knowledge, and process knowledge. Each of the two must be considered in relation to consistency and explicitness.

Mainly product knowledge is implemented in the configurator, while process knowledge is important to get the configurator integrated to and used in the configuration process in the organisation. This can be illustrated in a two-by-two matrix which takes the nature of the knowledge into consideration. The matrix has the characteristics tacit vs. explicit on one axis, and consistent vs. idiosyncratic on the other axis. Figure 11-3 shows the product knowledge matrix including suggestions for how one can change the status of the product knowledge. Figure 11-4 shows process knowledge with suggestions of how one can change the status of the process knowledge.

Figure 11-3: Product knowledge

<table>
<thead>
<tr>
<th>Product Knowledge</th>
<th>Consistent</th>
<th>Idiosyncratic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Explicit</td>
<td>Configuration Ready</td>
<td>Establish product rules through consensus</td>
</tr>
<tr>
<td>Tacit</td>
<td>Document products to make explicit</td>
<td>Formal product review</td>
</tr>
</tbody>
</table>
The aim of research question 3 has not been to develop a deep understanding of how configuration readiness can be estimated. It merely establishes a conceptual model for understanding the prerequisites for configuring. If the prerequisites for configuring are not fulfilled when a company initiates the project, it does not necessarily mean that the given project will fail. However, the model indicates where extra attention must be given, e.g. on change management or on a formal product review.

11.2.4 Research Question 4

“What is the motivation for configuration in engineering companies?”

It has been difficult to formulate a clear answer to research question 4, as the two cases differed. The configuration projects had very different scopes and amount of resources to complete the projects. Indeed, they also had different motivations for initiating the projects. Most importantly, in both cases, the intention of the configuration project was to move towards more standardisation, and in both cases the early phases of the engineering projects were targeted. In this way, the two cases lie in perfectly line with what we expected and described in Haug et al. (Haug et al., 2009). When an engineer-to-order company wants to become more standardised, the challenge is to move the time of customer differentiation closer to the time of delivery. In other words the challenge is to postpone the differentiation and place it later in the engineering phases. From an engineering point of view this means to increase the predefined part of the engineering work. However, the two case studies show that engineering companies find it hard to fully achieve this transition. In theory they may be able to deliver customised products at prices lower than traditional engineering companies by standardising their products but empirical proof for this claim is lacking.

During the development of the configuration system, NNE Pharmaplan abandoned the idea of creating a fixed price competition, and formalising their product knowledge. Even though standardisation was the motivation for committing to the project, the project took another route during the development and implementation.

GEA Niro has been closest to fulfilling the postponement of customer differentiation. GEA Niro operates with standard concepts and these are passed on to the design phase of their product.
This is a significant step for the postponement of differentiation as described above. However, they still keep two competing business processes alive – the old and the new. Perhaps this cannot be avoided but it defuses the possible standardisation and postponement benefits.

To be more precise, when considering the motivations for creating configuration one might have to distinguish between different types of engineering companies – those who have a closed solutions space and those who do not. When getting under the skin of GEA Niro and NNE Pharmaplan it turns out that they are significantly dissimilar. GEA Niro has manufacturing of their own product in the house while NNE Pharmaplan solely produces specifications. The solution space of GEA Niro is closed comparing to the open solution space of NNE Pharmaplan. NNE Pharmaplan has a low degree of similarity among projects.

11.2.5 Research Question 5

“What are the barriers for configuration in engineering companies?”

When it comes to both case studies, it turns out that the idealised process described by Haug (2007) is too simplified regarding knowledge elicitation in engineering companies. With the use of configuration readiness and Haug’s (2007) model for development of configuration project, two key processes have been identified concerning the formalising of knowledge for configuration systems. These can be seen in section 7.2. The two processes are: (i) Making tacit knowledge explicit, and (ii) establishing consensus about knowledge so that the foundation for the configuration system is based on consistent and not idiosyncratic knowledge.

In two case studies it was investigated whether these processes are a barrier to making knowledge formalised in engineering companies. It was expected that the conversion of tacit product knowledge into explicit knowledge would be a problem for engineering companies. Rather unexpectedly, it turned out that the creation of consistent knowledge which was the biggest issue.

Below, in Figure 11-5, a modified model shows the involvement of several domain experts.

**Figure 11-5: Revised knowledge elicitation process**
The establishing of consensus is difficult in engineering companies due to the power of the professionals. This group has fought to obtain the right of being autonomous. Every attempt to standardise or rationalise their work into a series of executable steps will be met by resistance and scepticism. Expressions such as: ‘that is impossible’ or ‘this work is way too complex to standardise’ will be met when one works as knowledge engineer. The domain expert does not refuse to cooperate and share their tacit knowledge, but they make it difficult for the knowledge engineer to create consistent knowledge. In engineering companies it is generally found difficult for middle line management or the strategic apex to force through decisions upon the professionals. Consequently, it is perfectly safe for the domain experts to drag on the establishing of consensus. Not two professionals are alike, and they have their personal preferences regarding how to solve a given task. The right to solve tasks in their own ways has been won through years of experience and training, so, naturally, this right is not forfeit easily.

This does not mean that it is impossible to develop and implement product configuration systems in engineering companies; it merely implies that it is a slow and expensive process.

NNE Pharmaplan had to abandon the vision of formalising product knowledge by offering standardised modules through the configurator. However, they stayed on track by implementing all variants of a given module which were requested by the users. This way, they avoided the tiresome discussion of establishing consensus. However, in the end, this strategy lead to the abandonment of the price calculation and the modular engineering approach, thus leaving NNE Pharmaplan with a visual sales configurator – a low-level meta-configurator.

The other case company, GEA Niro, chose the long road. GEA Niro developed a more complex configurator which maps functional requirements to a standardised structural solution by using standard concepts. This does not generate a complete description of the component structure of the product; nevertheless it is a very advanced configurator with integration to several other systems. The configuration project and the development of standard concepts have been progressing slowly. The delaying factor has been the process of establishing consistent knowledge, in other words, making the domain experts reach consensus about a formalised solution.

11.2.6 Meta-question

“How are configuration projects carried out in engineering companies?”

Engineering companies can have several reasons or motivations to pursue the development and implementation of a configurator. On a high abstraction level, the wish for more standardisation drives engineering companies rather than the wish to offer more product choices to the customers. Many cases in the configuration world shows as prime motivation a delivering of more customization to the customers by implementing a configuration system but in the case of engineering companies the prime motivation is standardisation.

One important question must be dealt with, however: Is it common sense to talk about product configuration in engineering companies? Strictly speaking, according to the definition of configuration, which is part of the frame of reference established in research question 1?

A configuration is the output of the configuration process, e.g. a description of the component structure of the product and any connections between the components in the set or a description of inconsistencies in the requirements.

Evidently, the configurators at GEA Niro and NNE Pharmaplan do not live up to the definition of configuration. The natural ensuing question is then: would a configurator in any engineering company live up to the definition of configuration? The answer must logically be no. If a
configurator lived up to the definition of configuration in an engineering company, the company could no longer be considered an engineering company but a make-to-order or assembly-to-order company\textsuperscript{30}.

Nevertheless, meta-configuration systems can be used in engineering companies to support the early phases of the engineering process. Engineering companies that develop and implement configuration systems can expect customers to lose flexibility in one area and gain it in another area; they lose customisation possibilities as the engineering company reduces product variety but they gain it by rationalisation effects of the early phases of a project in terms of shortened throughput time, lesser errors, etc.

Figure 11-6 is used as analytical model to understand how configuration projects are carried out in engineering companies.

Figure 11-6: Analytical model for understanding configuration projects in engineering companies

The development of a product configuration system requires cooperation between three different operators: Users, knowledge engineers, and domain experts. Due to the power of the professionals/domain experts in engineering companies, the cooperation is not without problems. The knowledge engineer must elicit knowledge from the domain experts and turn it into formalised knowledge in a product configuration system. We know from the answer of research question 3, that the prerequisites for configurering are consistent and explicit knowledge about both the configuration process as well as the product being configured. Elicitation of product knowledge is relatively unproblematic in the two case studies. The domain experts willingly share their knowledge, and the unwilling expert did exist but not predominately throughout the organisation. Of course elicitation of product knowledge requires that the knowledge engineer is able to understand the complex products which are usually found in engineering companies but, otherwise, their need be no problems. It was evidently more difficult to establish consistent knowledge i.e. to establish consensus about a favoured part or solution among the domain experts.

\textsuperscript{30} For further discussion of the customer order decoupling point see (Pagh J.D. & Cooper, 1998; Olhager, 2003; Rudberg & Wikner, 2004)
When developing a product configuration system in an engineering company the hardest task for the knowledge engineer is to establish consensus about the given product, services, and processes. Only when he has completed that task is it possible to formalise explicit and consistent knowledge in a configuration system. Establishing consensus about standardised solutions is not an easy task in engineering companies. Domain experts have fought to obtain the right of being autonomous and every attempt to standardise or rationalise their work into a series of executable steps will be met by resistance and scepticism. The problems of establishing consensus among the domain experts calls for a revised model of the knowledge elicitation process which is the outcome of research question 5. See Figure 11-7.

Figure 11-7: Revised knowledge elicitation process

Another important factor concerning the development of configuration systems in engineering companies is the solution space of the engineering company. In the case of NNE Pharmaplan, the solution space was enormous and open. This made it difficult to predict in what context the modules implemented in the configurator would be used in. Indeed, it made it hard to develop and maintain the price calculation part of the configuration system and the price calculation was consequently skipped in the later phases of the project. In GEA Niro, the solution space was smaller and closed, and thus it was possible to build a more advanced configurator.

11.3 Perspectives

There is still much research to be done in the area of product configuration. During the last couple of years, product configuration has not evolved in the same direction as research concerning knowledge based systems or knowledge management. This thesis has created new contributions to the area and proposed new interesting problems to be researched.

How human systems (or users) affect the configuration system and the configuration process is an important issue. In this research area also lays the question of how a graphical interface of the configuration system can be designed so that it supports the user in the best possible way.
Possibly, the most important research task in the future is the identifying relevant active environments and understanding relations between given active environments and human systems, product configuration systems, and the configuration process. In this thesis the main focus lies on organisations as the active environment, more specifically on the structure of organisations as frame for interpretation. However, since organisational theory is not my main field of expertise other theories than Mintzberg's structures in five could have been more suitable and other active environments could have shown more influence on the configuration task at hand. Looking at the structure of the organisations in relation to configuration projects is an interesting research area which should be researched further.

It has been known for years, that technological innovation has an effect on the organisation itself, see (Leonard-Barton, 1987a; Leonard-Barton, 1987b). One of the lessons learned from using Minzberg’s structures in five is that different forces predominate in different kinds of organisations (Mintzberg, 1993; Mintzberg, 1980). The two engineering companies used as cases in this report are best characterised as professional bureaucracies and operating adhocracies. Common for both of them are that the power of professionals are non-disputable. Clearly, the type of organisation must have an impact on the process of developing and implementing a configuration system. In engineering companies the main barrier of the implementation is to establish consensus amongst the specialists concerning a standardised solution. In these organisations, on the other hand, making tacit knowledge explicit turns out not to be a problem. The problems lie more in the establishing of consistent knowledge or the establishing of consensus about standardised solutions among the specialists. Nevertheless, the relation between the active environments and the configuration task and other subsystems is an interesting research theme which, were it explored, would benefit us all.

Although configuration systems have mostly been applied in manufacturing companies. These kinds of knowledge based systems are now applied to a vast range of different tasks and processes. The range of different task environments that arise is obviously vast if you look across the existing examples of configuration systems and the configuration process. According to Russell and Norvig (2003) the task environment can be categorised along 6 dimensions when talking about artificial intelligence: (i) Fully observable vs. partially observable, (ii) deterministic vs. stochastic, (iii) episodic vs. sequential, (iv) static vs. dynamic, (v) discrete vs. continuous, and (vi) single agent vs. multiagent.

The configuration community would learn from researching into knowledge based systems in order to incorporate knowledge on the task environment at hand and, consequently, understand the configuration process better. This could strengthen the understanding of scope, what it takes to be configuration ready and how you find the appropriate kind of configuration system. Research into the configuration process is almost lacking in the configuration world. Most procedures suggest that you map the ‘As-Is’ state as well as the ‘To-Be’ state of the process which you want to support by creating a configuration system. More research should be done in understanding the significance of the process when designing configuration systems. According to the theory of technical systems, the technical process cannot be designed, and thus it must be necessary to understand what the configuration task is, and, furthermore, how the configuration system supports it. By primarily understanding the configuration task and then designing the configuration system that supports the task, better configuration systems would probably be the outcome. However, more research is needed into that area as well.

Finally, the way configuration systems are developed is a research area with potential. In section 7.3, created on the basis of this thesis’ frame of reference, a model shows how configuration
projects evolve and how configuration systems are developed and implemented. This model could constitute a beneficial starting point for such research.
12 References


Ref Type: Unpublished Work

Ref Type: Unpublished Work


Planning and Design (pp. 143-166). Southampton: Computational Mechatronics Publications.


1 Addendum

This addendum is worked out to respond to the criticism of the evaluation committee prior to the public defence of my PhD-thesis. Critique expressed by the evaluation committee:

- The chosen scientific methodological approach could have been better motivated in part I and should be more thoroughly discussed in relation to the outcome in part IV
- The Meta-question should be left out
- RQ 3-5: 'are' and 'is' substituted by 'can be' to make the argumentation for the validity of the results more realistic.
- Treatment of reliability and validity do not suffice
- Missing concluding statements about scientific and industrial value and applicability

The critique is treated in the following way. First, a better description of the motivation for the choice of 'critical realism' as scientific standpoint, and a better description of the outcome in relation to the chosen scientific approach. Second, a better explanation of the role of the meta-question and a comment on the formulation of RQ 3-5. Third, a discussion of validity, applicability, reliability, and verification in relation to the outcome of this thesis. The treatment of the critique will be handled in chapter 2 to 4.

Before engaging in the discussion of the critique it is necessary to understand a few essential terms: (i) Hypothesis, (ii) Theory, (iii) Ontology and epistemology, (iv) Method (v) Reasoning methods and argumentation, (vi) Truth and validity, and (vii) Approach.

Ad. (i) A scientific hypothesis is a working assumption that explains a phenomenon for which is required that it is testable. Depending on the scientific standpoint there are different criteria for how the hypothesis should be formulated, tested, and how the results should be interpret.

Ad. (ii) A theory is an abstraction that describes a phenomenon or parts thereof. According to Weick (1995), theory belongs to the family of words that includes guess, speculation, supposition, conjecture, proposition, hypothesis, conception, explanation, and model. A theory can be very abstract or can consist of more concrete sets of hypothesis. Popper often refers to an empirical theoretical system instead of theory. Here, system indicates more interrelated elements, empirical indicates that the theory in principle should explain something in the empirical domain (which can be observed), and theoretical indicates that the theory should be able to explain or predict. (Koch, 2004, p. 91)

Ad. (iii) In short, ontology is the study of the nature of being, existence or reality in general, as well as of the basic categories of being and their relations. Epistemology concerns the nature and scope (limitations) of knowledge. It addresses the questions: What is knowledge?, how is knowledge acquired?, what do people know?, how do we know what we know?, and why do we know what we know? Consequently, when asking if something exists, this belongs to the ontological field, and when asking about objectivity and methods this belongs to epistemological field. (Buch-Hansen & Nielsen, 2007)

Ad. (iv) Decisions on what the research seeks to illuminate in relation to subject, i.e. intentions of actors, casual relations, trends and tendencies, etc. The methods are usually developed to general approaches such as grounded theory, quantitative studies, qualitative studies, etc. (Fuglsang & Olsen, 2004, p. 30)
Ad. (v) Accordingly to Fuglsang and Olsen (2004, p. 30) it is possible to distinguish between four different reasoning methods and forms of argumentation: (i) Deduction where the conclusion is purported to follow necessarily or be a logical consequence of the premises, (ii) Induction where general laws are formulated based on limited observations of recurring phenomenal patterns, (iii) Retroduction is the logical process by which a point of view is utilized to devise a conjecture or theory, and (iv) Abduction is the logical process by which a theoretical construct of one theory is utilized to analyze or interpret the parameters of another theory.

Ad. (vi) A true claim is a claim that is valid in respect to certain criteria. In an analytical setting the ‘true’ claim should be general approved and tested in a laboratory setting. How well the claim can be reproduced signals validity. In a more interpretive setting true claims are connected to time and space – the validity depends on how many thinks that the claim is suitable to explain a particular event. (Fuglsang & Olsen, 2004, p. 30)

Ad. (vii) The employed tools to gather data i.e. statistical analysis, surveys, interviews, etc. (Fuglsang & Olsen, 2004, p. 30)
2 Chosen Methodological Approach

Having explained these essential terms it is now possible to evaluate different scientific standpoints in relation to research into product configuration systems. Chapter 3 of my PhD thesis begins with a description of three different lines of scientific theories based on Fuglsang and Olsen (2004): Demarcationism, scientific realism, and complex idealism. To further exemplify, three scientific positions are described in Table 1 below, and evaluated in the coming three sections.

Table 1: Three different scientific standpoints, translated from (Fuglsang & Olsen, 2004, pp. 43-49)

<table>
<thead>
<tr>
<th></th>
<th>Critical Rationalism</th>
<th>Social Constructivism</th>
<th>Critical Realism</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ontology</strong></td>
<td>A selected part of the reality (i.e. consciousness and mental conditions are acceptable)</td>
<td>Ontological construction of the physical and/or social reality</td>
<td>The totality of the social reality</td>
</tr>
<tr>
<td><strong>Epistemology</strong></td>
<td>Casual relations. The language (in philosophical terms) is a tool to help understand the reality</td>
<td>Epistemological construction of the physical and/or social reality</td>
<td>Knowledge about the totality through data and theories related to reality.</td>
</tr>
<tr>
<td><strong>Method</strong></td>
<td>The scientific process starts with the acknowledgement of issues (such as 'Why does unemployment exist?'). The issue are sought to be explained with the help of theories that is undertaken empirical tests with an eye to falsification/corroboration</td>
<td>De-construction of established truths</td>
<td>Identification of trends</td>
</tr>
<tr>
<td><strong>Reasoning methods &amp; argumentation</strong></td>
<td>Two types of reasoning methods and argumentation are applied: (i) deduction, and (ii) falsification, where a single observation disputes a general rule, that then is dismissed.</td>
<td>In general all reasoning methods. But primarily induction and deduction.</td>
<td>Retroduction</td>
</tr>
<tr>
<td><strong>Truth &amp; validity</strong></td>
<td>A statement about the reality is true if it corresponds with the reality. A convergation towards the truth is the highest goal you realistically can achieve.</td>
<td>Relativism. In many forms of social constructivism the idea of objective truth is forfeit; the truth is merely a perspective.</td>
<td>If the theory is applicable, and can be falsified under relevant conditions.</td>
</tr>
<tr>
<td><strong>Approach</strong></td>
<td>Depends on the research area</td>
<td>Depends on the type of social constructivism</td>
<td>Covariance. Correlation of aggregated data.</td>
</tr>
</tbody>
</table>

2.1 Evaluation of critical rationalism in relation to configuration research

Most PhD studies carried out at Technical University of Denmark in relation to product configuration systems are subscribing to critical rationalism. An exception is the PhD study of Haug (2007) that also carried out a comprehensive study of which scientific approaches was suiting for research into configuration systems, and ended up with the conclusion that critical rationalism was not very suited for the research carried out.
According to critical rationalism, valid hypotheses must be falsifiable by logically possible statements. As described in chapter 3 of this thesis, Haug (2007) criticizes the use of critical rationalism in configuration research. Haug (2007) provides the following example, if to test the applicability of the procedure for development of product configuration systems (CPM procedure) it would require elimination or fully description of social factors, and this is an impossible mission since the procedure is applied in different social contexts. Hypotheses such as ‘the use of the CPM procedure can lead to significant benefits’ or ‘the use of the CPM procedure most often leads to significant benefits’ cannot be falsified by an observation statement and are therefore not valid. As counter example, the following statement is falsifiable: The use of the CPM procedure always leads to successful projects, and in fact this hypothesis has been falsified but is dismissed by claiming that in these cases it was not due to the CPM procedure not working but because of other factors (Haug, 2007). To avoid the falsification of the hypothesis it is necessary to ensure that the CPM procedure is only applied in situations where it holds. This is possible by defining criteria that has to be fulfilled before using the CPM procedure. However, defining criteria that measures when and how it works is a highly complex if not impossible task (Haug, 2007). At the bottom line, the problem by testing procedures from a critical rationalistic perspective is that the applicability of the procedure depends on the humans that apply it (and at times this leads to irrational human behaviour).

Applying configuration systems in engineering companies involves human systems, which is described in the frame of reference in chapter 4. Humans are neither predictable nor rational in the same vein as other aspects of nature. Consequently, examples that counter generalised statements about human behaviour can always be found. It is difficult to formulate general falsifiable hypotheses about application of configuration systems in engineering companies as a set of rules in a way that is not easy to falsify.

This lead to my conclusion that it is best to reject positivist notions when carrying out research that involves systems. When dealing with systems it is necessary to allow interpretation of the experience of the systems involved. This represents another scientific perception than as accounted for in demarcationisms.

### 2.2 Evaluation of social constructivism in relation to configuration research

My rejection of the positivist ideas of critical rationalism could lead me to take a position at the opposite end of the scientific spectre, as social constructivist. Social constructivism is an alternative to critical rationalism. Where the more positivistic subscribe to an objective reality that exists independent of our cognition of it, social constructivism emphasizes that the reality is shaped by our cognition of it (Rasborg, 2004). The basis of social constructivism is that social phenomenons is historical and social processes are everlasting changing.

Social constructivism argues that our cognition is not independent of the social context that we are part of, and the reality is shaped in a significant way by our cognition of it. Social constructivism focuses on an individual's learning that takes place as a consequence of the individual’s interaction in a group, and the objective of social constructivism is to ask how knowledge is created (not whether it is true or false). Social constructivism asserts that all knowledge is relative, and relativism is the basic problem of social constructivism. The problem of not being able to make generalizing claims is according to Flyvbjerg (2001) a significant problem related to much social science.
When all comes to all, it does not make sense to talk about social constructivism as a united concept since many social constructivist positions exist\textsuperscript{31}. Without going into detail with any of the different positions led me just note, that it is often the most radical variants of social constructivism that are criticized, often with reference to the problems of relativism which implies that in principle what relativist researchers are doing cannot be qualified as scientific or even meaningful.

To sum up, I do believe that there is a there is an independent natural and social reality to be studied. We might not be able to understand or observe it fully, but the reality is independent, and mechanisms, causal potentials and tendencies can be used to explain models in configuration research. This is in opposition to the methodology of complex idealism such as social constructivism. For this reason, this line of theory is ruled out, although one must recognize the importance of looking into the influence of social factors eminent. The use of tools, explanation models, and the creation of new knowledge depend on the context in which they are applied, and this is in opposition to demarcationism and more positivistic notions such as critical rationalism. However, I recognize elements of both extremes: The realist perspective from positivism, and the influence of social factors from social constructivism. A combination of these views would however most likely be futile, as the basically rule each other out. This motivated be to look further into the line of theories called scientific realisms.

2.3 Choice of Critical Realism - Motivation and Outcome

Critical realism confronts and breaks away from the dominating perception of social constructivism (which asserts that all knowledge is relative), and from the perception of positivism (which asserts that our knowledge is limited to what can be extracted from objective facts from reality) (Jespersen, 2004). On the other hand, critical realism emphasises that there exists an independent reality that is to be understood. Theories are fallible attempts that try to describe the real structure of reality. For this reason, the development of theories and knowledge must be seen in a historical setting, and knowledge about the reality is improved over time (Buch-Hansen & Nielsen, 2007).

Development of knowledge is a social activity that builds upon and/or extends existing knowledge. Besides actual events and empirical observations, the research domain contains an independent reality that researchers may not have full access to. Accordingly, the objective of critical realism is to understand events by describing mechanisms and not to predict outcome of future events, as the outcome of events depends on many underlying structures and mechanism not yet discovered. (Buch-Hansen & Nielsen, 2007)

The fundamental concept and understanding of critical realism can be divided into two dimensions: The transitive dimension, and the intransitive dimension. (Buch-Hansen & Nielsen, 2007)

The transitive dimension is our knowledge at a given point in time. This knowledge is a social product (knowledge is a social activity that builds upon and/or extends existing knowledge) that is fallible (knowledge is never definitive - as knowledge is not a reflection of reality but a reflection of what is observed there is always a possibility for extending existing knowledge). (Buch-Hansen & Nielsen, 2007)

\textsuperscript{31} Rasborg (2004) identifies seven distinct types of social constructivism: Anti-essentialism, anti-realism, the always historical and cultural character of knowledge, the primacy of language compared to thinking, language as action, focus on interaction and social praxis, focus on processes.
The intransitive dimension is the reality on a given time that exists independently of the existing knowledge on it. This reality is deep, layered, open, and differentiated.

Deep in the sense that it reality consists of three domains, the empirical domain, the actual domain, and the real domain. The empirical domain is existing knowledge in form of observations and experience. The actual domain consists of events and phenomenon, while the real domain is structures, mechanisms, causal relations, and tendencies that the researchers not fully can access. Accordingly, the objective of critical realism is to understand events by describing mechanisms and structures and not to predict outcome of future events, as the outcome of events depends on many underlying structures and mechanism that is not yet fully understood. (Buch-Hansen & Nielsen, 2007)

Layered in the sense that the structures and mechanisms of the real domain are divided into hierarchical levels. Higher levels such as social relations require lower levels such as physical equipment but are not reduced to the higher levels. (Buch-Hansen & Nielsen, 2007)

Open, in the sense that events are combinations of many underlying mechanisms and structures, and consequently, most often empiric regularities do not happen spontaneous. Following, science must abandon to predict and settle for explain and understand events. (Buch-Hansen & Nielsen, 2007)

Differentiated in the sense that the real domain consists of objects with different causal potentials and predispositions. (Buch-Hansen & Nielsen, 2007)

2.3.1 Motivation of Choice and Discussion of Outcome

Motivation of Choice

I do believe that there is a there is an independent natural and social reality to be studied. We might not be able to understand or observe it fully, but the reality is independent, and mechanisms, causal potentials and tendencies can be used to explain models in configuration research. This is in opposition to the methodology of complex idealism such as social constructivism. For this reason, this line of theory is ruled out, although one must recognise the importance of looking into the influence of social factors eminent in complex idealism. The use of tools, explanation models, and the creation of new knowledge depend on the context in which they are applied. This is in opposition to demarcationism. Correspondingly, the research of my thesis has been conducted from a critical realist perspective that lies in the area of scientific realism.

Critical realism is at its most basic level an understanding and elaboration of what science is, and what characterises good scientific research (Buch-Hansen & Nielsen, 2007). In the following, this is converted into a more practical procedure for studying the meta-question of this thesis. It is worth noticing that, according to one of the founders of critical realism (Bhaskar), it is vital that the domain determines what knowledge is possible to obtain and consequently how the knowledge can be obtained. You should be very careful with applying universal methods, as you cannot be certain that a given recognised procedure suits the particular domain (Buch-Hansen & Nielsen, 2007). While it is not possible to say anything about the ‘correct’ choice of method, the overall methodological reflections you carry out prior to the study must be (according to Jespersen (2004)):

1. What are we looking at?
2. What knowledge can we acquire?
3. How can this knowledge be acquired?
Ad.1: Understanding the ontology of the field of research is vital to the collection of knowledge for later analysis. Fundamental for critical realism is the distinction between the knowledge the ontology of the field of research and the epistemology of the research field. There is a risk of epistemological erroneous conclusions if the ontology of the field of research is reduced to the knowledge we can acquire in a structured manner. On the contrary, the ontology of the field of research has a voice on which knowledge can be acquired and what question can be answered in a meaningful way. Critical realism always assumes that the social ontology is open and not ergodic (unconditional repetitive - you could not step twice into the same river). Consequently, every analysis must be contextual. This does not mean that the research field is without structures that are stable. On the contrary, we are looking for sound and robust connections. It is just not possible to acquire full and sure knowledge on them. (Jespersen, 2004)

In relation to present PhD, the field of research is application of configuration systems in engineering companies. Knowledge must be seen in a historical setting as new knowledge modifies, extends, and build upon existing knowledge – this PhD extends existing knowledge about product configuration. This is essential to understand the scientific contribution of this thesis, as accounted for in section 3.2 of the thesis. The purpose of research question 1 - 3 is to establish clarity of concepts - to improve the description of the research field. Engineering companies (my two cases) are not ergodic; they are open and ever-changing environments. Therefore the conclusion drawn here depends on the context. Research question 4 and 5 has focus on engineering companies, and motivations and barriers towards the application of product configuration systems. The answer of theses questions must therefore be contextual, as it is not possible to make a closed system that resembles engineering companies, and where ergodic results can be established.

Ad.2: Understanding the ontology of the research field is necessary to determine what knowledge can be acquired. The epistemology address objectivity and methods used to acquire knowledge. The openness of social science must be characterized by coincidence and uncertainty. Consequently, any knowledge acquired must be limited. There does not exist any ‘invariable truths’ (as we are dealing with open systems), and even if there existed ‘invariable truths’ (in a closed system), it would be difficult to acknowledge this because of the general uncertainty of the field (Jespersen, 2004). New knowledge cannot be verified because the ontological stratification (into three dimensions) and the retroductive approach make it difficult to prove causal relations in social science. However, the causal relations can be more or less qualified (critical realism is still not based on relativism), but the step or resources taken to declare a theory for ‘true or false’ are immense. (Jespersen, 2004) In short, the epistemological conditions of social science is characterised by randomness and uncertainty resulting in limited knowledge (Jespersen, 2004, p. 160)

Regarding research question 1 - 3 the knowledge collected here are mostly existing knowledge, and the new knowledge obtained in RQ 1-3 extends existing knowledge. Regarding research question 4 and 5 the knowledge can be expected to be contextual, and as the context is assumed to be everlasting changing it cannot be expected that this knowledge is certain or ‘the truth’. Therefore the scientific challenge here must be to establish ‘reasons to believe’ or preferably ‘good reasons to believe’.

Ad.3: The ontology and epistemology of the research is decisive for how knowledge can be acquired, and which analytical methods can be used. In critical realism it is not possible to define a single best analytical method, as the analytical method must rely on the character of the research field. Traditionally, inductive reasoning is opposed to deductive reasoning. Critical realism advocates for a hybrid of deductive and inductive reasoning – retroduction and abduction. Instead
of considering these two methods as contradictionary, in critical realism induction and deduction are complementing each other (Jespersen, 2004). Retroduction is an analytical method that relies on elements from induction (observations, apparent regularity) combined with a subsequent deductive formulation of hypothesis in respect to the ontology of the particular field of research. Furthermore, the hypothetico deduction (conditional derivation) can be stochastic, which implies that it only is valid with a known (and sometimes unknown) probability. This contradicts with formal deduction where the statement always must be true. (Jespersen, 2004)

The motivation regarding research questions 4 and 5 was to discover ‘good reasons to believe’ according to the motivation and barriers for application of configuration systems in engineering companies. Based on observation of the two cases it was attempted to arrive to hypotheses for conditional derivation. The empirical starting point of this Ph.D. thesis was NNE Pharmaplan where I was employed as a researcher during my Ph.D. study. I also worked at NNE Pharmaplan during my one-year leave of absence. The empirical basis of the project is nine semi-structured interviews conducted with specialists from NNE Pharmaplan and GEA Niro, two engineering companies geographically placed in the area of Copenhagen in Denmark. From an ontological point of view, the knowledge discovered here are from the empirical and actual domain. Based on regularities I try to identify mechanism that could form hypothesis valid for conditional derivation. This resembles a retroductive approach, although the deductive testing of the observed regularities is not part of present PhD, as it was not possible inside the timeframe available.

**Discussion of Outcome**

This PhD brings a general contribution to the theory about configuration in terms of the answers to research questions 1 - 3. Answering these questions have created the frame of reference and belonging coherent models that make it possible to distinguish different types of configuration systems from each other. Furthermore it has made it possible to assess configuration readiness. This is a novel and theoretical contribution to the configuration community. The reference model, typology, and assessment of configuration readiness have all been presented to peers of the community on conferences with good feedback. The models from research questions 1, 2, and 3 are thought to be general and it is the intention that they can be applied to any company that works with product configuration systems. It was not the ambition to achieve empirical validation of the models (RQ 1 - 3). The models are theoretical constructs and have been a means to create structure in the product configuration research literature and ensuring clarity of concepts as advocated by Bhaskar. In this way, they have been beacons, stationary points of reference, which have made it possible to analyze and understand configuration in engineering companies. The models represent a specific view of the configuration world, and therefore it is necessary to understand the models before jumping to the conclusions on configuration in the engineering companies. Without the models, the complexity of the configuration world would have made the empirical work of this thesis difficult. All in all, it appears that the theoretical models can be applied in general.

Secondly, answering research questions 4 and 5 has yielded specific observations related to configuration in engineering companies. The contribution has been the analysis of what the motivation is in engineering companies prior to the start of a configuration project. Furthermore, a contribution is the description of the barriers to formalizing knowledge in engineering companies. It was expected that the main barrier to formalizing knowledge in engineering companies was making tacit knowledge explicit due to the high degree of tacit knowledge that is profound to the engineering world. This turned out not to be the case, and this is also the conclusion in the Ph.D. thesis of Haug (2007). However, the novel contribution of this thesis is to pinpoint why it is
difficult and time consuming to develop product configuration systems in engineering companies. It turns out it is challenging to establish consensus and consistent knowledge in professional bureaucracies and operating adhocracies.

The purpose of the study of engineering companies was to induce explanations on the motivations and barriers for application of configuration systems in engineering companies. The induction was based upon the key concepts developed in research question 1 – 3, and nine thematic interviews carried out in two Danish engineering companies. The primary goal was to establish ‘good reasons to believe’ as absolute truths are not possible in an open system. This corresponds to the first step in a retroductive approach. It was not possible to design and carry out deductive hypothesizes for subsequent testing within the timeframe of this PhD study.

The empirical studies are less capable of providing generalizations. As explained above, it is always difficult to draw general conclusions from qualitative research. Neither the motives nor the scope of the two development projects were alike. It has been difficult to compare the two projects regarding their motivations for starting configuration projects. It is clear, that the scope of the configuration project at GEA Niro is more ambitious than the scope at NNE Pharmaplan. The costs and resources used for the projects are also dissimilar. However, in both case companies, it has been the wish to standardize more rather than to customize more. Nothing general can be said about the motivation for starting a configuration project in an engineering company - yet. However, the two cases provide ‘good reason to believe’ that a barrier for the knowledge formalization in configuration projects in engineering companies is the establishing of standardized solutions. Converting tacit knowledge into explicit knowledge was expected to be a great challenge, as much of the knowledge in engineering companies is not particularly well documented. However, the opposite was the case. This seems to be an interesting conclusion. For all that, it is difficult to say whether it is a general feature or just a coincidence in these two cases. At least this hypothesis is interesting to follow in a subsequent deductive testing.

3 Metaquestion and Formulation of Research Questions

3.1 Metaquestion

The metaquestion of this PhD-thesis was what puzzled me when I started the PhD project. It is a rather ambiguous question which is not easy to answer, and to become more specific the five research questions were developed. The metaquestion outlines what puzzled me, and to some degree explains why I chose to define the project as I did, and that justifies the metaquestion. It could have been left out of the thesis, as the answer to the metaquestion is the sum of the answers to the research questions, and as such does not contribute with any new knowledge. However, in my opinion the metaquestion is the line that connects the dots, and should provide the reader with some sense of why the research questions were formulated as they were, and why they are relevant.

3.2 Formulation of Research Questions

The evaluation committee proposes the following critique: “RQ 3-5: 'are' and 'is' substituted by 'can be' to make the argumentation for the validity of the results more realistic”. In hindsight, the rephrasing of RQ 3-5 as suggested in the critique would make the validity of the results more realistic. The rephrasing would also be more in line with the viewpoint of critical realism, as the results of the research questions depends on the concepts proposed in part I of present thesis. If other concepts were used to answer RQ 3-5 the results would most likely have been different. Therefore it would have been proper to rephrase the research questions as proposed by the evaluation committee.
4 Validity, Reliability, and Applicability

4.1 Validity and reliability

Validity can be defined as:

“The property of an argument consisting in the fact that the truth of the premises logically guarantees the truth of the conclusion.”

Validity. (2009). In Encyclopædia Britannica

Reliability can be defined as:

“The extent to which an experiment, test, or measuring procedure yields the same results on repeated trials.

Reliability. (2009). In Merriam-Webster Online Dictionary

The models developed in RQ 1-3 establish clarity of concepts as advocated by Bhaskar (a significant proponent of critical realism). It was not the ambition to achieve empirical validation of the models (RQ 1 - 3). What is left to discuss is whether validation is a key task theory development in social science or not.

“…validation is not the key task of social science. It might be if we could do it, but we can’t…”

(Weick, 1989, p. 524)

If validation is not a criterion for theory development in social science, this leaves us with two implications. (i) The criteria used instead of validation must be explored carefully. (ii) The contribution of social science does not lie in validated knowledge, but rather in the suggestion of relationships and connections that had previously not been suspected. (Weick, 1989, p. 524)

Instead Weick (1989) suggests that conjectures generated during theory development are selected based on judgments of their plausibility, which can be assessed by the following criteria: That’s interesting, that’s obvious, that’s connected, that’s believable, that’s beautiful, that’s real. This has been guiding my development of my theoretical models (RQ 1-3). The criteria of validity related to critical realism are, whether the theory is applicable, and can be falsified under relevant conditions. I believe, that my frame of reference, typology and model for configuration readiness is applicable, and could be falsified.

According to Buch-Hansen and Nielsen (2007), Bhaskar argues that while measurements and quantitative methods make perfect sense in natural science, social science is subjected to clear limitations in that objects are based on meaning and concepts. Therefore, he suggests that concept clarity should be given the same status in social science as exact measurements are given in natural science. So the clarity of concepts developed in RQ 1-3 is necessary to make ‘exact measurements’ about configuration systems in engineering companies.

Research question 4 and 5 has focus on engineering companies, and tries to unravel motivations and barriers towards the application of product configuration systems in engineering companies. I perceive my two case companies as open and ever-changing systems, and the purpose

of RQ 4 and 5 is to induce and understand barriers and motivations towards application of product configuration systems in engineering companies – establishing ‘good reasons to believe’. Ideally deductive testing would have followed subsequently, and this would have completed a retroductive analysis of the two research questions. A possible way to strengthen the results of this Ph.D. could involve testing in other engineering companies. Thereby the hypothesis that the barrier to application of product configuration systems in engineering companies is establishing of consensus and not converting tacit knowledge into explicit knowledge would become more qualified, reliable and valid. It is important to note, that according to critical realism it is not possible to prove or establish absolute truths. The conclusion regarding barriers towards application of product configuration systems in engineering companies are interesting as it turned out that establishing consensus was not expected to be difficult, rather the amount of tacit knowledge in engineering was typically blamed to pose problems in configuration projects. The observation regarding tacit knowledge in this PhD study complies with the recent research of Haug (2007).

In hindsight, it would have been preferably to point out ppossible ways to handle reliability and validity issues in the thesis. There does not exist any ‘invariable truths’ (as we are dealing with open systems). However, this does not mean that knowledge can be more or less qualified. Although it is the objective of critical realism is to understand events by describing mechanisms and not to predict outcome of future events, critical realism still breaks away from the relativism of more interpretive approaches. As we remember, the truth and validity criteria for critical realism are, whether the theory is applicable, and can be falsified under relevant conditions. Regarding RQ 4, it was difficult to find any general traits regarding the motivation for product configuration. In respect to the outcome of RQ 5, I am convinced that the conclusions drawn here is applicable as well as falsifiable.

Engineering companies are not ergodic; they are open and ever-changing environments. This poses problems when trying to validate, verify, and generalize knowledge. As Hericlitius (Greek philosopher) notes:

"You could not step twice into the same river; for other waters are ever flowing on to you."

Heraclitius of Ephesus (c. 535–c. 475 BCE)

Panta rhei, "everything flows". Fresh water is flowing on, the flowing water erodes the riverbed, and the landscape is changing due to weather, season, or perhaps earthquake. Even seemingly unchanging physical settings is changed on a continuous basis - some changing faster some slower.

Therefore the conclusion drawn here depends on the context. The answer of theses questions must therefore be contextual, as it is not possible to make a closed system that resembles engineering companies, and where ergodic results can be created. RQ 4 and 5 induces hypotheses about the motivation and barriers to application of configuration systems in engineering companies. So the outcome here is hypothesis, which can be tested in other cases. To further test the reliability and validity of my claim it would be proper to carry out deductive testing. It is important to note, that is was possible to form a stronger hypothesis in RQ 5 than RQ 4 as the conclusions here was alike in both case companies.
4.2 Scientific and Industrial Value and Applicability

4.2.1 Scientific Value

Answering research questions 1-3 have created the frame of reference and belonging coherent models that make it possible to distinguish different types of configuration systems from each other. Furthermore it has made it possible to assess configuration readiness. This is a novel and theoretical contribution to the configuration community. The reference model, typology, and assessment of configuration readiness have all been presented to peers of the community on conferences with good feedback. Most importantly, answering RQ 1-3 establishes ‘clarity of concepts’ and enables ‘exact measurements’.

Secondly, answering research questions 4 and 5 has yielded specific observations related to configuration in engineering companies. The contribution has been the analysis of what the motivation is in engineering companies prior to the start of a configuration project. Furthermore, a contribution is the description of the barriers to formalizing knowledge in engineering companies. It was expected that the main barrier to formalizing knowledge in engineering companies was making tacit knowledge explicit due to the high degree of tacit knowledge that is profound to the engineering world. This turned out not to be the case, and this is also the conclusion in the Ph.D. thesis of Haug (2007). However, the novel contribution of this thesis is to pinpoint why it is difficult and time consuming to develop product configuration systems in engineering companies. It turns out it is challenging to establish consensus and consistent knowledge in professional bureaucracies and operating adhocracies. Tacit knowledge is not a problem when implementing product configuration systems in engineering companies, but establishing consensus is. This is opposed to general expectations in the configuration field or environment and is very interesting. More energy should be put in understanding the establishing of consensus when dealing with engineering companies.

4.2.2 Industrial Value

On a more practical levels, the theoretical models and frame of reference can be used understand which challenges could be encountered in a configuration project. Understanding how the configuration system affects the configuration process, and the role and relations of other systems is very valuable. As it is a coherent framework, it is easy to widen the discussion to desired type of configuration system, and configuration readiness.

4.2.3 Applicability

The models developed in RQ 1-3 are general applicable in product configuration projects across different sectors. The frame of reference can be used to understand the total configuration system (all the systems involved and how they relates to the configuration process). The typology can be used to reflect on which product configuration system should you be pursued in a given project, and what knowledge is necessary to formalise to implement the given type of configuration system. Finally, configuration readiness can be used to assess whether the knowledge needed are ready to become formalised.

Hopes this addendum answers your questions.

Best regards

Klaes R. Ladeby
5 References


This PhD thesis deals with the application of configuration systems in engineering companies and how configuration systems can be used to support their business processes. More specifically, this thesis creates a reference framework, defining key concepts and definitions. It identifies different kinds of product configuration systems, how they differ, and what the prerequisites for configuration are.