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Application of Product Configuration Systems in Engineering Companies

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Publication date:
2017

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Kristjansdottir, K. (2017). *Application of Product Configuration Systems in Engineering Companies*. DTU Management.

Application of Product Configuration Systems in Engineering Companies

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PhD Thesis
November 2017

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Title: Application of Product Configuration Systems in Engineering Companies

Published by: Department of Management Engineering Technical University of Denmark Kgs. Lyngby, Denmark

PREFACE

This PhD thesis is based on the PhD project conducted by Katrín Kristjánsdóttir. The project is carried out in collaboration with the Technical University of Denmark (DTU), the Manufacturing Academy of Denmark (MADE) and Haldor Topsoe. This thesis is the final product of the PhD project, which has been conducted over the course of three years from 15th of November 2014 until 14th of November 2017.

The PhD thesis is article-based and consists of eleven articles that have been selected for the thesis based on their relevance to the research questions. The overall objective of the thesis is to facilitate a successful application of product configuration systems (PCS) in engineering companies by providing theoretical and empirical-based evidence of the application and methods to improve the decision-making process. An overview of the articles presenting the findings of the thesis is listed in relation to each of the research questions as follows.

Research question 1: What are the main benefits of implementing and utilizing PCS in companies manufacturing customized products? The results concerning the first research question are presented with the following articles as a basis.

A. Kristjansdottir, K., Shafiee, S. and Hvam, L. (2016). Industrial Application of PCS: From Motivations to Realised Benefits. Proceedings of 18th International Conference on Industrial Engineering, October 2016, Seoul.
B. Myrodia, A., Kristjansdottir, K., and Hvam, L. (2017). Impact of Product Configuration Systems on Product Profitability and Costing Accuracy. Computers in Industry, vol. 88, pp. 12–18.
C. Kristjansdottir, K., Shafiee, S., Hvam, L., Bonev M. and Myrodia, A. The Economic Value from Applying Product Configuration Systems – A Case Study. Submitted to ISI journal (second revision), November 2017.

Research question 2: What are the main challenges that companies manufacturing customized products face in relation to the implementation and utilization of their PCS? The results concerning the second research question are presented with the following articles as a basis.

D. Kristjansdottir, K., Shafiee, S., Hvam, L., Forza C. and Mortensen, N.H. The Main Challenges for Manufacturing Companies in Implementing and Utilizing Configurators. Submitted to ISI journal (second revision), November 2017

Research question 3: How can engineering companies identify and evaluate possible applications of a PCS? The results concerning the third research question are presented with the following articles as a basis.

E. Kristjansdottir, K., Shafiee, S. and Hvam, L. How to Identify Possible Applications of Product Configuration Systems in Engineer-to-Order Companies, International Journal of Industrial Engineering and Management (Accepted).
F. Shafiee, S., Kristjansdottir, K., Hvam, L., Haug, A., Forza, C. and Sandrin, E. How to Frame Business Cases for Product Configuration Projects Success. To be submitted to ISI journal.

Research question 4: How to improve the development and maintenance of a PCS regarding product modelling and knowledge management in engineering companies? The results concerning the fourth research question are presented with the following articles as a basis.

G. Hvam, L., Kristjansdottir, K., Shafiee, S. and Mortensen, N.H. The Impact of Applying Product Modelling Techniques in Configurator Projects. Submitted to International Journal of Production Research (IJPR).
H. Shafiee, S., Kristjansdottir, K., Hvam, L. and Forza, C. How to Scope Configuration Projects and Manage the Knowledge they Require. Submitted to International Journal of Knowledge Management.

Research question 5: How can engineering companies increase the performance and accuracy of a PCS with the integration of product information retrieval in the configuration process? The results concerning the fifth research question are presented with the following articles as a basis.

I. Kristjansdottir, K., Shafiee, S., Bonev, M., Hvam, L., Bennick, M. H., & Andersen, C. S. (2016). Improved Performance and Quality of PCS by Receiving Real-Time Information from Suppliers. Proceedings of 18th International Configuration Workshop, September 2016, Toulouse.
J. Shafiee, S., Kristjansdottir, K. and Hvam, L. Automatic Identification of Products Similarities to Improve the Configuration Process in ETO Companies. International Journal of Industrial Engineering and Management (Accepted).
K. Kristjansdottir, K., Shafiee, S., Hvam, L., Battistello, L., and Forza, C. (2017). The Complexity of Configurators Relative to Integrations and Field of Application. Proceedings of the19th International Configuration Workshop, September 2017, Paris.

The full versions of the articles are appended at the end of this thesis.

Katrín Kristjánsdóttir, Kgs. Lyngby, November 14, 2017

Acknowledgements

I would like to express my sincere gratitude to those who have supported me and contributed to this PhD project.

I would especially like to thank my supervisor Professor Lars Hvam for his continuous support, motivation, enthusiasm, and his immense knowledge of the topic that he has shared with me. I am very grateful for the opportunities Lars has given me and for him making these three years of my PhD program the most enlightening period of my life. I would also like to thank my co-supervisor, Professor Niels Henrik Mortensen, for his enthusiasm, support, and knowledge sharing throughout this PhD project. I would also like to thank Professor Cipriano Forza for his support and knowledge sharing during the project and for welcoming me for an external stay at the University of Padova, in Italy. Thank you all from the bottom of my heart.

Next, would like to thank my colleagues at the Technical University of Denmark. I would like to thank Sara Shafiee and Anna Myrodia for their collaborations, support, and all the travelling over the past three years. I would also like to Sara Helene Markworth Johnsen, Martin Bonev, Manuel Korell, Alexandria Trattner, Diana Feibert, Daniel Sepúlveda Estay, Samuel Larsen, and Fatemeh Rahimi for your knowledge sharing and support as well as making this journey more enjoyable. It has been a true honour to work with you.

To my colleagues at Topsoe, I would like to thank you for your input on my research, support and motivation. I especially wish to thank my managers over the last three years—Sanna Tiina Kaarina Strand, Thomas Christensen, and Peter Elverskov—for your interest in the topic, support and motivation.

Finally, I would like to thank my family and friends for their patience and support during this period. I could not have done this without you.

SUMMARY

Engineering companies increasingly face the challenge of delivering highly customized products where time, cost, and quality are critical factors. To provide customized products efficiently, a product configuration system (PCS) is commonly implemented. A PCS supports the product configuration process, which consists of activities that involve gathering requirements from customers and generating the required product-related specifications. The application of a PCS in the industry has revealed benefits that include shorter lead-times, improved quality of specifications and products, and lower overall cost of the product. However, many PCS projects do encounter failure. With an increased focus on customized and personalized products, there is a growing need for the automation of business processes. For this reason, a PCS is becoming an essential part of IT strategy in different industries. With this point in mind, it is necessary to analyse how to facilitate a successful PCS application in engineering companies that make highly customized and complex products.

The objective of the PhD project is to facilitate a successful PCS application in engineering companies by providing theoretical and empirical based evidence of the impact from PCS applications and by suggesting methods to improve the implementation, development and maintenance of the PCS. More specifically, this project considers the main benefits and challenges related to implementing and utilising PCS. Additonally, this project takes into account identification and evaluation of PCS applications. Furthermore, the project focuses on improved development and maintenance of PCS projects by considering knowledge management and product modelling. Finally, possibilities for integrating with IT systems to retrieve product information in the configuration process are explored to increase performance and accuracy of the PCS.

This study focuses on engineering companies and aims to (1) strengthen the research field of PCS applications and (2) increase the successfulness of engineering companies in applying the PCS in terms of both successful implementation and benefits realization to greater extent. The findings presented in this PhD thesis contain empirical evidence gathered through case studies and surveys.

DANSK SAMMENFATNING

Ingeniørvirksomheder bliver i stigende grad udfordret på evnen til at levere kundetilpassede produkter i tilfælde hvor tid, omkostninger og kvalitet udgør kritiske faktorer. Konfigureringssystemer bliver derfor ofte implementeret for at kunne levere kundetilpassede produkter effektivt. Et konfigureringssystem understøtter produktkonfigureringsprocessen, som både indebærer indsamlingen af informationer fra kunder og den afledte specifikation af produkterne. Anvendelsen af konfigureringssystemer har ført til fordele som kortere lead-time, forbedret kvalitet af specifikationer og produkter samt lavere produktomkostninger. Mange konfigureringsprojekter fejler dog, og det øgede fokus på at kundetilpasse og personliggøre produkter øger derfor behovet for automatisering af forretningsprocesser. Konfigureringssystemer er som følge heraf ved at blive en vigtig del af virksomheders IT-strategier. Der er derfor et behov for at afdække hvordan konfigureringssystemer med succes kan anvendes i ingeniørvirksomheder, der producerer højt tilpassede og komplekse produkter.

Målet med dette projekt er at undersøge hvordan ingeniørvirksomheder bør facilitere anvendelsen af konfigureringssystemer ved at tilvejebringe teoretisk og empirisk evidens for anvendelsen af konfigureringssystemer samt foreskrive metoder til at forbedre beslutningsprocessen. Dette ph.d.-projekt undersøger i særdeleshed de primære fordele og udfordringer forbundet med at implementere og anvende konfigureringssystemer, samt identificerer og evaluerer mulige anvendelsesområder for konfigureringssystemer. Ydermere tager projektet højde for procesforbedringerne opnået gennem udviklingen af konfigureringssystemer såvel som muligheden for at integrere med IT-systemer for at indhente produktinformation i konfigureringsprocessen og dermed øge performance og nøjagtigheden af konfigureringssystemerne.

De præsenterede resultater søger at styrke forskningsområdet omkring anvendelsen af konfigureringssystemer og har særligt fokus på ingeniørvirksomheder. Det er ydermere ønsket, at de præsenterede resultater vil øge succesraten for anvendelsen af konfigureringssystemer i ingeniørvirksomheder, både i forhold til succesfuld implementering såvel som realisering af fordele. Denne ph.d.-afhandling er baseret på empirisk evidens indsamlet gennem case studier og spørgeskemaer.

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List of Abbreviations and Acronyms

ATO	Assembly-to-order
B2B	Business-to-business
BOM	Bill of material
CAD	Computer aided design
CM	Contribution margin
CODP	Customer order decoupling point
CR	Contribution ratio
CRC	Class Responsibility Collaborator
CRM	Customer relationship management
CTO	Configure-to-order
DRM	Design research methodology
ERP	Enterprise resource planning
ETO	Engineer-to-order
IT	Information technology
MADE	Manufacturing academy of Denmark
MTO	Make-to-order
MTS	Make-to-stock
OM	Operational management
OR	Operational research
PCS	Product configuration system
PIM	Product information management
PLM	Product lifecycle management
PVM	Product variant master
ROI	Return on investment
RQ	Research question
UML	Unified modelling language

1 INTRODUCTION

In today's competitive business environment, customers increasingly demand customized products with high quality, competitive prices, and short delivery time (Salvador and Forza 2004; Hvam et al. 2008). The present dilemma can be illustrated using a famous quote from Ford (1922): "A customer can have a car painted any colour that he wants as long as it is black." Henry Ford revolutionised the car industry by mass-producing cars, which made them affordable to a wider range of customers. However, companies today are faced with the diverse needs of the customers where it is not enough only to offer one colour, and it raises challenges to meet the diverse customers' need. Today, it is common to find customers putting their personal touch on a variety of products (e.g., cars, clothes, cosmetics, and computers) where they can select different specifications (e.g., colours, patterns, combinations, sizes, performance) as desired. A web-based product configuration system (PCS) enables customers to configure their desired products online easily and to visualize their selections before purchasing. Providing customers with customized products, however, raises challenges for companies, as they need to guide the customers in the sales processes. At the same time, the companies would need to cope with the increased complexity of both products and processes when making customized products without compromising cost, quality, and delivery time.

To address these challenges, companies have increasingly adopted principles of mass customizations and use of the PCS over the last decades. Mass customization offers a paradigm that provides an efficient way of designing and making customized products. An important support to reach this ability comes from PCS, which is an information system that supports the specification of the product configuration as well as creation and management of configuration knowledge (Heiskala et al. 2007). Companies use the PCS to guide the sales process and to increase efficiency by automating the generation of product specifications for the customized products. However, a growing tendency of engineering companies to apply the PCS for automating their specifications processes raises challenges due to product and process complexity. Engineering companies can be characterised by highly customized products, which are designed for optimal performance for each customer. Thus, challenges arise, as the implementation of PCS require the product structure to be defined so the knowledge can be incorporated into the system. Despite the challenges of implementing PCS in engineering companies substantial benefits can be achieved. Aligned increasing attention to automation of the sales and engineering processes with supporting IT systems, PCS are being applied to greater extent. Therefore, this PhD project focuses on how engineering companies can successfully apply the PCS.

1.1 BACKGROUND

This PhD project is done in collaboration with the Manufacturing Academy of Denmark (MADE), which strives "to make Denmark the world's most competitive manufacturing country" (MADE 2017). The project is part of the work package of a high-speed product development, which aims to "develop processes for product development using modular principles in product design and the use of supportive IT tools to achieve rapid development and introduction of new products" (MADE 2017). This project focuses on supporting IT tools—where the lead-time and profitability of highly customized products are considerably improved in engineering companies—by focusing on the application of a PCS. Furthermore, by integrating with other IT systems, a PCS enables companies to enhance re-usability of products designs and to retrieve information from sub-suppliers more efficiently. The overall aim of this PhD project is to foster the successful application of a PCS in engineering companies in order to increase the efficiency of the sales and engineering processes. The successfulness of the application is based on the companies' capabilities of both implementing the PCS and realizing the benefits of using the system. This section further elaborates on the theoretical background of the thesis with discussions on mass customizations, PCS, and the application of these concepts in engineering companies.

1.1.1 MASS CUSTOMIZATIONS

The concept of mass customizations was first introduced by Davis (1989) in the article "From "future perfect": Mass customizing" as a way to deliver customized products on a mass basis at a reasonable price. Thus, mass customization refers to an organization's ability to provide customized products and services that fulfil each customer's idiosyncratic needs without considerable trade-offs in cost, delivery, and quality (Pine II et al. 1993; Liu et al. 2006; Squire et al. 2009). To ensure successful implementation of mass customization, companies need to develop a solution space, and they also should have a robust process design and a choice of navigation (Salvador et al. 2009). During the last decade, the focus of mass customization has moved towards the development of rapid manufacturing technologies, web-based PCS and more structured customer interaction (Fogliatto et al. 2012). Research has shown that the PCS has become an important enabler of mass customization (Piller et al. 2004; Felfernig 2007; Heiskala et al. 2007; Trentin et al. 2011). Today, mass customization is a core strategy for successful companies, since it allows companies to profit from the fact that most customers are different (Piller and Walcher 2017). With this point in mind, this project focuses on the PCS as an enabler of mass customization in engineering companies in particular.

1.1.2 Product configuration systems

PCS is an IT system that supports design activities throughout the customization process. During the customization process, a set of components and their connections are pre-defined, and constraints are developed to prevent infeasible configurations (Felfernig et al. 2000a). The PCS is used to guide the communications with the customers and to automate the generation of the product specifications (Hvam et al. 2008).

Applications of the PCS are well known and reported in existing literature (e.g. Barker et al. 1989; Fleischanderl et al. 1998; Hvam 2006b; Petersen 2007), and the number of online web-based PCSs are continually growing. With these web-based PCS, customers are able to configure their unique product online. The increasing use of a PCS is also reflected in the car industry, where all the large brands provide an online PCS that allows customers to select different variants (e.g. colour, functionalities, and interiors) in customizing their car, both for luxury and budget cars. Thus, within specific industries, the PCS is becoming part of the industry’s standards. The cyLEDGE configurator database was established in 2007, and it now includes more than 1200 web-based configurators, supporting more than sixteen different industries (cyLEDGE Media 2013). In other words, the PCS is becoming an essential part of customers' online shopping experience across various industries.

The PCS is not only important in customers’ shopping processes, but it is also a powerful tool to improve the internal effectiveness and efficiency in companies by automating the specification process (Hvam et al. 2008). A specification process is defined as the process of generating the different product specifications (e.g., quotes, sales prices, bill of materials, CAD models). Usually, the specification process requires the involvement of employees from different departments when the company is not supported by a PCS (Hvam et al. 2008). As seen in existing studies on PCSs, there are various benefits of implementing a PCS to support the specification processes. Companies utilizing a PCS are better able to provide a variety of products, improve the quality of both specifications and products, simplify the customer ordering process, and enable more accurate cost calculations (Forza and Salvador 2002a; Salvador and Forza 2004; Trentin et al. 2012; Zhang et al. 2013; Myrodia et al. 2017). Furthermore, the PCS enables the perseverance of knowledge, the use of fewer resources, and less routine work; it also ensures timely delivery, reduces the time required to train new employees, and increases customer satisfaction (Felfernig et al. 2000b; Ardissono et al. 2003; Piller et al. 2004; Forza and Salvador 2007; Hvam et al. 2008; Zhang 2014).

1.1.3 Mass customization and PCS in engineering companies

Engineering companies have to keep up with new technologies and improve the capabilities of their products without compromising lead-time, quality, and prices (Mäkipää et al. 2012; Hvam et al. 2008). Furthermore, in the sales phase, companies make essential decisions regarding the profitability of projects and the inaccuracy in cost estimations, which can have significant consequences (Hvam et al. 2008). By overestimating the cost, the risk of losing customers increases, although conversely, underestimating the cost reduces profitability. In the pre-tender phase, inaccuracy of cost estimation is often the result of the estimation being made within a limited time and at a point when the project scope has not been entirely determined (Aibinu and Pasco 2008). Moreover, the dynamic and segregated character of the early sales and engineering processes limits the availability of design information and increases the uncertainty of a project's profitability (Mortensen et al. 2010). Studies have shown that ineffective communication across companies is a source of errors, which accounts for over 5% of the revenues in companies supplying highly complex products (Kratochvìl and Carson 2005). To respond to the above-mentioned challenges, companies have started to take advantage of mass customization. Using mass customization allows the product architecture to be improved for reusability; it also means that the PCS can be used for enhancing the availability of knowledge in the sales phase and for increasing the accuracy and efficiency of the specification processes.

Previous studies have described the transition of engineering companies towards mass customization, but the studies have mostly focused on how mass producers can move towards mass customization (Haug et al. 2009b). The movement towards mass customization requires finding the right balance between flexibility and standardization so that efficiency can be improved without compromising the capability of addressing specialised customers’ requirements (Haug et al. 2009b; Johnsen et al. 2017). Thus, companies strive to keep the external variety that provides value to the customers while reducing internal variety, which creates cost.

However, if the products are too complex, the cost of improving standardization could prove too high for the product to be profitable, especially if it is sold in low quantity (Forza and Salvador 2002a; Haug et al. 2009b). Studies indicate that engineering companies do not become true mass customizers, as they are not capable of producing customized products at prices close to standard products, even though the cost of making the specifications is significantly reduced (Haug et al. 2009b). The cost reduction of making the specifications is achieved by automating the sales and engineering processes by using the PCS; this requires improved standardization of the product range and also re-engineering of the business process that is supported with a PCS (Hvam et al. 2008). Although companies have been using PCSs since the late 1980s, companies still face challenges when implementing them for highly customized products involving engineering designs (Kratochvìl and Carson 2005; Petersen 2007). With this challenge in mind, this PhD project focuses on the successful application of PCS in engineering companies.

1.2 CHALLENGES OF APPLYING PCS IN ENGINEERING COMPANIES

Even though the literature has identified potential benefits from implementing PCS in engineering companies, many PCS projects fail to realize those benefits (Forza and Salvador 2007; Haug et al. 2012). The main reasons for project failures are lack of acceptance from the organization and PCS developments being too time-consuming and expensive (Haug et al. 2012). To ensure the successful application of a PCS in engineering companies, further research is required regarding both theoretical and empirical-based evidence of the impact from PCSs and methods to improve the implementation, development and maintenance of the systems.

Identifying the primary benefits and challenges allows for a further understanding of the current situation, and this guides the process of determining improvement areas concerning PCS application in engineering companies. First, to facilitate successful application of a PCS, the benefits of the system needs to be highlighted from the beginning of the project and emphasized throughout the project lifetime. On the contrary, the challenges of implementing and utilizing PCS have not been addressed to the same extent of the benefits (Haug et al. 2012). Thus, the main challenges of implementing and utilizing the PCS needs to be addressed in order to increase awareness of companies and to improve the rate of successful applications (Forza and Salvador 2007; Haug et al. 2012). Additionally, the importance of the challenges remains unknown. Because of this, it can be difficult for practitioners and researchers to prioritise attention to the different challenges.

Identification and evaluation of PCS application is a fundamental step, where effectiveness is increased by selecting the most promising PCS projects. Identification and evaluation of the PCS are critical to align different stakeholders and prioritize the various projects. This is especially important in engineering companies because of the vast product variety and process complexity (Hvam et al. 2008). This usually leads to the implementation of numbers of PCSs in the same company, i.e. supporting specific product families, product segments, or a specific process, e.g., sales or engineering. Thus, it is of importance both to identify and evaluate the different PCSs applications to allow for the projects to succeed.

Improving the development and maintenance process of the PCS is also essential for enabling a shorter, development time and for increasing reliability of the systems. In developing and maintaining a PCS, common challenges include knowledge management and product modelling (e.g. Tiihonen et al. 1996; Aldanondo et al. 2000; Felfernig et al. 2000; Forza and Salvador 2002a, b; Ardissono et al. 2003; Hvam et al. 2006; Haug and Hvam 2007; Heiskala et al. 2007; Shafiee et al. 2017). In PCS projects, knowledge management includes acquisition, modelling, validating, testing, and the documentation of knowledge. These activities need to be performed throughout the PCS's lifetime so that the system can be aligned with the company's product offerings. Product modelling is an activity within the knowledge management, which is concerned with formalising the knowledge in a structured way; this way allows for communication and validation, and it provides the mechanism to model the knowledge into the PCS (Hvam et al. 2008). The reliability of the PCS is highly dependent on the quality of the knowledge.

Finally, in engineering companies, customization exists on different levels of design, and as a result, there is a great variety of information from within the companies and outside the companies from different sub-suppliers. This point underlines the fact that a centralised knowledge base is not desired and that there is the need to have distributed PCSs across the organisation's supply chains (Ardissono et al. 2003a; Zheng et al. 2017). Furthermore, it is important to have the PCS integrated with other IT systems so that product information can be retrieved in the configuration process and that similar previously made products can be easily identified. Thus, by establishing integrations with other IT systems, the efficiency in PCS projects can be increased. Moreover, the quality and the accuracy of the system's performance can also be improved simultaneously.

For a successful application of the PCS in engineering companies, the above-mentioned challenges are addressed in this study. Five main research questions are developed—these are illustrated in Figure 1-1 and are further elaborated in Section 2.3.

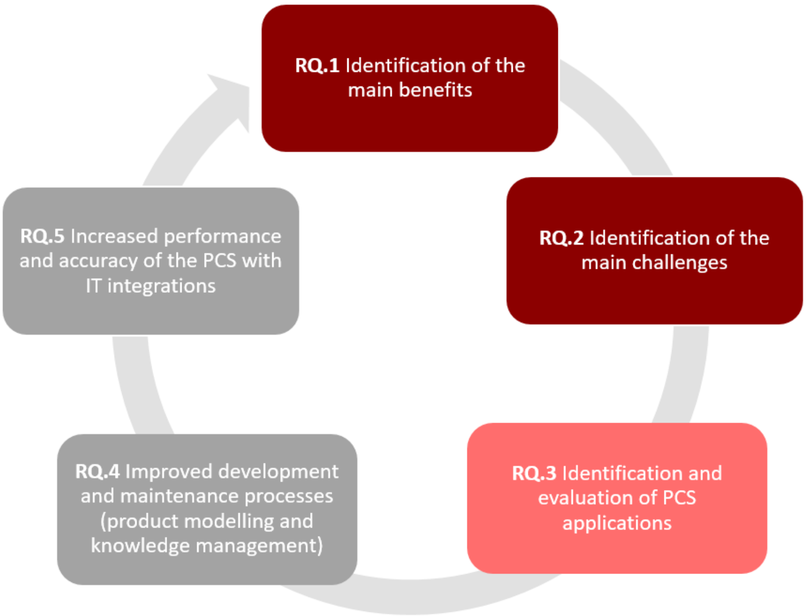

Figure 1-1 The identified aspects influencing successful application of PCS in engineering companies

This study analyses the impact and the outcomes of using a PCS and proposes methods to improve the decision-making process, especially in relation to identifying and evaluating PCS projects, the development and maintenance phases, and IT integrations to allow for retrieval of product information in the configuration process. Empirical data is gathered through both case studies and surveys to supplement the findings of the PhD project.

1.3 Delimitations

Aligned with the aim of analysing the application of PCS in engineering companies, this PhD project does not address the technical challenges of a PCS, nor does it investigate how these systems can be made more powerful. Thus, detailed descriptions of the programming, algorithms for solving configuration problems are not within the scope of this PhD project. Furthermore, challenges mentioned in the literature related to organizational challenges and product-related challenges are not addressed. The disciplines for addressing those disciplines are very specialised and they involve different theoretical domains that cannot be covered in the timeframe of this PhD project. Even though IT related, organizational and product-related challenges play an essential role in the successfulness of applying the PCS in engineering companies, they are left for future studies.

Finally, this project focuses on manufacturing companies that provide engineered solutions. Thus, companies offering services and products—such as finance, logistic, cosmetics, and clothing—are not considered in this PhD project. Furthermore, in engineering companies, a PCS is often used as an internal tool to increase the efficiency of the sales and design processes. For this reason, this project does not focus on the customers' experience in utilizing a PCS.

1.4 STRUCTURE OF THE THESIS

The remainder of the PhD thesis is structured as follows. Chapter 2 presents the research design, while Chapter 3 presents the theoretical background of the study concerning the research questions. Chapter 4 presents the main findings of the PhD project based on the selected articles concerning the research questions. Chapter 5 discusses the results from individual studies and elaborates on their limitations. Chapter 6 concludes the study with the main findings, and answers to the research questions are provided. The contribution to the theory and the practice are discussed and direction for further research is presented. Finally, the articles introduced in this PhD thesis are attached as an appendix.

2 RESEARCH DESIGN

This chapter introduces the research design. First, the philosophical position of the thesis is presented, followed by the research methodology, which is based on Design Research Methodology (DRM). The research aim, research questions, and the research methods used in the PhD project are presented. The chapter concludes with the communication of the obtained results in this PhD project.

2.1 PHILOSOPHICAL POSITION OF THE THESIS

This section introduces the philosophical position of the thesis, and the purpose is to provide insight into the fundamental beliefs and assumptions behind this PhD project.

In research, beliefs and assumptions are undertaken when developing knowledge, and these can be explained regarding research philosophy or paradigms adopted by the researcher (Saunders et al. 2009). These paradigms can be distinguished based on the answers concerning the ontology, epistemology, and methodology (Wynn and Williams 2012). Ontology can be defined based on assumptions of reality, while epistemology defines the assumptions about knowledge, and methodology is concerned with how individuals discover knowledge in a systematic way. Regarding the paradigms, there are five of them commonly adopted in research, and these are positivism, interpretivism, critical realism, postmodernism and pragmatism (Saunders et al. 2009).

In this thesis, the philosophical position taken is critical realism. Critical realism was first proposed by Bhaskar (1985) as an alternative philosophical paradigm to positivism and interpretivism (Bhaskar 2008; Wynn and Williams 2012). Positivism is concerned with believers of objective reality where the world is external to the individuals. On the other hand, interpretivism (or constructivism) is concerned with observations and social constructs that are dependent, and the reality is dependent on the individuals (Croom 2009). Contradictory to direct (or naive) realism where the assumption is that viewers get what they see, critical realism focus on understanding "what they see" regarding underlying structures of reality, which influences the observable events (Saunders et al. 2009).

For critical realism, the ontology can be defined based on realism, and the epistemology is based on eclectic realist/interpretivism (Easton 2010). In greater detail, the ontology can be seen through three layers—the empirical, the actual and the real (Bhaskar 1978; Saunders et al. 2009). The empirical layer defines events that are observed and experienced, while the actual layer defines events or non-events—or even both—that are generated by the real layer which may or may not be observed. Finally, the real layer defines causal relations and mechanism with constant properties, where the epistemology can be based on the historical value of knowledge and on social facts that do not exist independently (Bhaskar 1978; Saunders et al. 2009).

Critical realism does not depend on quantitative and correlation analysis alone. With critical realism, various methods are acceptable and certain choices of research methods should be made in line with the phenomenon studied and concerning the aim of the analysis (Sayer 2000; Saunders et al. 2009). Mingers (2000) argued that critical realism is particularly relevant for operations research (OR) and operations management (OM). Firstly, it allows for a realistic stance where the critiques of direct (naive) realism are accepted. Secondly, it addresses both social and natural science by covering hard, soft and critical approaches. Finally, it fits the applied nature of OR/OM disciplines.

This section aimed to provide explanations for the fundamental assumptions taken in this project concerning ontology and epistemology. The following sections form the core of this chapter, and it concerns all aspects of the research design.

2.2 RESEARCH METHODOLOGY

This section explains the research methodology adopted in this PhD project, and it elaborates on the main concept and the stages of the research methodology. To guide the research methodology, this project uses the design research methodology (DRM) framework presented by Blessing and Chakrabarti (2009). The DRM framework is proposed for design research, and it should enable researchers to succeed in the academic and practical arenas (Blessing and Chakrabarti 2009). Through an iterative process, the DRM framework enables increased understanding (e.g. knowledge and theory) and development of support (e.g. tools and methods) as the primary outcome of the framework (Blessing and Chakrabarti 2009).

The DRM framework offers clear guidelines for young researchers, and thus the framework is particularly meaningful for this project. Additionally, it allows for iterative research design where both qualitative and quantitative data can be used to increase the understanding of the phenomenon.

The main concept of the DRM framework is to view the research as it is continually progressing through distinct research stages with specific outcomes and deliverables (Blessing and Chakrabarti 2009). The DRM framework consists of four different stages: (1) research clarification, (2) the descriptive study I, (3) prescriptive study, and (4) descriptive study II (Blessing and Chakrabarti 2009). Figure 2-1 illustrates the main stages of the framework where the red arrows represent the main process flow and the white arrows represent the iterations between the stages.

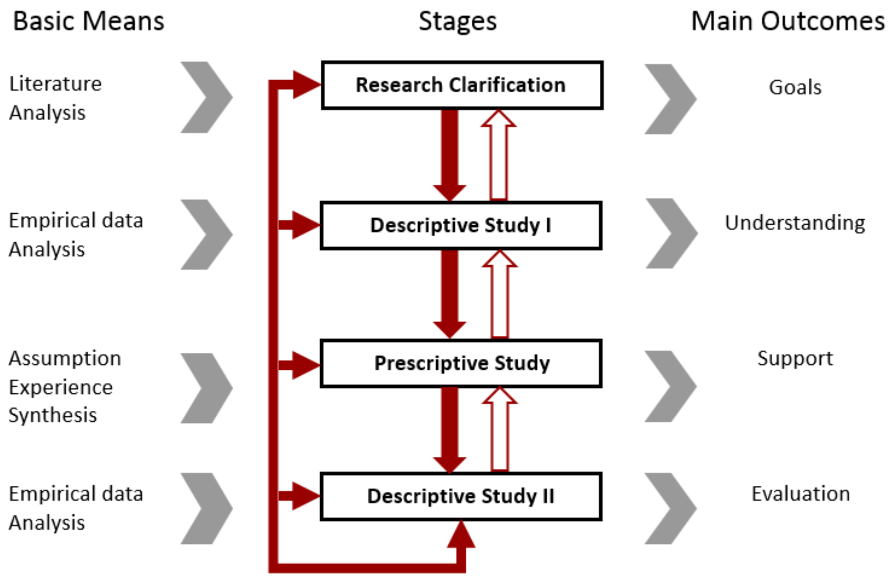

Figure 2-1 DRM framework ***adopted*** *from* Blessing and Chakrabarti (2009)

The four stages of the DRM framework by Blessing and Chakrabarti (2009) are explained below in addition to how they contribute to this PhD project.

Research clarification is concerned with clarifying the goal of the research. This is achieved by reviewing the literature to describe the current situation and the desired future situations. The main deliverables at this stage include the development of initial reference and the impact models describing the current situation and the future desired situation. At this stage, the overall research plan is made. This plan describes the main research problem, the formulation of research questions and hypothesis, a review of relevant disciplines and areas, and an identification of the area where contribution is expected. This work should guide the process in the following stages.

The work related to research clarification includes initial literature review conducted at the start of the PhD project. Reviews and discussions were conducted with supervisors and industrial partners; based on these reviews and discussions, the initial research aim, questions and plan were developed. During the PhD project, these three items were consistently adjusted to be in line with the changes in the project. At times when addressing one question, new questions would also appear, and some of these became included in the research design. Thus, the primary research questions presented are not the result of the initial project design; rather, they have been developed in an iterative process over the time of this PhD project. Furthermore, to evaluate and improve the results from this stage, feedback from researchers and PhD students is used to improve the research design, and this was obtained from the doctoral seminars (e.g., organised by EUROMA, MADE).

Descriptive study I is where literature and empirical data are used for developing a detailed description of the current situation. At this stage, a comprehensive literature review is performed to clarify the focus. Furthermore, initial empirical data to support the focus of the study is also gathered. The primary deliverables at this stage are a completed reference model, which includes both success criteria and measurable success criteria.

In the descriptive study I stage, the literature related to the primary research questions is examined in order to gain an understanding of the phenomenon of interest. This stage also includes an initial empirical analysis of the phenomenon, and in this project the analysis is based on case studies and surveys. Furthermore, as this project is done in close collaboration with Haldor Topsoe, initial empirical data could be used to verify the research questions before analysing the phenomenon in greater details.

Prescriptive study is concerned with the description of the desired situation based on the current one. Thus, the support for improving the current situation is developed at this stage. The main deliverables include an intended impact model, an intended support description, and an introduction plan.

In the prescriptive study stage—which is based on literature and empirical analyses—support is proposed to improve the current situation and move closer to the desired future situation. Thus, in this stage, different frameworks have been developed to help practitioners identify and evaluate PCS applications, improve development and maintenance of PCS projects, and improve performance and accuracy of PCS projects with integrated IT systems. The development of the proposed frameworks was discussed with both the research team and the industrial partners in order to validate and guarantee that essential aspects are covered. Furthermore, the proposed frameworks were presented in conferences to receive feedback from other researchers and practitioners.

Descriptive study II is concerned with investigating the impact of the identified support from the prescriptive study stage. The deliverables of this stage include the final documentation of the support, evaluation, and the results of applying the support and the implications.

In the descriptive study II, the developed frameworks (or supports) are evaluated in collaboration with the case companies. Application evaluation—also known as support that can be used for the intended situation—was achieved through collaboration with other researchers and practitioners. Success evaluation—or the usefulness and implications of support—was considered through the reflection of the obtained results from applying the frameworks.

The DRM framework is not considered to be a linear process with start and end points; rather, depending on the project, the starting point can be on any of the stages where all of them do not necessarily have to be finalised. Figure 2-2 shows how the overall research questions and the publications of this PhD project are placed concerning the different stages of the DRM framework. The research questions are further elaborated in Section 2.3, and the publications are introduced in Section 2.5.

Research questions / Stages of the DRM framework	Research Clarification	Descriptive Study I	Prescriptive Study	Descriptive Study II
Research design	Initial literature review Project plan			
RQ.1 What are the main benefits of implementing and utilizing PCS in companies manufacturing customized products?		A, B, C		
RQ.2 What are the main challenges that companies manufacturing customized products face in relation to the implementation and utilization of their PCS?		D		
RQ.3 How can engineering companies identify and evaluate possible applications of PCS?				E, F
RQ.4 How to improve the development and maintenance of a PCS regarding product modelling and knowledge management in engineering companies?		G		H
RQ.5 How can engineering companies increase the performance and accuracy of a PCS with the integration of product information retrieval in the configuration process?		I, K		J

☐ Stages covered in this PhD project

Figure 2-2 The stages of the DRM applied in relation to the publications included in the PhD thesis. Adjusted from Blessing and Chakrabarti (2009)

2.3 RESEARCH AIM AND RESEARCH QUESTIONS

This section introduces the research aim and the research questions of the project.

RESEARCH AIM:

To facilitate successful application of a PCS in engineering companies by providing theoretical and empirical based evidence of the impact from PCS application and by suggesting methods to improve the implementation, development and maintenance of the PCS.

The overall research aim is broken down into five research questions, each dealing with a specific area. The individual research questions are then further broken down into sub-questions. The following sections explain the individual research questions and the relevance in addressing them.

2.3.1 The main benefits of implementing and utilising PCS

The first research question explores the main benefits that companies can realise by implementing and utilising PCS. To explore the benefits, a literature review is conducted, from which numerous benefits are identified and categorised (Section 3.2). Based on the initial literature review, some open questions about the benefits are identified as further explained in Section 3.2.2. To address these open questions, RQ1 is formulated as follows.

RESEARCH QUESTION 1:
What are the main benefits of implementing and utilizing PCS in companies providing customized products?

RQ 1.1: What are the main motivations that companies manufacturing customized products have for implementing a PCS?
RQ 1.2: How successful are companies manufacturing customized products in achieving the benefits associated with the initial motivations?

First, previous studies have mentioned various benefits that companies have realised from implementing PCS. However, prior to the implementation, the clarity of the initial motivations and to which extent the companies realise the related benefits needs further research. Few studies have described the motivation behind the implementation of a PCS based on single case studies, (e.g. Sviokla 1990; Ariano and Dagnino 1996; Forza and Salvador 2002b; Hvam 2006b). However, these studies do not explicitly determine to which extent the benefits related to the motivations are realised. Thus, this project explores this point more thoroughly, as well as the main categories of motivations that companies have for implementing a PCS.

RQ 1.3: What is the impact on the accuracy of the cost calculations and consequently the impact on product profitability when supported with PCS?

Second, the impact of the PCS on the accuracy of the cost calculations and the product profitability is analysed. The literature has mentioned that the PCS improves quality of the generated product specifications (e.g. Sviokla 1990; Forza and Salvador 2002a; Heiskala et al. 2005a). Furthermore, the PCS enables the salesperson to offer custom-tailored products within the boundaries of standard product architectures, thereby allowing companies to be in more control of their product assortment (Forza and Salvador 2002a; Hvam et al. 2008). As the various benefits are described from implementing a PCS, it can be assumed that those benefits have a direct impact on the company's profitability relating to increased contribution ratios and more accurate cost estimations in the sales phase. However, this relationship has not yet been established in the literature, and thus highlights the importance of addressing the PCS impact on the accuracy of the cost calculations and consequently product profitability.

RQ 1.4: What is the actual economic value creation from implementing and utilising a PCS companies manufacturing customized products?

Third, the economic value creation from implementing and utilising a PCS is analysed. Several studies have noted that companies can achieve an economic value from implementing and utilising a PCS (e.g. Barker et al. 1989; Sviokla 1990; Fleischanderl et al. 1998; Forza and Salvador 2002b). However, there is a lack of research that breaks down the actual savings (e.g., regarding reduced work-hours) to the cost of development, implementation, and maintenance. Even though numerous of benefits can be expected, it is necessary to compare them with the cost to realise the return on investment, referred to here as economic value creation.

2.3.2 The main challenges of implementing and utilising PCS

The second research question explores the main challenges of implementing and utilising a PCS. The challenges related to a PCS have not been addressed in the literature to the same extent as the benefits where the success of implementations tend to be highlighted instead (Haug et al. 2012). However, many projects involving the adoption of PCS do experience failure (Forza and Salvador 2007), and consequently, the benefits from the use of company resources and the company innovativeness are lower than they could be. To address these challenges, RQ2 is formulated as follows.

RESEARCH QUESTION 2:
What are the main challenges that companies manufacturing customized products face in relation to the implementation and utilization of their PCS?

RQ 2.1: What are the main categories of challenges that companies manufacturing customized products face when implementing and utilising their PCS?

First, to provide more understanding of the actual challenges companies face when implementing and utilising PCS, the main categories of challenges needs to be identified.

RQ 2.2: What is the importance of each category of challenges that companies manufacturing customized products face when implementing and utilising their PCS?

Second, the importance of the main categories of challenges is analysed. While previous studies have identified a number of challenges associated with PCSs, the relative importance of the challenges remains unknown. The impact is mentioned by researchers (e.g., Barker et al. 1989; Ariano and Dagnino 1996; Forza and Salvador 2002a, b; Haug and Hvam 2007; Haug et al. 2012; Myrodia et al. 2017; Shafiee et al. 2017) however these studies are all based on single companies and do not compare the importance of the different challenges. For practitioners and academics, it would be useful to know which of the many challenges have the most significant impact. This would inform companies regarding the critical areas needing managerial attention and research efforts, and this information could support a strategic prioritisation of investment to address these challenges.

RQ 2.3: Which specific challenges within each category do companies manufacturing customized products face when implementing and utilising a PCS?

Third, the specific challenges within each of the main categories are analysed. Thus, the specific challenges within each of the main categories are identified to provide more understanding of the actual challenges within each of the identified main categories of challenges.

2.3.3 Identification and evaluation of PCS applications

The third research question explores how to identify and evaluate application areas for PCSs. This is an especially important topic in engineering companies where there are vast product variety and the complexity of products and processes, which require gradual implementation of PCS. This usually leads to the implementation of multiple PCSs, namely supporting specific product families, product segments, or a specific process (e.g., sales or engineering). This point raises the questions of how the different applications can be identified and how they can be evaluated so they can be prioritised and stakeholders would be aligned accordingly to increase the successfulness of the PCSs implementation. To address these challenges, RQ 3 is formulated as follows.

RESEARCH QUESTION 3:
How can engineering companies identify and evaluate possible applications of PCSs?

RQ 3.1: How can possible applications of PCSs be identified in engineering companies?

First, the identification of PCSs application in engineering companies is analysed. Several studies have described different strategies for the development of a PCS (e.g., Felfernig et al. 2001; Forza and Salvador 2007; Hvam et al. 2008; Haug et al. 2012; Shafiee et al. 2014), but they neglect to identify the different applications of the strategies. This is especially important in engineering companies because of the vast product variety and the process complexity that result in multiple PCSs

(Hvam et al. 2008). Thus, identifying the possible applications of PCSs in a structured way is essential in providing an overview and in aligning different stakeholders by providing a plan for the different PCS projects to pursue.

RQ 3.2: How can business cases be framed in order to evaluate the potential applications of PCSs?

Second, to evaluate different application areas of PCSs, the framing of business cases is analysed. The successfulness of PCS is not only concerned with identifying different areas but also with constructing business cases. Such a construction enables a comparison of different applications so they can be prioritised, and the benefits and economic value from the implementation can be highlighted and communicated throughout the project. Even though the benefits from implementing a PCS are evident, there are still difficulties associated with high cost of development, as well as chances of failure in PCS projects (Forza and Salvador 2006; Haug et al. 2012). The complexity of a PCS (Ardissono et al. 2003; Salvador and Forza 2004) and the range of different stakeholders with different expertise (Hvam et al. 2008; Haug 2010) makes it difficult to anticipate the expectations and implementation costs of the PCS (Friedrich et al. 2014b). This highlights the need of providing a systematic way of constructing business cases for PCS projects.

2.3.4 Improved development and maintenance of PCS

The fourth research question is concerned with the improved development and maintenance of PCS projects. Aligned with the scope of this study, this question focuses on product modelling and knowledge management, which are common challenges in PCS projects due to vast knowledge that needs to be continuously validated and updated throughout the system's lifetime. To address these challenges, RQ4 is formulated as follows.

RESEARCH QUESTION 4:
How to improve the development and maintenance of a PCS regarding product modelling and knowledge management in engineering companies?

RQ 4.1: What is the impact of using formal modelling techniques in PCS projects?

First, the impact of using formal modelling techniques in PCS projects is analysed. In PCS projects, one primary task is to structure and represent the knowledge of the configuration model (e.g., Aldanondo et al. 2000; Forza and Salvador 2002; Felfernig et al. 2004; Hvam 2006; Shafiee et al. 2017). This task is described as one of the challenges in PCS projects (e.g., Tiihonen et al. 1996b, 2013; Felfernig 2007; Shafiee et al. 2017). To address these challenges, previous studies have proposed different modelling methods and knowledge representation methods for PCS projects. Thus, the aim of this study is not to propose a new method but rather to explore the impact of utilising the existing methods in PCS projects. This is important for justifying the resources spent on developing and maintaining these product models and for making analyses when more formalised modelling methods are needed.

RQ 4.2: How is knowledge acquired and maintained in PCS projects?

Second, the ways in acquiring and managing knowledge in PCS projects are analysed. Knowledge management in PCS projects is one of the most time-consuming tasks for stakeholders involved in PCS projects. Knowledge management is an integrated process incorporating a set of activities to create, store, transfer, and apply knowledge to a knowledge business value chain (Aurum et al. 2008). The challenge of knowledge management can be seen in the entire life cycle of knowledge—from the stage of acquisition (Tiihonen et al. 1996b; Hvam et al. 2008) to modelling, validating, testing (e.g. Magro and Torasso 2003; Tseng et al. 2005; Yang et al. 2009; Hansen et al. 2012), and finally to documenting and updating (Haug and Hvam 2007; Hvam et al. 2008; Shafiee et al. 2017). Such a multi-step cycle highlights the need for a systematic way to acquire and manage knowledge in PCS projects.

2.3.5 Improved performance and accuracy of the PCS with IT integrations

This part of the study is especially aimed at engineering companies where there is a high customisation on the different level of the designs. This results in an overflow of product information that has to be included both internally with the companies and externally from different sub-suppliers. This information might not be easily accessible, and there is a risk of them not being up-to-date. This can result in the PCS not being able to handle different configurations or the output from the PCS not being accurate. To address these challenges, RQ5 is formulated as follows.

RESEARCH QUESTION 5:
How can engineering companies increase the performance and accuracy of a PCS with integrations allowing for product information retrieval in the configuration process?

RQ 5.1: What is the impact of integrating multiple PCS across supply chains to retrieve product information in the configuration processes?

To address the complexity of vertically integrated supply chains in engineering companies, the PCS knowledge base needs to cover up-to-date product information related to both the companies' own designs and the outsourced components or modules from suppliers. There are some limitations in including the suppliers' information as sub-models in the PCS, since the information is often confidential and sensitive. Therefore, critical design details and cost structures, which are often considered as confidential information, are not shared from the suppliers' side. This can result in an insufficient level of detailed information being provided that can affect the overall quality of the configuration. Furthermore, the rapidly changing components and modules supplied internally or externally increases the effort for maintaining the PCS knowledge base. This increases the risk of operating with outdated prices and variant designs, thereby decreasing the overall quality of the systems and the generated output. This point underlines that centralised knowledge base is not desired, which emphasises the need of having distributed PCS across the organisations supply chains (Ardissono et al. 2003). However, its successful implementation and the actual impact of receiving the information directly from suppliers in the configuration processes have not been addressed in previous literature.

RQ 5.2: How to automatically identify the most similar previously made products to improve the configuration process?

Second, the identification of the most similar previously made project in the configuration process is analysed. With producing complex and highly engineered products, a significant problem arises when calculating the prices in the presale and sale processes, especially when domain experts cannot determine accurate price curves, or when vendors fail to provide sufficient information for modelling within the PCS. Alternatively, in engineering companies, prices and other data based on previously made products are used as a base for the new design. However, this method affects the accuracy of calculations as previous projects are not easily accessible; also, significant work is required for manually comparing new products with previous ones to find the relevant information (Hvam et al. 2008). Thus, it is of importance to quickly and automatically identify the most similar products previously made in the configuration process.

RQ 5.3: What is the relationship between the complexity of the PCS and the users of the system?
RQ 5.4: What is the relationship between the complexity of the PCS to integrated IT systems?

Finally, the last set of research questions aims to analyse the complexity of the PCS regarding the users of the system—namely sales, engineering, or both—and integrations to other IT systems. PCS can be used to support different specification processes at companies, and these processes can include sales, design, engineering, production, or a combination of the above; usually, PCS supports the engineering processes that are considered more complex (Hvam et al. 2008; Shafiee et al. 2017). However, a direct comparison of PCS supporting the different types of users within the same company has not been conducted. Furthermore, a PCS is usually integrated with other IT systems (e.g., ERP, CAD, CRM, PLM and PIM systems).

However, previous literature has not addressed what influences integrated IT systems will have on the PCS complexity when integrations to other system are made. This is an important aspect as the complexity affects the performance of the PCS and influences the developing and maintenance effort.

2.4 RESEARCH METHODS

This section describes research methods used in the research. To gather empirical data, the research method adopted in this project is based on case studies and surveys, both of which address the nature of the questions *what* and *how*. Figure 2-3 gives an overview of the different studies in relation to the articles, research methods, case companies and research questions.

RQ. 1 What are the main benefits of implementing and utilizing PCS in companies manufacturing customized products?

Article A	Survey (S1)		RQ. 1.1 and 1.2
Article B	Case Research	Case company 1	RQ. 1.3
Article C	Case Research	Case company 2	RQ. 1.4

RQ. 2 What are the main challenges that companies manufacturing customized products face in relation to the implementation and utilization of their PCS?

Article D	Survey (S1)		RQ. 2.1, 2.2, and 2,3

RQ. 3 How can engineering companies identify and evaluate possible applications of a PCS?

Article E	Case Research	Case company 3	RQ. 3.1
Article F	Case Research	Case companies 3 and 4	RQ. 3.2

RQ. 4 How to improve the development and maintenance of a PCS regarding product modelling and knowledge management in engineering companies?

Article G	Survey (S1)		RQ. 4.1
Article H	Case Research	Case companies 3 and 4	RQ. 4.2

RQ. 5 How can engineering companies increase the performance and accuracy of a PCS with the integration of product information retrieval in the configuration process?

Article I	Case Research	Case company 5	RQ. 5.1
Article J	Case Research	Case company 3	RQ. 5.2
Article K	Survey (S2)		RQ. 5.3 and 5.4

Figure 2-3 Overview of the different studies in relation to the research method and research questions

2.4.1 Case Research

The main strength of case research is seen in how the phenomenon can be studied in its natural settings using the questions of *why*, *what* and *how* (Meredith 1998; Voss 2009). For this reason, case research is used for answering the research question of *how* and *what* in this project. Case research can be defined as “a study that investigates a contemporary phenomenon (the ‘case’) in depth and its real-world context, especially when the boundaries between phenomenon and context may not be evident” (Yin 2013). The phenomenon investigated in the project is the application of a PCS, with engineering companies as the context. For this project, it is important to understand the phenomenon in its context, as the application of PCS within engineering companies has different requirements than for companies making less complex products. In addition, case research can be used for different research purposes, which include exploration, theory building and testing, and theory extension and refinement (Voss 2009). This type of study highlights the real-world context in which the phenomenon occurs and where the theory-building process can be conducted by a cycling process with the data gathered from the case study, the emerging theory, and extant literature (Eisenhardt and Melissa 2007). The reliability and validity of case research can be described using the dimesons of construct validity, internal validity, external validity and reliability (Voss 2009).

In this project, case research is used as the primary method to collect empirical data, and five case companies are used. The companies are presented anonymously since some of the presented findings involve sensitive data of the companies (e.g., the accuracy of the cost calculations and profitability). It should be observed that case companies C3 and C4 are used in several studies, while case companies C1, C2 and C5 are only used in single studies. Table 2-1 lists the main characteristics of the case companies included in this project.

Table 2-1 Overview of the case companies used in this PhD project

Case Company	Production Strategy	Industrial Sector	Product Type	Business Type	Market
C1	CTO and ETO	Construction	Building units	Consumers	Local and Global
C2	CTO and ETO	Mechanical	Mechanical devices	Business and Consumer	Global
C3	ETO	Machines, plants	Process plants, machines	Business	Global
C4	ETO	Construction	Buildings	Business	Local and Global
C5	ETO	Machines, plants	Process plants, machines	Business	Global

2.4.1.1 Selection of cases

Single cases allow the phenomenon to be studied in greater detail, but the main disadvantage with single cases is generalisability (Voss 2009). By using multiple cases, the limitation of generalisability can be overcome, but an in-depth study of the phenomenon may not be possible since more resources are required (Voss 2009). Using multiple cases studies can show whether the findings are merely distinctive to a single case or consistently replicated by several cases (Eisenhardt 1991).

In this project, both single and multiple cases studies are used. Studies B, C, E, I, and J contain single case studies, while in studies F and H, multiple cases are used. There are two considerations for including both single and multiple cases studies in this project. The first is based on the required depth of the analysis, and this point is addressed using studies B, C, and I, all of which deal with the impact of using PCS. The second is based on availability and time constraints, and this is addressed using Studies E and J, both of which are on validating frameworks. In studies F and J, multiple cases are used, where a case is defined based on PCS projects, and thus allows more than one case to be defined by the same company.

The case companies selected for the research have some similarities that make it possible to compare the results across the cases. In line with the focus of the project on successful PCS application in engineering companies, all of the case companies are companies that provide engineered solutions. Companies C1 and C2 provide customised solutions, where the solution space is more defined and thus classified primary by CTO products. Both companies are not classified as traditional engineering companies, but they both have some projects that require engineered solutions and thus share some of the traits as engineering companies. Companies C3, C4, and C5 can be classified as traditional engineering companies where their products offerings are primary classified based on ETO products, which are made based on the specific customer's requirements. The five companies have an established market share globally with primary operations in Denmark. Another point they have in common is that they fit the research objective of this project as they either have a PCS currently in place or are in the process of developing a PCS.

2.4.1.2 Setup of the case studies and data gathering

This section elaborates on the execution of the case research in Studies B, C, E, F, H, I, J. Studies A, D, G, K are based on surveys, and these are later explained in Section 2.4.2. Table 2-2 summarises the setup of the case studies of this project and the data gathering.

Table 2-2 Setup of the case studies and data gathered

Setup	Data gathered
Study B (C1) • Analysed the impact on the accuracy of the cost calculations and the impact on product profitability when supported by the PCS. • Historical data was gathered before and after implementation of the PCS.	• Estimated cost and actual cost of each project sold was recorded • After the implementation, the projects sold are categorised based on whether the PCS is used or whether Excel was used to generate the proposals in the sales phase • The data was extracted from the company's databases and verified with specialists
Study C (C2) • Analysed the economic value creation from implementing and utilising the PCS • Historical data was gathered at the company, which included analysis before and after the implementation of the PCS • Analysis covers two product families at the company	• Process flow description was based on interviews • The time required to generate specifications was based on interviews • The sales quantity of the product families was extracted from the company's internal system • Measurements of the quality of specifications were extracted from the company's internal systems, which covers a one-year period • Cost of the developing, implementing (2-year period) and cost of maintenance (5-year period) were based on interviews and project reports.

Study E. (C3) • Analysed framework validation: Identification of possible applications of a PCS • Five workshops over the five-month period were organised, each of which lasted an average of 1.5 hours.	• Result of main steps of the framework was recorded • Feedback was taken from the workshops, both on the framework and the results from the frameworks' individual steps.
Study F. (C3, C4) • Analysed framework validation: Framing business cases for PCS projects. • The unit of analysis in the study is company projects; in Company C3, the presented framework was tested on two PCS projects, and in Company C4, it was tested on one PCS project.	• Workshops were held for the primary stakeholders to introduce the proposed framework and the tools suggested in the individual steps of the framework • Semi-structured interviews were used to collect data about the team's satisfaction with the proposed framework • Results were taken from the individual steps of the frameworks and the benefits and challenges of applying the framework.
Study H. (C3, C4) • Analysed framework validation: Scoping and managing knowledge in PCS projects • The unit of analysis in the study is company projects; in Company C3, the presented framework was tested on three PCS projects, and in company C4, it was tested on one PCS project. The framework is tested on the second version of the PCS projects.	• Workshops were held for the primary stakeholders to introduce the proposed framework and the tools suggested in the individual steps of the framework. • Semi-structured interviews were used to collect knowledge about the team's satisfaction with the proposed framework. • Results were taken from the individual steps of the frameworks and the benefits and challenges of applying the framework.
Study I. (C5) • Analysed the impact of having integrated PCS across companies supply chains. • Interviews were conducted at the case company and with the sub-supplier that had been set up with the integration	• The interviews were recorded and afterwards written up and coded to analyse the responses. From the case company, both the manager of the configuration team and a business developer were interviewed. From the sub-supplier, a business manager and IT specialist were interviewed. • Data of the accuracy of the configuration generated before and after the integration with the sub-supplier was provided from the case company.
Study L. (C3) Analysed framework validation: Automatic identification of product similarities to improve the configuration process The framework is validated in C3, where one highly customised product of a currently running PCS in the company is selected for the framework validation	• Data of the analysed product over a 10-year period was taken. • Feedback was taken from workshops with the primary stakeholders regarding the usability of the framework and the developed IT system

2.4.2 Surveys

In operational management, surveys are widely used for gathering empirical data (Forza 2016). In survey research, information from individuals is gathered concerning the individuals themselves or they social unit they belong to (Malhotra and Grover 1998; Forza 2016). This is usually done through mailed questionnaires, telephone interviews, and face-to-face interviews. A population can be considered a group of people, firms, or plants; to represent a population, a sample is used for collecting information, where the sample is a fraction of the population (Malhotra and Grover 1998; Forza 2016). The selection of the sample determines the accuracy of the analysis and thus the sample is selected according to certain rules (Rea and Parker 2005).

There are different types of surveys, which can be classified as exploratory, descriptive, and explanatory (Kerlinger 1986; Filippini 1997; Malhotra and Grover 1998). Exploratory research is conducted to become more familiar with the studied phenomenon and provide a foundation for more in-depth survey research (Malhotra and Grover 1998; Forza 2016). Descriptive studies examine the distribution of a phenomenon within a population (Malhotra and Grover 1998). Finally, the explanatory phase is where a framework is defined to justify the relations between variables (Filippini 1997). In this phase, the causal relations among the variables are tested (Malhotra and Grover 1998). Aligned with the maturity of the literature on the application of PCS in engineering companies, this PhD project takes advantages of explorative surveys. The results from the surveys thus provide a vital insight into the phenomenon studied and where the results can be used to guide the design for larger surveys (descriptive and explanatory).

The survey research process is linked to the theoretical aspects of the study, and it also involves design, pilot testing (can lead to revised design), data collection, data analysis, and the generation of a report (Forza 2002, 2016). The conceptual model developed would differ depending on the type of research, but it can generally be said that the more developed the model is, the better it is for any survey research (Forza 2016). When designing and conducting a survey research, there is a trade-off between time and cost constraints while taking into the account errors, which can be categorised as sampling errors, measurement errors, statistical conclusion errors, and internal validity errors (Forza 2016). In this project, two explorative surveys are used, which are further elaborated in the following sections.

2.4.2.1 Survey 1

Survey 1 (S1) is used in this project to explore the main motivations, challenges and the impact of using formal modelling techniques in PCS projects (Table 2-3). The aim of the survey is to provide more understanding in relation to the successful application of PCS and thus explorative research design is selected. To obtain a clearer understanding of the companies, the survey was administered by a combination of e-mails questionnaires and telephone interviews. Following section describe the respondents, the questionnaire design, and the data collection in details.

Table 2-3 Overview how the survey 1 (S1) is used in this PhD project

Aim	Research questions	Article
Identification of the main motivations and realised benefits	RQ 1.1 and RQ 1.2	A
Identification of the main challenges	RQ 2.1, RQ 2.2 and RQ 2.3	D
Identification of the impact of using formalised modelling methods	RQ 4.1	G

Population and sampling

The Danish Association for Product Modelling are used for identifying companies that fulfil the selection criteria for the study. The criteria required manufacturing companies that provide customised solutions and have experience of using PCS to support their specification processes. Brainstorming sessions were conducted to identify additional companies of relevance. During the interviews, respondents were also asked to list other companies that might fulfil the selection criteria. However, it was not possible to obtain answers from all of the companies, and in some cases, the companies did not complete the questionnaires. Thus in the different studies, the number of companies varies depending on the results presented. In studies A and D, the results are presented based on 22 companies, while in study G the result presented is based on 18 companies. Research has shown that small sample sizes are justifiable in the context of exploratory research, which is the case for this study (Isaac and Michael 1995; Dattalo 2007). In Table 2-4 to Table 2-7, some of the main companies' characteristics are illustrated.

Table 2-4 Company size with regard to the number of employees

Number of Employees in the Companies	Distribution
Minimum number of employees: 20	
450	≤ 25%
500	≤ 50%
1100	≤ 75%
Maximum number of employees: 15,000	

Table 2-5 Company experience using PCS

Years of Using the Configurators	Distribution
Minimum numbers of years using configurators: 3	
7	≤ 25%
10	≤ 50%
13	≤ 75%
Maximum numbers of years using configurators: 25	

Table 2-6 Number of PCS in use at the companies

Number of Configurators in Use	Distribution
Minimum number of configurators: 1	
1	≤ 25%
2	≤ 50%
5	≤ 75%
Maximum number of configurators: 20	

Table 2-7 Main product types offered by the companies

Product types	Number of companies
Agricultural machines	2
Boilers	1
Building systems	6
Control boards	1
Heating systems and components	1
Hydraulic components	1
Machines	2
Machining tools	1
Mechanical devices	3
Plants and machines	1
Power infrastructure and electronic systems	1
Ventilation systems	2

One person from each company was responsible for answering the survey. These representatives were chosen based on their familiarity with the PCS, irrespective of their formal role at the company. It should be noted that top-level management might not possess the required in-depth knowledge of the PCS. Another point worth noting is that those responsible for managing PCS occupy different positions within the organisational structure of participating companies.

Questionnaire design

In the design phase, a rough draft of the questionnaire was developed based on the literature and on brainstorming sessions, which helped to specify the survey's primary constructs. This study is a part of a more extensive data set, but the following is a further description of the questions used as a part of this project. Table 2-8 shows an example of the questions in the questionnaire in relation to the studies, which are based on the survey.

Table 2-8 Examples of the questions asked in the questionnaire

Sections	Examples of topics or questions
General information	Number of employees, product type offered, number of PCS used, number of users, the year in which the first PCS is implemented
Identification of the main motivations and realised benefits	What are the main motivations for the implementation of the configurator? [Open question] To which extent do you agree that the company has obtained the following benefits from using the PCS [On a 5-point scale where 1 represents *strongly disagrees*, and 5 *strongly agrees*]. In total, the companies were asked about 22 benefits (e.g., shorter time to generate proposals, better documentation, and maintenance of knowledge, and reduction of routine work).
Identification of the main challenges	What are the three greatest challenges your company has faced when implementing and utilizing the PCS as planned? [Open question] On a 5-point scale, ranging from 1 (*not important*) to 5 (*very important*), please rate the importance of the following challenges: IT challenges, product modelling, organizational challenges, resource constraints, product-related challenges, and knowledge acquisition.
Identification of the impact of using formalised modelling methods	The following questions are asked in relation to the PCS to determine the complexity: number of attributes, number of constraints and is the PCS integrated with the following IT systems. [ERP, CRM, CAD, PLM, calculation system, other. If other, what?] The following questions are asked to identify modelling methods used in PCS project: were modelling techniques used during the development and maintenance of the PCS? [Yes, No] If modelling techniques were used, please indicate if some of the following techniques were used: [Class diagrams, PVM, CRC cards, structured bill of materials, flowcharts, other. If other, what?].

To establish external validation of the questionnaire and ensure that the respondents were familiar with how the questionnaire worked in practice, three pilot studies were conducted. The pilot interviews focused on testing the relevance of questions and instruments to ensure that they were sensible. The interviews also ensured that the formulations were accurate and that assumptions were explicit. The pilot interviews led to a moderate update of the questionnaire, mainly concerning the wording for increased clarity.

Data collection

First, the questionnaires were e-mailed to respondents, along with a description of the study's purpose, the interview procedure, and follow-up notification. Appointments were made for phone interviews, which were conducted as a walkthrough of the questionnaire. The interview process enabled clarification and elaboration of responses to ensure correct and consistent interpretation of the questions. The process also ensured that the interviewer would gain a comprehensive understanding of the company setting. During the interview, the researcher made notes of the respondent's answers. Immediately after the interview, the completed questionnaire was e-mailed to the respondents for verification while the interview was fresh in their minds, and a few respondents used the opportunity to modify their answers. Each interview lasted from 40 to 90 minutes, depending on the complexity of the configuration setting and the particular situation.

2.4.2.2 Survey 2 (*S*2)

Survey (S2) is used in this PhD project to analyse the complexity of PCS regarding the users of the system and concerning integrated IT systems. This study is still ongoing where the aim is to gather information from more companies. The following sub-sections provide more details on the respondents, the questionnaire design, and data collection. Table 2-9 lists how the results of the survey are used in this project.

Table 2-9 Overview how the survey 2 (S2) is used in this PhD project

Objective	Research questions	Publication
Complexity of PCS related to field of application and integration	RQ 5.3 and RQ 5.4	K

Population and sampling

The respondents of the survey include a company that has a world-leading position in providing process plants and related equipment for industrial use. The company has utilised the PCS since 1999 and has currently 159 operational PCSs, which support the product specification processes in both sales and the engineering. Thus, the company has extensive experience from working with the PCS. The unit of analysis in this study is based on the number of operational PCSs, and a questionnaire was filled out for each of the PCS at the company.

Questionnaire design

To analyse the complexity of the PCS in relation to the field of application and integrated IT systems, a questionnaire was developed and reviewed several times by the research team in order to check consistency. This study is part of a more extensive data set, but the focus here is on the questions related to the complexity of the PCS, which constitutes to the focus in this project. Table 2-8 provides an example of the questions of the questionnaire in relation to the findings of this project.

Table 2-10 Example of the questions asked in questionnaire

Sections	**Examples**
Users of the PCS and department supported	For what purpose is the PCS used for? To support sales (front-office), to support engineering/design (back-office), or both? Who are the users of the PCS? Proposal engineers, design engineers, sales, after sales, management, procurement, R&D, or other?
Complexity of the PCS	Number of rules, number of attributes, and number of input fields (are fields in the PCS the require some actions from the user, e.g. numerical or text input, selection from dropdown list)
Integrations with other IT systems	Is the PCS integrated with other IT systems? Yes, No If yes, which IT systems are integrated with the PCS? ERP, CAD, simulation systems, CRM, PLM, calculation systems (e.g. Matlab), other?

Data collection

The questionnaire was e-mailed to the company, and an interview was later set up. Based on the first interview, it was decided that the data gathering process would be conducted in collaboration with one of the project manager from the configuration team for two days. The data was gathered from internals systems and evaluated by the project manager to check for accuracy and consistency.

2.5 COMMUNICATION OF THE RESEARCH AND LIST OF PUBLICATIONS

The primary results of this project have been submitted to international conferences and academic journals. In total, 25 articles have been written in the period of this project; 16 of these were submitted to conferences, and nine were written for academic journals. Out of the 16 conference articles, seven have been further developed into journal articles. The reason for not developing the other nine conference articles is due to the time constraint of this PhD project, which is limited to three years. Additionally, two articles were written directly for the journal version, which means that nine journal papers have been produced over the entire period of the PhD project. Out of these nine journal papers, four were accepted, with two under a third revision, another two under a second revision, and one is to be submitted.

In the remaining parts of this thesis, some selected articles are addressed. The reason for not including all articles is to limit the focus of the PhD thesis, and thus only the most essential contributions in line with the research questions are included. However, all the articles are introduced in this section as they contribute to the final results of the PhD project based on the knowledge obtained from the studies. Their results have guided the research design (as explained in Section 2.2) where the iterative approach is used to identify the presented research questions. The following sub-sections introduces the conference articles and then the journal articles.

2.5.1 CONFERENCE ARTICLES

Throughout the project, conferences have been used as a platform to obtain verification and feedback for further improvements of the different articles. Additionally, conferences are a platform to make the research more visible in the research community and invoke the interest of other researchers. As previously mentioned, 16 papers have been published in international conferences during the course of this project. All of the conference papers have been peer-reviewed and improved upon based on the received comments. The following table is the list of publications in relation to the research questions of this thesis. The publications that are further elaborated in the thesis are indicated by an uppercase letter.

RQ 1: What are the main benefits of implementing and utilizing PCS in companies manufacturing customized products?

A Kristjansdottir, K., Shafiee, S. and Hvam, L. (2016). Industrial Application of PCS: From Motivations to Realised Benefits. Proceedings of 18th International Conference on Industrial Engineering, October 2016, Seoul.

B Myrodia, A., Kristjansdottir, K. and Hvam, L. (2015). Impact on Cost Accuracy and Profitability from Implementing Product Configuration System – A Case-study. Proceedings of 17th International Configuration Workshop, pp. 11–17, September 2015, Vienna.

C Kristjansdottir, K., Shafiee, S., Hvam, L., Bonev, M. and Myrodia, A. (2016). Quantification of Benefits and Cost from Applying a Product Configuration System. Proceedings of the 7th international conference on mass customisation and personalization in Central Europe, September 2016, Novi Sad.

\- Myrodia, A., Kristjansdottir, K., Shafiee, S. and Hvam, L. (2016). Product Configuration System and its Impact on Product's Life Cycle Complexity. Proceedings of In Industrial Engineering and Engineering Management (IEEM), 2016 IEEE International Conference, pp. 670-674, December 2016, Bali. doi:10.1109/IEEM.2016.7797960

RQ 3: How can engineering companies identify and evaluate possible applications of a PCS?

E Kristjansdottir, K., Shafiee, S., & Hvam, L. (2016). Development and Implementation Strategy for the of Product Configuration Systems in Engineer-to-Order Companies. Proceedings of In Industrial Engineering and Engineering Management (IEEM), 2016 IEEE International Conference, pp. 1809-1813, December 2016, Bali. doi:10.1109/IEEM.2016.7798190

\- Kristjansdottir, K., Shafiee, S. and Hvam, L. (2015). Utilising Product Configuration Systems for Supporting the Critical Parts of the Engineering Processes. Proceedings of In Industrial Engineering and Engineering Management (IEEM), 2015 IEEE International Conference, pp. 1777–1781, December 2015, Singapore. doi:10.1109/IEEM.2015.7385953

\- Kristjansdottir, K., Hvam, L., Shafiee, S. and Bonev, M. (2016). Identification of Profitable Areas to Apply Product Configuration Systems in Engineering-to-Order Companies. In Managing Complexity (pp. 335-350). Springer International Publishing.

\- Shafiee, S., Kristjansdottir, K. and Hvam, L. (2016). Business Cases for Product Configuration Systems. Proceedings of 7th international conference on mass customisation and personalization in Central Europe, September 2016, Novi Sad

\- Johnsen, S.M., Kristjansdottir, K and Hvam, L. (2017). Improving Product Configurability in ETO Companies. Proceedings of the 21st International Conference on Engineering Design (ICED 17) Vol 3: Product, Services and Systems Design, Vancouver, August 2017, Vancouver.

RQ 4: How to improve the development and maintenance of a PCS regarding product modelling and knowledge management in engineering companies?

H Shafiee, S., Hvam, L. and Kristjansdottir, K. (2015). Goal-Oriented Data Collection Framework in Configuration Projects. In Managing Complexity (pp. 351-365). Springer International Publishing.

\- Shafiee, S., Kristjansdottir, K. and Hvam, L. (2016). Industrial Experience from Using the CPM-Procedure for Developing, Implementing and Maintaining Product Configuration Systems. Proceedings of 18th International Conference on Industrial Engineering, October 2016, Seoul.

\- Shafiee, S., Kristjansdottir, K., Hvam, L., Felfernig, A. and Myrodia, A. (2016). Analysis of Visual Representation Techniques for Product Configuration Systems in Industrial Companies. Proceedings of In Industrial Engineering and Engineering Management (IEEM), 2016 IEEE International Conference, pp. 793–797, December 2016, Bali. doi:10.1109/IEEM.2016.7797985.

RQ 5: How can engineering companies increase the performance and accuracy of a PCS with integrations of product information retrieval in the configuration process?

I Kristjansdottir, K., Shafiee, S., Bonev, M., Hvam, L., Bennick, M. H., & Andersen, C. S. (2016). Improved Performance and Quality of PCS by Receiving Real-Time Information from Suppliers. Proceedings of 18th International Configuration Workshop, September 2016, Toulouse.

J Shafiee, S., Hvam, L., & Kristjansdottir, K. (2015). How to Analyse and Quantify Similarities between Configured Engineer-To-Order Products by Comparing the Highlighted Features Utilising the Configuration System Abilities. Proceedings of 17th International Configuration Workshop, pp. 139-145, September 2015, Vienna.

K Katrin Kristjansdottir, Sara Shafiee, Lars Hvam, Loris Battistello and Cipriano Forza (2017). The Complexity of PCS Relative to Integrations and Field of Application. Proceedings of 19th International Configuration Workshop, September 2017, Paris.

\- Sara Shafiee, Katrin Kristjansdottir, Lars Hvam, Loris Battistello and Enrico Sandrin, Usage Frequency of Product Configuration Systems Relative to Integrations and Fields of Application, IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), 10-13 December 2017, Singapore

2.5.2 JOURNAL ARTICLES

To establish communication with an audience regarding research, journal articles is a reliable platform resulting from a more intensive reviewing process. As mentioned in Section 2.5, nine journal papers have been written in the period of the PhD project; the majority are these are undergoing revision. As for the conference articles, the publications with an uppercase letter are further elaborated in the thesis. It should also be observed that some of the journal publications have the same uppercase letter as the conference articles, which means that the journal article is based on the conference article. The journal publications included in the PhD are listed as follows in relation to the research questions.

RQ 1: What are the main benefits of implementing and utilizing PCS in companies manufacturing customized products?

B Myrodia, A., Kristjansdottir, K., and Hvam, L. (2017). Impact of Product Configuration Systems on Product Profitability and Costing accuracy. Computers in Industry, vol. 88, pp. 12–18. doi:10.1016/j.compind.2017.03.001.

C Kristjansdottir, K., Shafiee, S., Hvam, L., Bonev M. and Myrodia, A. The Economic Value from Applying Product Configuration Systems – A Case Study. Submitted to ISI journal (second revision), November 2017.

RQ 2: What are the main challenges that companies manufacturing customized products face in relation to the implementation and utilization of their PCS?

D Kristjansdottir, K., Shafiee, S., Hvam, L., Forza C. and Mortensen, N.H. The Main Challenges for Manufacturing Companies in Implementing and Utilizing Configurators". Submitted to ISI journal (second revision), November 2017.

RQ 3: How can engineering companies identify and evaluate possible applications of a PCS?

E Kristjansdottir, K., Shafiee, S. and Hvam, L. How to Identify Possible Applications of Product Configuration Systems in Engineer-to-Order Companies, International Journal of Industrial Engineering and Management (Accepted).

F Shafiee, S., Kristjansdottir, K., Hvam, L., Haug, A., Forza, C. and Sandrin, E. How to Frame Business Cases for Product Configuration Projects Success. To be submitted to ISI journal.

RQ 4: How to improve the development and maintenance of a PCS regarding product modelling and knowledge management in engineering companies?

G Hvam, L., Kristjansdottir, K., Shafiee, S. and Mortensen, N.H. The Impact of Applying Product Modelling Techniques in Configurator Projects. Submitted to International Journal of Production Research (IJPR).

H Shafiee, S., Kristjansdottir, K., Hvam, L. and Forza , C. How to Scope Configuration Projects and Manage the Knowledge they Require. Submitted to International Journal of Knowledge Management.

\- Shafiee, S., Hvam, L., Haug, A., Dam, M. and Kristjansdottir, K. (2017). The Documentation of Product Configuration Systems: A Framework and an IT solution. *Advanced Engineering Informatics*, 32, 163–175. doi:10.1016/j.aei.2017.02.004.

RQ 5: How can engineering companies increase the performance and accuracy of a PCS with integrations of product information retrieval in the configuration process?

J Shafiee, S., Kristjansdottir, K. and Hvam, L. Automatic Identification of Products Similarities to Improve the Configuration Process in ETO Companies. International Journal of Industrial Engineering and Management (Accepted).

3 THEORETICAL BASIS

This chapter establishes the ground for the theoretical background of this project based on the presented articles. First, the structure of a PCS and its applications are elaborated to provide more understanding of the nature of the PCS. The primary motivations and the benefits of implementing and utilising a PCS are explained and categorised, followed by the main challenges of implementing and utilising a PCS. The chapter also discusses the development and maintenance of a PCS, particularly with business cases, product modelling and knowledge management. Lastly, the chapter concludes with a discussion on integrated IT technologies and PCSs that allow for automatic retrieval of product information in the configuration process.

3.1 STRUCTURE AND APPLICATIONS OF PCS

The section describes the structure, integrations, and applications of a PCS in order to establish a more fundamental understanding of these type of IT systems.

3.1.1 STRUCTURE OF PCS

First to define the configuration task the definition by Mittal and Frayman (1989) is used. Based on a pre-defined set of components, which are described by set of properties (attributes) and their values, connections of the components (ports) and constraints to prevent infeasible configurations and possible criteria for for making optimal selections; the task can be defined as building one or more configurations satisfying all of the requirements (Mittal and Frayman 1989). According to Trentin et al. (2012), the fundamental functions of a PCS are described in several ways. A PCS communicates product offerings to customers and performs completeness and validity checks. Moreover, it generates real-time information of the product variant; such information can be related to price, costs, delivery terms, and technical characteristics. In addition, it generates quotations and produces the product data required to build the product variant requested (Trentin et al. 2012).

The underlying IT structure of a PCS consists of configuration knowledge representation and reasoning, conflict detection and explanation, and a user interface (Felfernig et al. 2014a). The knowledge base, which represents the actual product data and the configuration logic, is the most fundamental component of the PCS

(Blecker et al. 2004). The configuration processes for complex products can be overwhelming in terms of the number of solutions that can be selected, which can result in optimal solutions being ignored (Tiihonen and Felfernig 2010). Another important aspect is to provide an explanation for the users of the system, such as why specific choices are not allowed in the configuration process (Jannach et al. 2007). Furthermore, the users of the system should not be overloaded by choices in the configuration processes, which require the PCS to guide the user and recommend suitable solutions. Thus, a recommendation system is suggested in the IT architecture of the PCS (Tiihonen and Felfernig 2010). These recommendation technologies can be integrated into the PCS to support the user in the configuration process (Tiihonen et al. 2014).

The PCS can be applied as standalone software; it can also be applied as data-integrative and application-integrative systems (Blecker et al. 2004). Data-integrative PCS can be used to avoid data redundancies, as application-integrative PCS allow communication across different of IT systems (Blecker et al. 2004). Sources for master data for the configuration process can be described as follows. Customer relationship management (CRM) systems keep track of information and communications with customers (Forza and Salvador 2007). Meanwhile, enterprise resource planning (ERP) systems store the production-relevant data of materials required for the assembly process (Krebs 2014; Arana et al. 2007). Product data management (PDM) and product lifecycle management (PLM) systems are used to keep track and to store production-related data, and product information management (PIM) systems are used to maintain sales relevant data (Krebs 2014).

In addition, calculation software capable of performing complex calculations and simulations can be integrated with PCSs. To generate drawing models of the configured product, PCSs are integrated with CAD systems (Arana et al. 2007; Stjepandić et al. 2015). Furthermore, the PCS can be integrated into suppliers' configurators to retrieve the required product data of outsourced components in the configuration processes (Ardissono et al. 2003; Zheng et al. 2017). Finally, different multiple PCSs within the same company can be integrated to increase the level of automation in the overall process, such as with commercial and technical PCSs (Forza and Salvador 2007).

However, challenges arise when enabling interoperability across different applications. This can result from having diverse software applications, models, data repositories programming languages, and operating systems (Jardim-Goncalves et al. 2007). Thus, a model-driven architecture combined with service-oriented architecture is proposed for managing the interoperability of internal and external applications and systems for the PCSs (Jardim-Goncalves et al. 2007).

3.1.2 Application of PCS

PCS support the specification processes in companies, PCS can be applied to support the processes partially or entirely. A specification is defined as a description that explicitly demonstrates the needs or intention of one group to another and which also is generated throughout the product's lifecycle (Hvam et al. 2008). A specification process can be defined as the business process required to make these specifications. Figure 3-1 illustrates a simplified specification process in engineering companies.

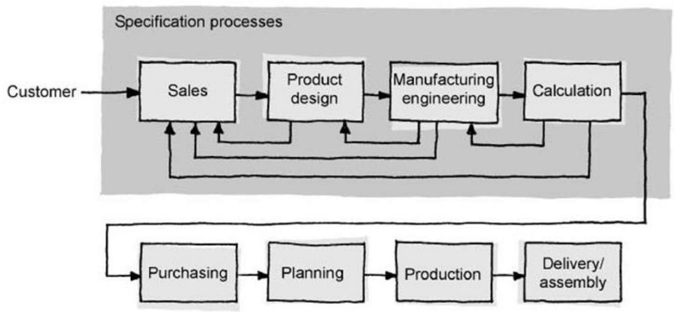

Figure 3-1 Example of specification processes in engineering companies (Hvam et al. 2008)

In the specification processes, there are numerous departments and actors involved. For instance, in the sales phase, the input is often required from product design and manufacturing. This knowledge separation leads to a change of responsibility, and this separation increases both time and potentials errors (Hvam et al. 2008). By embedding the knowledge of the product in the PCS, there can be a greater accessibility to the knowledge for a wider range of employees in the different phases of the specification processes, and thus different departments are less dependent on input from each other. Figure 3-2 illustrates how the specification processes can be supported with a PCS.

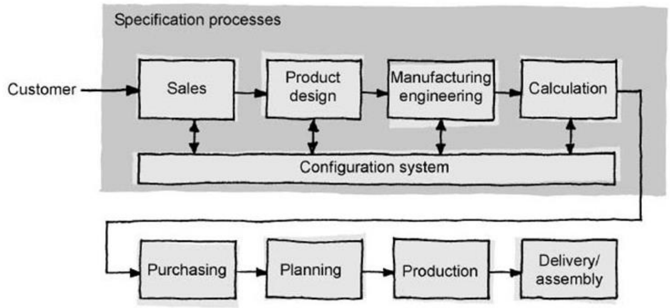

Figure 3-2 Example of specification process in an engineering company when supported by a PCS (Hvam et al. 2008)

The actual product configuration process can be defined as "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 and Salvador 2007). The overall product configuration process can be divided into the commercial and technical configuration processes (Forza and Salvador 2007), which are also defined as sales and order-fulfilment configurators respectively (Arana et al. 2007).

The commercial configuration process is when a product that fulfils the customer's need is identified and the main characteristics of the product are determined (Forza and Salvador 2007). The commercial configurators may be used by the customer where the system allows them to configure a product (e.g., on the Internet) and visualise the changes and impacts of specific selections. Alternatively, the system can be used as an internal tool to support the company's employees (e.g. salespersons, product designer, engineers) during the product configuration process (Blecker et al. 2004; Hvam et al. 2008). The technical configuration process generates documentation for the product based on the input gathered during the sales phase (Forza and Salvador 2007). At this stage, the technical specifications of the product are made based on the commercial configuration. This process can vary in engineering companies where the product is not only based on standard components and thus requires design customisation (Arana et al. 2007). The technical specifications can then be used as a basis for production or assembly planning (Arana et al. 2007).

The application of a PCS in companies is highly dependent on the order fulfilment strategy that is a definitive component of the manufacturing strategy. Order fulfilment strategies can be defined based on the customer-order-decoupling point (CODP), which distinguishes between the work carried out before and after the customer places the order (Hvam et al. 2008). The CODP can also be defined in terms of the separation of the decisions made under uncertainty from the decisions made based on customers' demand; the position of the CODP determines the optimal balance between the productivity and flexibility in companies (Rudberg and Wikner 2004). To this end, Hvam, Mortensen and Riis (2008) focused on the specification process where they distinguished between order fulfilment strategies in terms of engineer-to-order (ETO), modify-to-order (MTO), configure-to-order (CTO) products, and selected variants based on the degree of preparedness of the specifications when the customer enters the ordering process (Figure 3-3). This classification is also named ETO, MTO, assemble-to-order (ATO) and make-to-stock (MTS) (Rudberg and Wikner 2004).

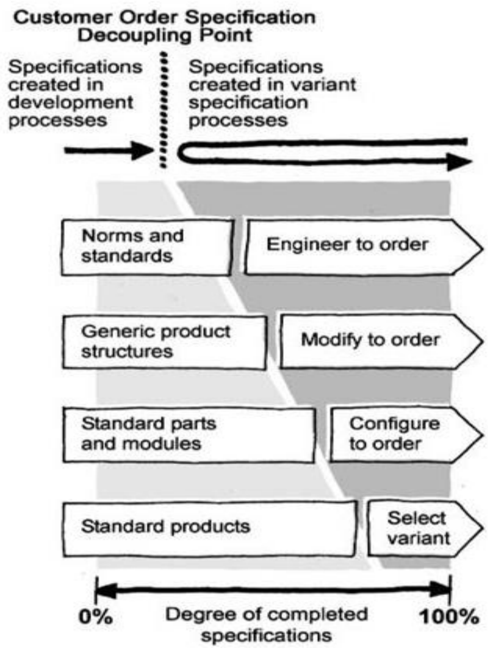

Figure 3-3 Classification of different order fulfilment strategies based on the CODP (Hvam et al. 2008) .

The application of PCS would depend on the definition of different order fulfilment strategies used in companies. In MTO and CTO/ATO companies, there is a defined solution space where modules and components are combined according to pre-defined constraints. Solution space can be defined in terms of all the product attributes a company offers to cover diverse customers' needs (Salvador et al. 2009). However, in engineering companies, the solution space is not as defined where a number of possible configurations can be close to infinite (Blecker et al., 2004). To this end, Konijnendijk (1994) argued that even for engineering companies, the solution space is limited by certain factors, such as industry standards, legislation, and internal resource constraints—therefore, the solution is not entirely unlimited. In engineering companies, PCSs are usually gradually implemented as they support a specific part of the specification process or a subset of the product families. Such is the case since it requires significant work to acquire and structure the product information that is needed to be modelled into the PCS due to the complexity of products and the specification processes. Therefore, it may not be profitable to formalise the complete product knowledge, especially if the sales volumes are low (Forza and Salvador 2002a; Haug et al. 2009b)

PCSs in engineering companies are often created with a high level of abstraction, as it can be too time-consuming to define the solution space in a more detailed way (Haug et al. 2011). This is in contrast to MTO and CTO/ATO companies where the quotes can be generated on a more detailed level (Hvam 2006a). The main output types generated by the PCS can divide the process of generating the products' specifications into three phases: (1) initial specification, (2) further product specification and (3) quote creation (Haug et al. 2011). Figure 3-4 illustrates how the level of details for the PCS can be determined based on the output generated in the sales phase.

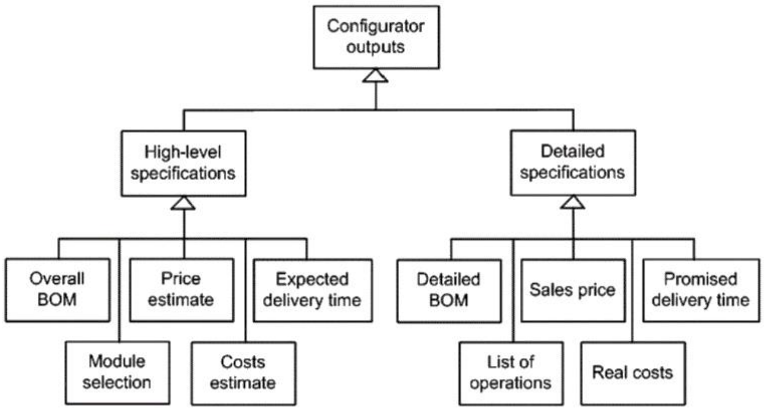

Figure 3-4 The primary output from the PCS and level of detail required (Haug et al. 2011).

Previous studies have mentioned several applications of how PCSs support highly customized products. For instance, Barker et al. (1989) presented the case of Digital Equipment Corporation. In the study, PCSs were developed for checking the technical correctness, guiding the assembly of customer's order, selecting parts that can be purchased, illustrating the computer room under design, and configuring clusters. The PCS was gradually implemented to support the complete product range, which consists of 42 product families. In a study of complex telephone switching systems presented by Fleischanderl et al. (1998), the configuration task involved selecting the right components, connecting them together and setting the different parameters. The system supported various functions at the company and the products' life cycle, such as sales, engineering, manufacturing, assembly and maintenance.

In the study by Forza and Salvador (2002), they examined a company making voltage transformers. The company implemented a PCS to support the information exchange in the sales phase, to gather data, and to ensure the validity of the configurations. The technical features were only included in the system for the simplest product family. For the more complex product families, the system supported the design activities by collecting the technical characteristics. Hvam (2006) also presented a study where a PCS was used for supporting complex engineering processes in the sales phase by automating the quotation generation for a cement plant. In the first prototype of the system, the focus was set for 20% of the parts, which generated 80% of the cost. Finally, Petersen's (2007) study explained how a PCS is used to support the sales and engineering process at Aalborg Industries A/S, which produces marine boiler for ships. The PCS was gradually implemented where one to two product families was added at each time to support the sales processes.

3.1.3 Summary: The structure and applications of PCS

This section elaborated the structure and the application of a PCS in engineering companies. The application of a PCS in engineering companies is more challenging due to less defined solution space and the complexity of products and processes. Thus, the primary focus of this project is to address the application of a PCS in engineering companies. Furthermore, the implementation and the coverage of a PCS in engineering companies have to be evaluated, and this highlights the need for identifying and evaluating the most beneficial applications of PCSs. In the following sections, different applications of PCSs in industrial settings are described based on the primary benefits and the main challenges.

3.2 THE MAIN BENEFITS OF IMPLEMENTING AND UTILISING PCS

This section describes the primary motivations expressed in the literature of implementing PCS and the benefits achieved from utilising these systems in companies where the quantifications of the described benefits are highlighted. Based on the literature, the main categories of benefits are categorised (Table 3-2).

Barker et al. (1989) presented one of the first PCS based XCON at Digital Equipment Corporation. The initial purpose of the PCS was to help employees in manufacturing to validate the technical correctness before production. Since then, the system has expanded to fulfil the different business needs to a greater extent. The main benefits of the PCS are described with an overall net return of $40 million per year. These savings can be attributed to several factors, namely the avoidance of incomplete orders, the optimisation of system performance, more efficient processes when releasing new products, increased manufacturing flexibility, and an improvement in the technical quality of the orders before entering manufacturing and thus eliminating rework. Another study is presented by Sviokla (1990), and he noted that the required demand for flexibility and constant new product development resulted in a high number of possible configurations at the company. This situation led to a lack of overview and resulted in a number of errors. To guarantee the quality of the products, a time-consuming test was performed before shipping the product to the customer. To address these challenges, a PCS was implemented eventually, and the testing process was eliminated. The benefits from eliminating the process were around $15 million in savings. Other benefits are described in terms of increased correctness (65-90% to 95-98%), increased order volumes, and shorter cycle time in the assembly process (10-13 weeks to 2-3 weeks).

Heatley, Agarwal, and Tanniru (1995) presented a Carrier corporation where a PCS was used to support operational tasks at a company making air-conditioning equipment. Initially, the PCS was implemented to support the ordering process as errors caused delays and threatened the overall quality, cost and customers' satisfaction. By implementing the PCS, correctness and completeness of the orders were significantly improved. Furthermore, the PCS eliminated both the time required for validation and the cost of re-work, which came from inaccurate specifications when entering the manufacturing. In addition, the average selection time per unit was reduced from 2 hours to 6 minutes, and the throughput cycle was reduced from 6 days to 1 day. Moreover, the orders feasible for manufacturing was increased from 40% to 100%, and orders containing pricing errors were reduced from 80% to 0%. Finally, a salesperson who has sold equipment for $2 million on average can now sell up to $4 million due to increased efficiency.

Ariano and Dagnino (1996) presented a case study based on a manufacturing furniture company. There are a few primary motivations for implementing a PCS, starting with the need to provide a system for employees to enter orders quickly and accurately. The company also wished to develop a mechanism to check the product configuration, and it also wanted to generate BOM and drawings. Several benefits came from implementing the PCS in line with the objectives of the company. First, the implementation provided an organised way to structure the company's product line. It also created a more efficient way to enter orders that can be verified for correctness and for alignment with the company's product offerings. Furthermore, it generated the dynamic BOM that enabled more accurate price estimations, and it also helped to reduce duplicated information.

Tiihonen et al. (1996) conducted a survey in 10 Finish companies to study the problems in the configuration process. In the study, a few primary motivations for

PCS implementation were mentioned. For instance, there was the need to transfer up-to-date information to the sales units and enable them to use it in the right ways. Another need was to reduce the number of errors, which should lead to improved quality. In the study by Fleischanderl et al. (1998), the applied PCS system has achieved a positive return on investment in the first year. The benefits included a greater quality of the configuration and an elimination of error-prone manual editing of parameters. Furthermore, the implementation of the PCS has enabled the training of new employees to be done in a more structured way, and knowledge also became more accessible to a broader range of employees.

Yu and Skovgaard (1998) presented a study of a SalesPlus PCS. The goals of implementation include ensuring consistency and correctness of the configurations, handling constraints, overcoming limitations with regard to maintainability, and supporting the use of configuration application in user-friendly manners. In the study by Slater (1999), the benefits of a web-based PCS are described. By using PCS, companies were able to offer the right product from the start to each customer. The PCS assisted the salespersons to have an overview of the valid configurations, and thus mistakes in communication with the customers were avoided. This resulted in the elimination of reworks on the customers' orders. The same knowledge embedded in the PCS was used for providing unique manufacturing instructions and for making rules with the correct configuration accessible to the engineers. Aldanondo et al. (2000) described how PCS could be used in industries that provide highly customised products. In such industries, there are iterative steps that lead to a long cycle time and inaccurate cost estimations. These steps also create the risk of wasted time and money if the customer rejects the solution, as well as the risk of a proposed solution being unfeasible. To address these challenges, a PCS is used to limit the number of iterations as the PCS supports knowledge gathering and error avoidance in the process.

Forza and Salvador (2002a) presented a case study where the introduction of a PCS positively affected the sales, design, engineering, and manufacturing processes at the company. Several benefits were noted, including the near elimination of errors generated in the sales process due to the automatic validity and completeness check performed by the PCS. Other benefits included a reduction of the time for generating a proposal, and consequently the work-hours were significantly reduced. The technical productivity was also increased as a result of the automation of simpler technical configurations. Finally, in the production, the correctness of the BOM generated by the PCS made it possible to avoid production stoppages that would cause delivery delays. In another study also by Forza and Salvador (2002b), a case company faced challenges in developing a correctness check of the products specifications without increasing the control cost and reducing product variety. A PCS was implemented to address these challenges, and the main benefits were reduced work-hours and lead-time (5-6 days to 1 day) and the correctness of product information generated, which became close to 100%. Furthermore, the ability to deliver on time has improved due to improved correctness and fewer errors identified in the assembly process. Finally, the PCS helped in driving the customer towards a solution within the company's preferred product range. In the third study, Forza, Trentin and Salvador (2006) presented a company that implemented a PCS along with a different product strategy, which involved postponing product differentiation. The benefits included an enabling of communications on product assortment, a faster and easier way to explore the company's product solutions, and an increased accuracy when using less time to make the offers. Finally, the PCS supported an accurate production of the products code, BOM and the production cycle. To this end, the benefits of using a PCS in the sales process were further investigated by Forza and Salvador (2007). One of the primary advantages was the PCS's capability of illustrating all possible configurations of the products in a way that is simple and understandable by the customers. This ensured that there would be no contradicting requirements and no missing specifications, and that product configurations produced are valid. Moreover, since the PCS dealt with real-time information, it helped with reducing dialogue time between salespersons and customers. Finally, the study highlighted that any kind of miscommunication between the salespersons and the customers was eliminated, and possible errors were reduced.

Hvam et al. (2004) presented a case study on a company building cement plants. The company was faced with a changed market environment and an increased pressure to deliver in a shorter time with a lower cost and improved overall performance. To respond to those challenges, a PCS was implemented to support the overall design and generation of the products' specifications in the sales process. The main benefits were a reduction in lead-time for generating quotations (15-25 days to 1-2 days), an improved quality of the quotations, the ability to optimise plant performance, and a reduction in engineering hours for making quotations (5 man-weeks to 1-2 man-days). In another study performed by Hvam (2006) at the same case company, the aim with the PCS was to increase efficiency in the sales and engineering processes. The main benefits included having a 50% reduction of manned activities in the sale process, improved quality, and more consistent budget quotations. By using default values, a quotation can be generated based on the limited input from the customer, and different solutions can be simulated; there was also an optimisation of the plant, improved communication with customers, and increased knowledge sharing. Hvam et al. (2011) performed another case study measuring the impact of implementing a PCS in the ordering process of a manufacturing company. It was noted that only a 0.45% of the specification process time was value adding; the non-value adding time spent on making the specifications could be reduced by the use of a PCS. Automating the process brought several benefits, including fewer errors, an improved productivity of employees, and a higher quality of information and documents. This was due to both reducing the standard deviation of the duration of the processes and avoiding errors in quotations. Finally, Hvam et al. (2013) conducted a study based on four companies in which the impact of using PCS was analysed. The result presented in the study showed that the lead-time for generating the specifications was reduced by about 94–99%, while on-time delivery was improved to 95–100%. The time spent on making the specification was also reduced by about 50–95%.

Using two case studies, Heiskala, Paloheimo and Tiihonen (2005) assessed service-focused benefits related to PCS that have been previously identified in the literature. The common benefits of using product PCS are described based on the point of views of customers and suppliers. These benefits were also confirmed to be applicable to service sales. Based on the previous study addressing the benefits of configurators, Heiskala et al. (2007) described benefits related to the introduction and long-term management of PCS. In this study, the challenges of mass customisation that could be addressed by using PCS were examined.

Petersen (2007) focused on the benefits in engineering companies from implementing a PCS. The benefits included a reduction of both lead-time and resources for generating quotations. The risk of errors in the sales process was also reduced because of the knowledge that has been embedded into the system and automated in the workflow. Haug, Hvam and Mortensen (2011) presented a study where 14 companies were analysed in order to evaluate the impact of implementing PCS on the lead-time for generating quotes and detailed products' specifications. For generating quotes, the average lead-time reduction was stated to be 83.7% while the average savings in work-hours was 78.4%. In terms of detailed product specifications, the average lead-time reduction was 83.5% as a result of utilising a PCS.

Trentin, Perin and Forza (2012) explored the impact of using a PCS on product quality based on survey. The findings confirmed that the use of a PCS supports higher product quality. Furthermore, their study revealed that the use of a PCS affects compatibility between product variety and product quality that can be improved. To this end, Tenhiala and Ketokivi (2012) also performed a survey of manufacturing companies, where they supported the hypothesis that the use of a PCS positively affects the production processes and the product conformance. Additionally, their findings indicated that generally among custom assemblers and producers, the use of a PCS to support the production processes is positively associated with product conformance and delivery performance.

The literature review highlighted a number of benefits in relation to implementing and utilising PCSs. In this project, the different benefits described in the literature are grouped into several main categories. These are summarised in Table 3-1, where the main categories of benefits are listed along with their quantifications.

Table 3-1 The main categories of benefits and their quantifications in relation to implementing and utilising PCS.

Benefit	Research Work	Contribution (Quantification)
Reduction in lead-time for making specifications	Heatley, Agarwal and Tanniru, 1995; Ariano and Dagnino, 1996; Aldanondo, Rougé and Véron, 2000; Forza and Salvador, 2002a, 2002b; Ardissono *et al.*, 2003; Hvam *et al.*, 2004, 2011, 2013; Hvam, 2006b; Haug, Hvam and Mortensen, 2011	- The time required for manned activities in the tendering process went from 5–6 days to 1 day (Forza and Salvador 2002b). - The lead time required for generating tenders was reduced from 15–25 days to 1–2 days (Hvam et al. 2004). - The average time needed to make an offer was reduced from 1–2 days to a few hours, and for technical specifications, from 2.5 days to a few minutes (Forza et al. 2006).

		- The real working time for preparing offers and production instructions is near zero (Hvam 2006a). - On average, the lead time required for generating proposals is reduced by 83.7% (Haug et al. 2011). - The lead time required to generate an offer was reduced by 94–99% (Hvam et al. 2013).
Conservation of work-hours and increased employee productivity	Sviokla 1990; Ariano and Dagnino 1996; Slater 1999; Forza and Salvador 2002a, b; Ardissono et al. 200b; Hvam et al. 2004, 2011, 2013; Heiskala et al. 2005a; Petersen 2007	- The engineering hours for creating quotations were reduced from 5 work-weeks to 1 to 2 work-days (Hvam et al. 2004). - The average selection time was reduced from 2 hours to 6 minutes, and the throughput cycle was reduced from 6 days to 1 day (Heiskala et al. 2005a). - The resources required to generate the quotations were reduced by 50% (Hvam 2006b). - The work-hours in the configuration process was reduced by up to 78.4% (Haug et al. 2011). - The resources needed to create product specifications were reduced by 50–95% (Hvam et al. 2013).
Improved quality of product information/specifications	Barker *et al.*, 1989; Sviokla, 1990; Heatley, Agarwal and Tanniru, 1995; Ariano and Dagnino, 1996; Tiihonen *et al.*, 1996; Yu and Skovgaard, 1998; Slater, 1999; Forza and Salvador, 2002a, 2002b, 2008; Liliana Ardissono *et al.*, 2003; Hvam *et al.*, 2004, 2011; Heiskala, Paloheimo and Tiihonen, 2005	- The accuracy of product specifications improved from 65–90% to 95–98% (Sviokla 1990). - The configuration accuracy reached 100% (Yu and Skovgaard, 1998). - Errors reduced to almost zero in configurations released by the sales office (Forza and Salvador 2002a). - The level of correctness of product information increased to almost 100% (Forza and Salvador 2002b) - The quality of specifications improved from 60% to 100%, and specifications were always ready for manufacturing (without errors). Furthermore, the pricing accuracy improved from 80% to 100% (Heiskala et al. 2005a).
Increased sales	Heatley et al. 1995; Hvam 2006b; Heiskala et al. 2007; Hvam et al. 2013	- Due to increased efficiency, a salesperson who has sold equipment for $2 million on average can now sell for $4 million (Heatley et al. 1995).
Improved product quality	Barker et al. 1989; Trentin et al. 2012	N/A

Improved on-time delivery	Forza and Salvador 2002a, b; Tenhiälä and Ketokivi 2012	N/A
Reduced production costs	Barker et al. 1989; Sviokla, 1990; Hvam 2006a	- Fixed production costs were reduced by 50% and variable costs by 30% (Hvam 2006a). - The number of assembly errors was reduced from 30% to less than 2% (Hvam 2006a).
Improved efficiency in after-sales	Hvam 2006a	- The time for replacement was reduced from 5–6 hours to 20–30 minutes (Hvam 2006a)
Improved knowledge management	Tiihonen et al., 1996; Fleischanderl et al. 1998, Slater, 1999; Forza and Salvador, 2002a; Hvam, 2006b	N/A
Improved control of product variants	Forza and Salvador 2002a, b, 2008; Tenhiälä and Ketokivi 2012	N/A
Reduced product lifecycle cost	Fleischanderl et al. 1998	- PCS supporting the complete configuration process may reduce the configuration cost up to 60% over the product lifecycle (Fleischanderl et al. 1998).
Improved customer relationships/communications	Barker et al. 1989; Heatley et al., 1995; Slater, 1999; Forza and Salvador, 2002a, 2002b, 2007	N/A

3.2.1 Economic value creation from utilising PCS

Based on the number of benefits described in relation to implementing and utilising PCS, it can be assumed that these benefits result in direct cost savings for the companies. To build upon this point, this section elaborates on the literature to provide a further understanding of the economic value creation from implementing and utilising PCS.

3.2.1.1 Cost factors in relation to PCS

Few researchers have addressed the cost factors in relation to PCS implementation. Forza and Salvador (2002a) mentioned that a high investment in terms of work-hours might be needed to introduce a PCS into a company. According to Hvam (2006b), the cost of developing and implementing a PCS is approximately $1 million with operating costs of $100,000 per year; these figures were based on an engineering company that implemented a PCS to support their sales processes. In the study, the cost is compared with the revenues of the sales going through the system, which is $500 million on a yearly basis. However, Hvam (2006b) did not link the direct cost savings achieved with PCS utilization to the actual cost, as the cost was compared to the sum of the total sales revenues in the quotations generated by the PCS. Table 3-2 summarises the previous studies that quantified the cost factors in relation to PCS.

Table 3-2 Literature that quantifies cost factors in relation to PCS

Research Work	**Method**	**Contribution (Quantification)**
Hvam 2006b	Case study based on - one company	The overall cost of developing and implementing a PCS is approximately $1 million, and the operating cost is around $100,000 per year.

3.2.1.2 Return on investment from using PCS

Some researchers have investigated the return on investment in relation to PCSs. In the study by Barker et al. (1989), even though the return on investment was not discussed, the authors did investigate the net return of the system, which is estimated to be in excess of $ 40 million per year. In another study, Fleischanderl et al. (1998) reported that the PCS in their case company achieved a complete return on investment within its first year of operation. Sviokla (1990) estimated that the system produced a savings of $15 million plus other savings from previous years, given that an expensive testing phase has been eliminated. Finally, Forza and Salvador (2002b) described how small enterprises could benefit from implementing PCSs, where they gain not only a rapid return on investment but also a competitive advantage. Table 3-3 summarises the studies that quantify the savings accrued from using PCS.

Table 3-3 Literature that quantifies the return on investment from PCS

Research Work	Method		Contribution (Quantification)
Barker et al. 1989	Case study based on one company	-	Overall net return of the PCS is over $ 40 million per year.
Fleischanderl et al. 1998	Case study based on one company	-	Using the PCS to support the complete configuration process was shown to reduce products' lifecycle cost by up to 60%.
		-	The PCS had a positive return on investment within its first year of operation.
Sviokla 1990	Case study based on one company.	-	Savings were estimated to be $15 million, plus other savings from previous years given that an expensive testing phase is no longer required.

3.2.2 Summary: The main benefits of implementing and utilising PCS

In this section, categories were formed based on the primary benefits of implementing and using a PCS, as well as the economic value creation with a particular focus on the quantification. Based on the literature presented in this section, three main research gaps are identified, which are described as follows.

Motivations. The literature described various benefits that were realised in companies from implementing and using PCS. In a few of the studies, the initial motivations for the implementation of the PCS are described. However, the literature has not provided explicit evidence on the initial motivations and to what extent the companies achieve the associated benefits.

The impact of cost accuracy on product profitability. In summarising the findings from the literature review, it can be seen that the implementation of a PCS provides various benefits. Out these benefits (e.g., increased quality of product information/specifications improved control of product, reduced production cost, and reduced product lifecycle cost) it can be that the PCS also influences the accuracy of the cost calculations and consequently the product profitability. However, there is few empirical evidence on quantifying the impact of PCS use on the accuracy of the cost calculations and the impact on improved product profitability.

Economic value creation. Research has quantified the benefits of a PCS in terms of the reduced work-hours, lead-time, and quality of product specifications. However, the literature has not explicitly described the actual economic value creation, in which the cost savings from the benefits are linked to the actual cost of the PCS. Only Hvam (2006b) mentioned and quantified the cost of PCS development and implementation. Furthermore, in terms of economic value creation, only Barker et al. (1989) quantified the net return, and Sviokla (1990) mentioned the savings; however, they did not break down the net return into cost savings and cost factors. Thus, the quantification of cost savings and cost factors related to PCS and the return on investment (referred to here as economic value creation) have not been addressed in the literature.

3.3 THE MAIN CHALLENGES OF IMPLEMENTING AND UTILISING PCS

This section explains the main challenges in relation to implementing and utilising PCS. This project concerns the challenges of implementing and utilising PCS, rather than the algorithms developed to make those systems more powerful (Section 1.3). With this point in mind, the literature review only focuses on managerial rather than technical challenges. In the reviewed studies published between 1989 and 2017, some of these challenges have been solved, such as the underdeveloped functionalities of commercial systems that fail to support users in the configuration process (Barker et al. 1989; Ardissono et al. 2003; Blecker et al. 2004). However, these these studies are still included in the literature review since their managerial implications are of relevance for present purposes.

In reporting the case of Digital Equipment Corporation, Barker et al. (1989) described strategic business challenges as cross-functional business needs. These needs could be traced to the implementation of PCS for enhancement of business processes, and they require support from top management. Several technical challenges were identified, including an underdeveloped commercial configuration software with limited functionalities. The size and complexity of the PCS was also a challenge. There were also application challenges in aligning the system with rapid product updates, as well as a problem with having limited scope to expand the system (i.e., in response to increased user requirements and an increased number of users). In managerial terms, the challenge was to develop an explicit understanding of the software. It is generally time-consuming to train new configuration experts, and maintenance has to be prioritised without limiting development tasks. Finally, resource and organisational challenges are described in relation to the awareness of key players and the roles requiring organisational change.

Ariano and Dagnino’s (1996) study found that too few employees understood the structure of the PCS, and this caused difficulties when the only employee who fully understood the system left the company. Additionally, when the primary sponsor of the projects left, the company failed to develop the system further because of a lack of support and resistance to changing traditional work practices. The company lacked the expert knowledge needed to expand the system and was unwilling to allocate the required resources despite the known benefits. In the study, it was concluded that the company lacked overall commitment.

Tiihonen et al. (1996) in 1996, published a study based on a survey of 10 Finnish industrial companies (answer rate 5.6%) to assess the state-of-the-practice in product configuration (The National Product Configuration Survey, 1995). The studied companies had not yet implemented configurators, but almost all of them were planning to do so. They identified the following five problems areas in the product configuration: economic importance of product configuration, product configuration task, product configuration processes, long-term management of product knowledge and configurations, and interfaces to other systems and processes. The identified problem areas of the product configuration and the long-term management of products and relevant information are tightly interconnected and visible in the 10 companies that the study analyzes. The challenges of configurators, when supporting the product configuration process, include: configuration knowledge (that is often not systematically documented), configurators’ ability to support parametric components, geometry, and product configuration (e.g., to generate 2D and 3D drawings of parametric instances), customer requirements at different levels of abstraction, level of automatic operations (where it is not always desirable to automate the complete process), long-term management of configurators’ models, semi-configurable products, and finally market areas that the configurator should support.

Aldanondo et al. (2000) distinguished two kinds of knowledge that are needed to develop a PCS—industrial expertise and configuration expertise. However, it can be too time-consuming to train people to become experts in both areas. Those with industrial knowledge do not usually develop the PCS, and industrial knowledge is often distributed among various employees, making it difficult to develop a comprehensive understanding. To this end, Felfernig et al. (2000) found that the complexity of PCS software development requires highly technical expert knowledge and that the knowledge base must be adapted continuously because of changing components and configuration constraints. Furthermore, the development and maintenance time for PCS was found to be short and strict.

Forza and Salvador (2002b) described the main challenges of implementing a PCS in a small manufacturing company in terms of product modelling. High product variety is often required to meet customers' differing technical needs, resulting in a complex product model, especially when there is heavy interdependency among product characteristics. Difficulties in constructing the product model can result in project delays, and challenges in documenting the product model can arise after the PCS is implemented. In another study, Forza and Salvador (2002a) identified the main challenges of PCS implementation, which were namely personal role changes, inter-function collaboration, and software personalisation. Personal role changes occurred as the system took over routine tasks, and this was considered by some employees to be a threat to their position. Moreover, difficulties in inter-function collaboration within the company made it more difficult to build the product model. Due to the consequent increases in workloads and time taken to build the product model, the company did not implement the most complex products into the PCS. Software personalisation was also considered challenging because the commercial PCS was unable to meet the company's specific needs. Forza et al. (2006) explained that for highly complex products involving a large solution space, it might not be economically feasible to implement a PCS to support all variations, not only because the costs of implementation were higher than the benefits but also because the amount of time and effort involved increased the burden. Finally, Forza and Salvodor (2007) identified several factors that would decrease the effectiveness of PCS projects, and these are related to employees roles and responsibilities. This include employees having a reduced freedom of actions, conflicts between the front and back office regarding the requirements of the PCS, excessive workload resulting from collaboration across the companies, unreasonable architecture of the product families, and excessive software customisation.

Ardissono et al. (2003) identified the main challenges experienced with PCSs, such as the increased complexity of products and services offered, which resulted in an increased complexity of the systems, making it difficult for the end-user to utilise the system due to a lack of technical knowledge. Another challenge is that companies needed to retrieve information from suppliers regarding customised products. To address this issue, a PCS software is introduced to support the end-users in the configuration process, and the software allows companies to retrieve information from suppliers. In arguing that a PCS does not sufficiently support the front-end activates, Blecker et al. (2004) emphasised the need to support customers in the configuration process and to develop an optimal solution that meets these requirements.

In the study by Heiskala et al. (2005) using two case studies, they found several challenges. These included dealing with the rapid update and maintenance requirements, knowledge acquisition, knowledge testing, maintenance that required configuration and product experts, high dependency on configuration experts, and specification errors arising from misunderstandings. Based on previous the studies addressing PCSs, Heiskala et al. (2007) described the challenges in relation to the introduction and long-term management of PCS. In the introduction phase, the main challenges were configuration knowledge acquisition, configuration of knowledge systematisation and formalisation, expertise in products and industry (in PCS, modelling, and IT), validation and testing of configuration models, integration with other IT systems, and user interface development.

Hvam, Pape and Nielsen (2006) described challenges in relation to knowledge acquisition and product modelling in configuration projects for complex products, as well as communication difficulties between domain and configuration experts. They also reported the challenges of implementing a PCS in a case company, such as the company's resistance to use the PCS because of previous unsuccessful implementations of other IT systems. In another study, Haug and Hvam (2007) reported that it is common to find that PCS documentation is not maintained once the system becomes operational because the documentation process is too time-consuming. Consequently, companies may be unable to maintain or further develop their PCS.

Petersen (2007) found that the main challenges in implementing a PCS in engineering companies were product characteristics, customer requirements, and long project time spans. In relation to product characteristics—where the complexity of products offered by engineering companies is high—product families may not be clearly defined. As customer requirements can be both diverse and highly specific, the PCS must be able to support products that have not previously been defined in the system. Finally, Petersen (2007) mentioned that it might not always be cost-effective to include all requirements in the PCS.

In the study by Haug et al. (2012), they investigated the reasons why configuration projects dealing with complex products and multiple users do not deliver the expected results or are even abandoned. Two significant difficulties have been noted in their work. First, if the configuration project is more expensive than anticipated, companies may abandon implementation to prevent further losses before a prototype is fully developed. Second, the company may refuse to accept the PCS because of the system insufficient capability to support sales and engineering processes. Finally, Haug et al. (2012) mentioned the need for sufficient accuracy and the allocation of maintenance resources to preserve alignment with the company's offerings.

Zhang and Helo (2016) conducted a survey to analyse changes in companies' business activities and also to identify difficulties and potential barriers to designing, developing, and using configurators. The survey analysed 61 companies (answer rate 20%) in computer, telecommunication systems, and industrial machinery industries. The respondents were mainly IT managers or managers with sales IT responsibilities. Their findings showed that continuous product evolution is the challenge mentioned by most respondents. Other challenges frequently mentioned included a lack of IT designers, unclear customer requirements, and employees' concern about losing their work.

Shafiee et al. (2017) described the main challenges for PCS projects in engineering companies in terms of documentation and communication with domain experts. The significant time and effort needed to maintain PCS model documentation meant that insufficient time was spent on documentation, and a lack of validation by domain experts can lead to errors in the PCS. Finally, in a study analysing the impact of PCS on the accuracy of cost calculations and consequently on product profitability, Myrodia et al. (2017) identified three challenges: lack of proper testing before launching the PCS, failure to support the entire product portfolio, and employee resistance to changes in work routines.

The literature review has highlighted six main categories of challenges: IT related, product modelling, organisational, resource constraints, product-related, and knowledge acquisition. While the studies have also described other challenges, this categorisation encompasses the most commonly reported challenges, as summarised in Table 3-4.

Table 3-4 Categories of challenges related to implementation and utilisation of PCS

The main categories of challenges	*Nature of challenges within the category*	*Main contributions*
1. IT-related	All technical challenges related to IT systems (e.g., software personalization, design of a user interface, scope expansion, interaction with software suppliers, functionalities)	(Barker et al. 1989; Tiihonen et al. 1996, 1998; Ariano and Dagnino 1996; Aldanondo et al. 2000; Felfernig et al. 2000; Forza and Salvador 2002a, 2007; Ardissono et al. 2003; Heiskala et al. 2007)
2. Product modelling	Challenges related to formalizing the product knowledge and model to be embedded in the PCS	(Tiihonen et al. 1996, 1998; Aldanondo et al. 2000; Felfernig et al. 2000; Forza and Salvador 2002a, b, Heiskala et al. 2005b, 2007; Hvam et al. 2006; Haug and Hvam 2007; Petersen 2007; Haug et al. 2012; Shafiee et al. 2017)
4. Organizational	Lack of support from management, resistance to change, allocation of resources	(Barker et al. 1989; Ariano and Dagnino 1996; Tiihonen et al. 1998; Forza and Salvador 2002a, 2007; Hvam et al. 2006; Heiskala et al. 2007; Haug et al. 2012; Zhang and Helo 2016; Myrodia et al. 2017)
3. Resource constraints	Lack of personnel to model the configurator, to gather and provide information, and dependency on resources	(Barker et al. 1989; Ariano and Dagnino 1996; Aldanondo et al. 2000; Heiskala et al. 2005b; Forza and Salvador 2007; Haug et al. 2012; Zhang and Helo 2016)

5. Product-related	Challenges in the product range, commonly described as complexity of product structure and continuous change in products	(Barker et al. 1989; Tiihonen et al. 1996, 1998; Felfernig et al. 2000; Forza and Salvador 2002a, b, 2007; Ardissono et al. 2003; Heiskala et al. 2005b, 2007; Forza et al. 2006; Hvam et al. 2006; Petersen 2007; Zhang and Helo 2016)
6. Knowledge acquisition	Difficulties in knowledge-gathering and availability of information in the development and maintenance phases	(Tiihonen et al. 1996, 1998; Aldanondo et al. 2000; Felfernig et al. 2000; Ardissono et al. 2003; Heiskala et al. 2005b, 2007; Hvam et al. 2006; Zhang and Helo 2016)

3.3.1 Summary: The main challenges of implementing and utilising PCS

While previous studies have identified a number of challenges associated with PCS, their relative importance remains unknown. For practitioners and academics, it would be useful to know which of the many challenges have the most significant impact. This would help companies to focus their managerial attention and research efforts on the most critical challenges, which in turn could support a strategic prioritisation of investment to address these challenges. The lack of surveys and studies of this kind means that companies may face other unknown challenges.

3.4 IMPROVED DEVELOPMENT AND MAINTENANCE OF PCS

This section elaborates on the literature in the field of PCS that focus on the proposed tools and methods for PCS projects. In line with the focus of the study, the section first examines development strategies proposed for PCS projects. Afterwards, business cases are reviewed and knowledge management is described based on IT projects in general and also specifically for PCS projects. Finally, product modelling and knowledge management in PCS projects is explained.

3.4.1 Frameworks for development and implementation of PCS

Studies have proposed frameworks to guide the development and implementation process in PCS projects.

Starting by defining the different activities in a PCS development projects, which include analysis and redesign of the business processes, modelling of the product range, selection of configuration software, programming, implementation and maintenance (Hvam et al. 2008). To address the different phases in PCS projects, Hvam et al. (2008) define the activities to be performed in the different phases and supporting tools and methods. Another framework was proposed by Forza and Salvador (2007), where guidelines for the implementation of PCS are provided, including preliminary analysis, macro-analysis, micro-analysis, system design and planning for implementation, and finally implementation and launching. Felfernig, Friedrich and Jannach (2001) proposed a development strategy based on the standard Unified Modelling Language (UML), which is a design language to cope with the increased complexity of the PCS' knowledge base. The three main components of the configuration environment are knowledge acquisition, configuration, and reconfiguration; each stage has been given a diagnosis proposed by the authors (Felfernig et al. 2001). Other studies are more focused on the specific aspect of the PCS projects. Shafiee et al. (2014) proposed a framework for scoping PCS projects in engineering companies. The framework is designed to help companies identify the users, IT architecture, prioritisation of products and product features, and project plan. Finally, Haug et al. (2012) defined strategies for a PCS in engineering companies by focusing on the involvement of different experts (product, knowledge representation, and configuration software) in the development and implementation processes of a PCS. The first strategy proposed is to have each task performed by a specialist in the area. The second strategy is to have the person with the product knowledge to program the PCS software. Finally, the third strategy is to have the product experts only be involved in the evaluation in the testing phase (Haug et al. 2012).

These frameworks aim to increase the efficiency of PCS projects by highlighting different development strategies, but none of them provides guidelines on how to identify different applications for PCSs. In addition, only two of the frameworks mentioned above (Haug et al. 2012; Shafiee et al. 2014) are specifically aimed at engineering companies. Authors of a few studies (Felfernig et al. 2001; Forza and Salvador 2007; Hvam et al. 2008) have proposed comprehensive frameworks that describe different processes involved in PCS projects. However, the literature has not provided instructions on how to identify different applications for PCS.

3.4.2 Business cases for PCS projects

This sub-section gives the literature background for framing business cases in PCS projects. To do this, the sub-section begins with reviewing related studies that include frameworks to construct business cases for IT projects in general. After this, the study considers how the PCS literature addresses the main steps of business cases.

A business case can be defined as a "description of a situation or sequence of events confronting an individual, a set of individuals, or an organisation and includes a detailed account of the events leading to the point in time at which the case concludes" (Matejka and Cosse 1981). To identify the most critical steps and their sequence when framing business cases for PCS, frameworks for general IT projects are analysed. The framework identified includes several important studies (Ashurst et al. 2008; Häkkinen and Hilmola 2008; Gambles 2009; Bechor et al. 2010; McNaughton et al. 2010; Taylor et al. 2012; Nielsen and Persson 2017). These frameworks have some similarities in how the different steps are defined. From the analysed frameworks, it is observed that some focus on constructing business cases on a high level of abstraction (e.g. Ashurst et al. 2008; Taylor et al. 2012) while others have a more detailed focus (e.g. McNaughton et al. 2010; Nielsen and Persson 2017). Furthermore, some researchers use different terms to describe the same steps, such as *cost modelling* and *cost estimation* (Ashurst et al. 2008; Gambles 2009). Based on the literature, it is concluded that the main elements for business cases in IT projects can be described in terms of (1) a benefit analysis, (2) a stakeholder's analysis, (3) IT requirements, and (4) a risk and cost analysis.

PCS projects are categorised as IT projects, but here are some differences in comparing them to typical IT projects that need to be considered when framing business cases. These differences include having a diverse set of processes elements (e.g., machines, operations), a high variety of component parts and assemblies, and a high number of constraints and rules (Zhang and Rodrigues 2010). Furthermore, the knowledge required to build the PCS is spread out among various experts and often includes a less tacit form (Hvam et al. 2008). Additionally, PCS projects typically involve a number of different stakeholders, making it difficult to anticipate the expectations and implementation costs beforehand (Friedrich et al. 2014a).

Even though the PCS studies do not particularly address how to frame business cases, some of the aspects are covered in the studies, as described in the following.

A *benefit analysis* is a challenge in PCS projects; it determines the requirements of the project and provides insight on project scoping (Hvam et al. 2008; Shafiee et al. 2014). The goal of the PCS implementation can be determined by the output of the system, which supports the identification of stakeholders and the required knowledge (Forza and Salvador 2006; Mortensen et al. 2008). Furthermore, the *stakeholders' analysis* is of importance for anticipating the requirements of the different stakeholders. When aligned with successfulness of the PCS, the user's expectations and requirements increase, and thus the scope of the system expands (Barker et al. 1989). Stakeholders management is another challenge in PCS projects as the stakeholder may have different expertise and background (Forza and Salvador 2002a). Thus, identifying the main stakeholders and analysing their requirements before starting a project can both lead to improved decision making and decrease the time of development (Mortensen et al. 2008; Shafiee et al. 2014).

The *process analysis* is a fundamental step to obtaining an understanding of the current processes so that they can be redesigned and supported by a PCS (Forza and Salvador 2002a; Hvam et al. 2008). This typically involves analysing the current processes and redesigning the future processes where a PCS is used. Furthermore, a gap analysis can be used to demonstrate how the different scenarios contribute towards the targeted performance (Hvam et al. 2008; Shafiee et al. 2014; Kristjansdottir et al. 2016b). Finally, a *cost and risk analysis* is carried out to compare the different scenarios developed for the implementation of the PCS. In the literature, the cost estimation for evaluating the savings from PCS and further sensitivity analysis has been conducted (Kristjansdottir et al. 2016b). Furthermore, the risk of implementing and utilising a PCS needs to be identified and categorised (Hvam et al. 2008).

3.4.3 Product modelling and knowledge representation in PCS projects

This sub-section elaborates on product modelling and knowledge representation for PCS projects.

In configuration projects, one primary task is to structure and represent the knowledge of the configuration model (Aldanondo et al. 2000b; Forza and Salvador 2002a; Ardissono et al. 2003; Felfernig et al. 2004, 2014a; Hvam 2006b; Stark 2007; Shafiee et al. 2017). This includes communication with domain experts, as it can be easy to lose control of knowledge due to incomplete communication (Tseng et al. 2005) and there could be a risk of having a low-quality or unmaintained documentation of the configuration models (Tiihonen et al. 2013; Shafiee et al. 2017). Research has shown that a configuration model which is not adequately documented can lead to a lack of overview and even a restructuring of the PCS in the worst cases (Haug et al. 2009a). Furthermore, researchers have emphasised the importance of standard knowledge representation in configuration projects for the effective integration of configuration technologies into software environments dealing with highly complex products (Felfernig 2007).

Product modelling is a method of representing the structure and knowledge of a product to ensure that the product is understandable to all persons involved in its development and maintenance processes. In PCS projects, four basic representations are proposed for structuring the knowledge of the PCS, as seen in Figure 3-5 (Duffy and Andreasen 1995). First, the real world represents the product knowledge available within a company, where a formal representation of the knowledge has not been established. Second, the phenomenon model describes a product's structure, its function and other properties, and the product's lifecycle properties—such as manufacturing, assembly, and maintainability—in a way that can be communicated to domain experts (Hvam et al. 2008). Third, the information model is formalized, which is an IT representation of the phenomenon model, which often supports UML notation (e.g. Felfernig et al. 2000; Hvam et al. 2008). Fourth, the actual computer model is built on the previously described representations of the product.

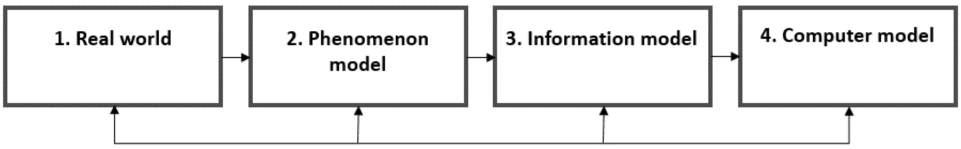

Figure 3-5 Four basic representations of product modelling for a PCS. Revised from Duffy and Andreasen (1995).

The concept of PCS can be traced back to the 1980s where the first PCSs were developed as rule-based systems (Barker et al. 1989). However, the maintenance of those systems proved to be a challenge due to the vast knowledge included in the systems and frequent updates (e.g. Mailharro 1998; Felfernig 2007; Jannach and Zanker 2013). To address those challenges, researchers have addressed both the knowledge representation and the conceptual modelling for PCS, as further elaborated in this section.

Soininen et al. (1998) first proposed a general ontology for a configuration that combines approaches that are based on connections, resources, product structure, and functions. The ontology aims to reuse and share configuration knowledge, and it also aims to allow interaction between PCS agents. Another approach is proposed by Felfernig et al. (2000) where UML is used for representing domain-specific notation—as UML can be understandable for domain experts and can be used to represent the formalism of the PCS. In their approach, contextual diagrams are proposed for more complex domain knowledge. A similar approach was provided by Yang et al. (2009), who proposed using a method-based systematic web technology (OWL and SWRL) that support the reuse and modelling of the configuration knowledge. OWL is based on description logic, and it supports a well-defined logic semantics creation; in contrast with the UML approach, OWL does not need any translation.

Another essential aspect in configuration projects is to structure the configuration knowledge sufficiently where components and their relations are defined (Zhang 2014). To that end, Stumptner, Friedrich, and Haselböck (1998) proposed a method based on a standard constraint satisfaction problem named generative constraint satisfaction problem, which allows for the reasoning of component existence and the reasoning of a large and variable number of components. Furthermore, Mailharro (1998) defined a configuration problem to be both a classification problem and a constraint satisfaction problem, where a framework based on object-oriented and constraint satisfaction paradigms is proposed that focus on domain knowledge representation. To address the challenges of semantic web applications, Felfernig et al. (2003) analysed the applicability of commonly used languages based on semantics (description logic) in relation to configuration knowledge representation. Their research showed that description logics are equivalence with consistency-based definitions and thus are useful in configuration projects. In another study, Felfernig (2007) extended the work to support product structures constraints and complex structural properties for configuration problems. In the study, a model-driven architecture (MDA) based on UML and object constraint langue (OCL) for PCS was proposed, and this MDA should enable more efficient communication with other software application and ease the technical support (Felfernig 2007). To address the challenges of distributed PCSs, Ardissono et al. (2003) proposed a framework and developed a configuration shell (CAWICOMS). Jannach and Zanker (2013) later added to this work by offering an approach based on distributed constraint satisfaction where generative constraint satisfaction is used for modelling the knowledge to solve the challenge of distributed PCSs.

Conceptual modelling of configuration knowledge is an important aspect of structuring configuration knowledge. McGuinness and Wright (1998) proposed a conceptual approach for structuring knowledge for PCSs where they emphasised the need for PCS accuracy over optimisation by developing a modelling technique based on description logic. Peltonen et al. (1998) defined concepts for modelling configurable products based on hierarchical product structure, and subsequently, the configuration model is divided into explicit structure and constraints. The explicit structure is based on BOM with optional, alternative parts and parametric components—although other constructs can also be described, such as connection ports— while constraints can be related to specification, implementation or structure. Aldanondo et al. (2000) offered a method based on a function breakdown structure and a physical breakdown structure that builds on an object modelling technique; this technique represents both the functions and components in terms of objects, dependencies and composition operators. Felfernig et al. (2001) proposed a conceptual modelling for PCSs, which was built on their previous research (Felfernig et al. 2000) that used UML to structure the domain knowledge and based on the functional architecture, as proposed by Mittal and Frayman (1989). Magro and Torasso (2003) described decomposition strategies for PCSs to improve performance and support interactive configuration, where frames, parts, and components are used to represent the configuration domain knowledge. In another study, Zheng et al. (2017) addressed the challenge of having a centralised PCS constructed for a single company's product family. In that study, a conceptual framework was proposed based on an open architecture product platform that supports integrations with suppliers to allow for co-creation in the configuration process.

Chao and Chen (2001) introduced an assembly model that includes information regarding functionalities and components for the assembly for configuration management in product data management systems. Jinsong et al. (2005) proposed a method aimed at MTO manufacturers where the product architecture usually consists of modules and standardised components. The method is based on knowledge components that include configuration rules and attributes, which capture and represent configuration knowledge (Jinsong et al. 2005). Hong et al. (2008) offered an approach to identify optimal product configuration for one-of-a-kind products based on a customer's requirements on the product's cost and performance. The approach models the functions and structure of the products through an AND-OR tree. Hong and Tu (2010) expanded this approach and presented a customer-centric product-modelling scheme to model one-of-a-kind products; in this approach, the customers are grouped into product and customers patterns. Tseng et al. (2005) suggested the use of a graph-based BOM and case-based-reasoning to construct a new BOM in the configuration processes. To do this, previous similar cases were identified and adjusted to meet the constraints for the product under design. Finally, Zhang et al. (2013) analysed the SAP2 configurator, where the production view is considered in addition to the functional and the physical structure. In that study, the authors proposed using the generic bill of functions, materials and operations (GBoFMO) to present the knowledge from different domains (Zhang et al. 2013).

Hvam et al. (2008) proposed an alternative approach—the CPM procedure—which is a conceptual modelling for PCS. The approach builds on concept object-oriented modelling (Bennet et al. 1999; Booch et al. 1999; Felfernig et al. 2000a; Hvam 2001), systems theory (Bertalanffy 1968; Skyttner 2005), and modelling mechanical products (Hubka and Eder 1988; Schwarze 1996; Jiao et al. 2007). To support this method, Haug and Hvam (2007) and Shafiee et al. (2017) have proposed using IT tools. The CPM procedure represents both the phenomenon and the information model by using UML notation where product variant master (PVM) and CRC-cards represent the phenomenon model, and class diagrams and CRC cards form the information model. As the CPM procedure is used as the primary product modelling method in this project, the following section explains the central concept of the procedure.

3.4.3.1 The CPM procedure

The central concepts of the CPM procedure were first proposed by Hvam (2001), and they have since been extended through various publication (e.g. Hvam, Riis, and Hansen 2003; Hvam and Ladeby 2007; Haug, Hvam, and Mortensen 2010). The application of the CPM procedure involves product variant master (PVM) and class diagrams associated with Class Responsibility Collaboration (CRC) cards. The PVM is a modelling technique that structures the phenomenon model in a visual way so that it can be used in communications with domain experts. Class diagrams are used to represent the information model in places where the structure corresponds to the PVM. Finally, CRC cards that are associated with the PVM and the class diagrams describe the individual classes in more details.

The product variant master (PVM)

The PVM is used for modelling the product range, and it represents the phenomenon model. A company's product range often appears to be large and have a vast number of variants. To obtain an overall view of the products, the product range is drawn up in a PVM (Hvam 2001; Hvamet et al. 2008). The PVM consists of two structures, which are the *part-of* structure and *kind-of* structure (Figure 3-6). The part-of structure represents the parts that appear in the entire product family. It includes object classes, which can be described as a collection of objects with common characteristics (attributes) and common behaviours (methods). Each class is given a unique name that should be descriptive for the class, and each contains attributes, methods, and cardinalities. The kind-of structure describes the different variants the individual parts can have.

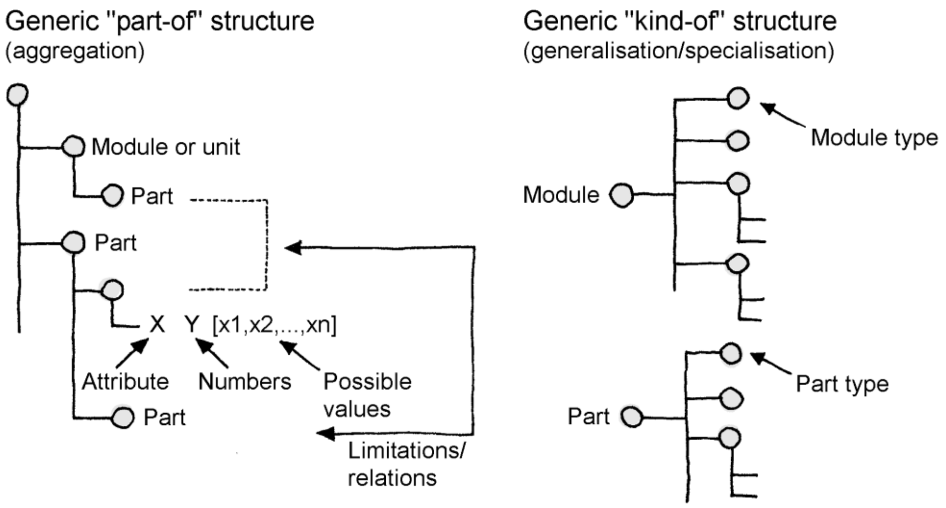

Figure 3-6 Principles of the PVM (Hvam et al. 2008).

The PVM contains a description of the most important connections between parts; this description contains the rules for how parts are permitted to be combined. This is done by drawing a line between the two parts and writing the rules that apply to the concerned parts. In order to preserve the overview of the PVM, CRC cards are associated with the PVM to describe the individual parts in detail. Furthermore, the PVM supports a multi-domain description of the products based on the customers, engineering and production/part views where a causal connection can be drawn between the views in order to identify both the complexity and the non-value adding variety in the product range.

The class diagrams

The class diagrams represent the information model. The individual classes in the class diagram are defined from the PVM; the part-of structure of the PVM corresponds to the aggregation structure and the kind-of structure corresponds to the generalisation/specialisation structure of the class diagram (Hvam et al. 2008). Figure 3-7 illustrates the relations between the structures of the PVM and the class diagrams.

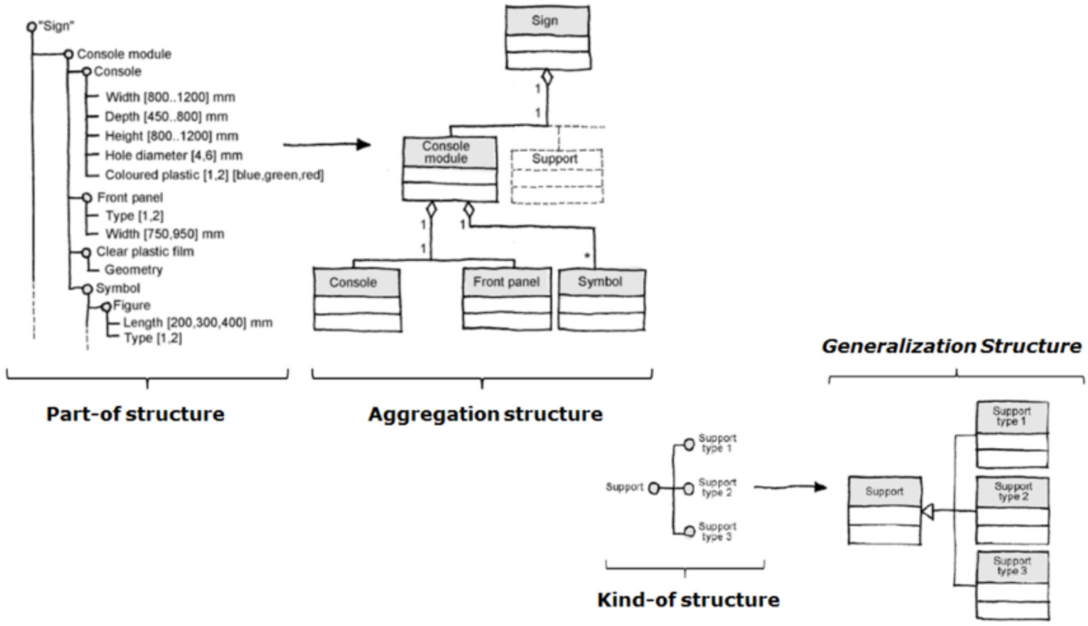

Figure 3-7 Structural relations between the PVM and the class diagrams (Hvam et al. 2008).

The CRC cards

The CRC-cards are associated with both the PVM and the class diagrams, and they describe the classes in more detail. The CRC cards were first proposed as a way to teach object-oriented thinking (Beck and Cunningham 1989). Later, they were developed to be used in PCS projects (Hvam et al. 2008). The CRC cards can be associated with both the PVM and the class diagram. The purpose of the CRC cards is to document detailed knowledge about the attributes and methods for the individual object classes; it is also used for describing the classes' mutual relations (Figure 3-8). The CRC cards serve as documentation for both domain experts and system developers; together with the PVM and the class diagram, CRC cards have become an essential means of communicating and documenting knowledge within the project group in PCS projects.

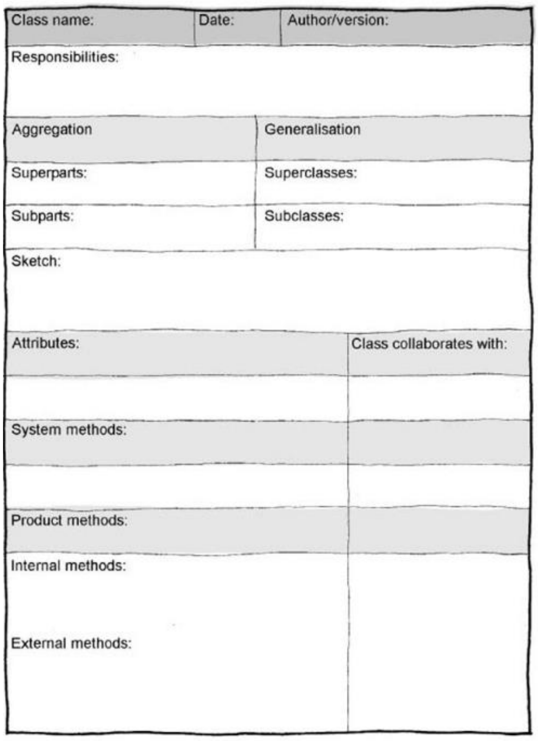

Figure 3-8 Example of CRC card (Hvam et al. 2008).

3.4.4 Knowledge management in PCS projects

This sub-section provides the literature background for knowledge management in PCS projects. The section begins with a literature review of related work that includes a framework for knowledge management for IT projects in general; this is done to identify the required steps and their sequence. Second, specific tools and methods proposed for PCS projects that can be applied in the different steps of the knowledge management process are elaborated.

PCS incorporate information about product features, product structure, production processes, costs, and prices (Forza and Salvador 2006). An increased complexity of products increases the number of product features to be modelled and maintained in a PCS (Ardissono et al. 2003). The required knowledge for the PCS involves different parts of products that are often spread among various experts in a company (Hvam et al. 2008). Other valuable sources of knowledge are available in internal IT systems (Friedrich et al. 2014b). Therefore, a knowledge acquisition and a cleansing stage are required at an early point in a PCS project's development phase (Friedrich et al. 2014b). Once the PCS is up and running, further knowledge may be necessary to keep the PCS up-to-date and aligned with the product offerings; thus, the knowledge needs to be managed throughout the PCS's life cycle. In other words, the quality of the PCS is determined by the knowledge included. Even though a knowledge management is an essential part of PCS projects, a comprehensive framework for knowledge management in projects of this nature is missing.

To identify the most critical steps and their sequence related manage knowledge in PCS projects different, frameworks for general IT projects are analysed (Basili and Weiss 1984; Kucza and Komi-Sirviö 2001; Komi-Sirviö et al. 2002; Rodríguez et al. 2004; McGinnis and Huang 2007; Gemino and Sauer 2012; Lech 2014). The identified frameworks include three phases/actions to six phases/actions, depending on the level of abstraction. Furthermore, some studies focus more on knowledge acquisition (e.g. Basili and Weiss, 1984), while others consider the entire knowledge management lifecycle, including maintenance (e.g. Kucsa and Komi-Sirviö, 2001). It is also observed that certain studies use different terms to denote the same thing, such as *knowledge identification* and *knowledge scoping*. Some frameworks use different terms even for similar activities/phases; for instance, the terms *knowledge stock*, *scope*, and *socialisation* all refer to identifying needs and goals. Even though the frameworks use different terms for the various phases of knowledge management in IT projects, they exhibit a number of similarities (Rubenstein-Montano et al. 2001). In the identified frameworks, the first step is concerned with determining the scope of the project to establish the goals, requirements and deliverables of the system. After this, there is a collection and categorisation of the knowledge to ascertain the knowledge sources and resources. This step is followed by knowledge acquisition, where modelling and clarification of the acquired knowledge are elaborated. In all the frameworks, validation and documentation of the knowledge are considered as a separate step. Finally, many frameworks include knowledge maintenance as the final step.

In terms of knowledge management, there are several differences between a general IT project and PCS projects, even though PCS can technically be classified under IT projects. The first difference is found with respect to knowledge complexity and project extensions. The scope of the PCS often expands; it is aligned with the system success and a higher number of users (Barker et al. 1989). Furthermore, the knowledge included in the PCS needs to be continuously updated so that it could be aligned with the company's product offerings (Hvam et al. 2008; Shafiee et al. 2014). In general IT projects, there are different levels of complexity based on the type of the system, such as minor or significant extensions (Whitney and Daniels 2013). Second, in relation to communications in PCS projects, the knowledge is spread across the company; in addition to the constant validation of the existing knowledge, all this requires intensive communications through the system's lifecycle (Forza and Salvador 2002a; Hvam et al. 2008). In other IT projects, there is not as high need for communication with different experts and constant validation. Finally, with the documentation and maintenance of knowledge, there is a different kind of knowledge found in PCS that continually needs to be maintained to reflect the company's product offerings. This includes not only updating the PCS but also documenting the products using modelling methods; this needs to be done in addition to the formal documentation of the actual system (Tiihonen et al. 1996b; Friedrich et al. 2014b). By contrast, the documentation in other IT projects is more limited to codes (Coram and Bohner 2005). Even though a knowledge management framework is not proposed in PCS studies, the literature shows the different steps of the knowledge management process. This is described as follows.

Determining the scope of PCS is concerned with clarifying the knowledge requirements for the entire project. In the early phases of a PCS project, the scope of the products to be included in the system provides insight on the nature of the project, such as project goals and outputs, objectives and requirements from the stakeholders, and IT architecture (Shafiee et al. 2014). *Knowledge acquisition* is also frequently considered to be a challenge in PCS projects, as it can be challenging to identify and retrieve the most appropriate product knowledge to implement in the system (Shafiee et al. 2014). Knowledge acquisition entails categorising the knowledge based on the relevant stakeholders' needs and recognising all the sources and resources of knowledge. It also involves collecting the knowledge and categorising it based on previous analyses of the product or process. The processes by which the products are developed do not usually create the configuration-related knowledge as a part of the development effort. Instead, this additional knowledge acquisition task is performed by persons who are not product experts, which might lead to loss of data and erroneous configuration of the knowledge being used in the configuration process (Tiihonen et al. 1996; Aldanondo et al. 2000).

Product modelling and knowledge validation are one of the most challenging tasks in PCS projects (Sabin and Weigel 1998; Hvam et al. 2008). A considerable amount of research is therefore devoted to product modelling and communicating with domain experts to validate the knowledge. Finally, *documentation and maintenance* are one of the most important phases of the knowledge management process of PCSs (Forza and Salvador 2002a; Shafiee et al. 2017). Studies of companies using a PCS have shown that without proper documentation, the companies often become unable to utilise the PCS and have had to abandon or rebuild the system (Haug et al. 2009a). It is therefore important to have a reliable configuration model for the products implemented to the PCS, specifically a model that has no technical errors and mirrors the product design's updates exactly (Forza and Salvador 2002a).

3.4.5 Summary: Improved development and maintenance of PCS

The previous sub-sections have introduced the literature background for development strategies, business cases, product modelling, and knowledge management in PCS projects. Even though different frameworks have been proposed to increase efficiency in PCS projects, the identification of different fields of applications has not been addressed. For both business cases and knowledge management, different frameworks have been proposed for general IT systems but not specifically for PCS projects. Nevertheless, the literature in the field of PCS has provided insight on some of the specific aspects of making business cases and on managing knowledge in these type of projects. In both cases, it is highlighted that even though PCS are categorised as IT systems, they have unique requirements and thus customised frameworks are needed. In terms of product modelling and knowledge representation, it has received considerable attention over the years. However, to justify the time and resources spent on constructing and maintaining the product models, the impact of using them needs to be analysed.

3.5 IMPROVED PERFORMANCE AND ACCURACY OF THE PCS WITH IT INTEGRATIONS

In engineering companies, the supply chains can be characterised as being tailored and complex (Konijnendijk 1994), and manufacturing tends to have vertical integration, including both internal manufacturing processes and outsourced supply (Hicks et al. 2000). Furthermore, the dynamic and segregated characteristic of the early sales and engineering processes limits the availability of design information, while also increasing the uncertainty of a project's profitability (Mortensen et al. 2010). As a result, there is a high dependency of retrieving information across organisations in the early sales design phases.

In the sales phase, the most critical decisions regarding the profitability of projects are taken, and inaccuracy in the cost estimations can have significant consequences (Hvam et al. 2008). By overestimating the cost, the risk of losing the customer increases; by underestimating the cost, profitability is reduced. In the pre-tender phase, inaccuracy of the cost estimation is often the result of decisions being made within a limited time and when the project scope has not been entirely determined (Aibinu and Pasco 2008). Other factors that can influence the cost estimations are project complexity, technological requirements, project information, project team requirement, contractual arrangement, project duration, and market requirements (Akintoye 2000). Studies have shown ineffective communication across companies could lead to costs traced to errors, which are proven to be costly for companies (Kratochvìl and Carson 2005).

To address these challenges, this project explores two different methods. One method involves retrieving information from suppliers by integrating PCSs across companies in the configuration process. The other method explores an automatic function in the configuration process to identify the most similar projects that have already been made.

3.5.1 RETRIEVING INFORMATION FROM SUPPLIERS IN THE CONFIGURATION PROCESS

In engineering companies that produce highly customised and complex products, a significant problem arises when calculating the prices in the presale and sale processes. This problem reflects the integrations across supply chains, where companies are highly dependent on retrieving information from sub-suppliers in the configuration process regarding outsourced components, which are often highly customised. Additionally, as the components may not be clearly defined, the accurate cost might be unknown in the sales phase (Brunoe and Nielsen 2012).

Supply chain management involves the activities concerned with flow information and the transformation of raw materials to the end-user. There have been studies on companies performance in relation to the integrations across supply chains (Stevens 1989; Johnston and Lawrence 1991; Metters 1997; Hines et al. 1998; Frohlich and Westbrook 2001; Lee et al. 2004). Having a linked IT systems is identified as a key success factor for integrating suppliers into the new product, process, or service development process (Ragatz 1997). Thus, a linkage between integrative IT and the supply chain is a key aspect of supply chain integration. To this end, Mukhopadhyay and Kekre (2002) quantified both strategical and operational impacts of electronic integration, where business processes across companies are integrated with the use of IT systems. This can lead to substantial benefits, which include additional revenues, reduced transaction costs, and improved procedural specificity (Mukhopadhyay and Kekre 2002). It should be noted that the operational benefits are generated by electronic integrations through re-engineering of the internal processes of an organisation, unlike strategic benefits, which result from changes in the buyer-supplier trading relationship (Mukhopadhyay and Kekre 2002). A supply chain strategy recognises that integrated business processes create value for the customers of the companies if these processes reach beyond the boundaries of the firm by drawing suppliers and customers into the value creation process (Stevens 1989; Tan et al. 1998). IT development can lead to process innovation, or more broadly, it can lead to supply chain integration followed by products that are cheaper, more diverse, and customer-specific. Internet-based technologies support the goal of customisation efforts efficiently and economically; with such technologies, customers can obtain real-time or direct access to the information maintained by service providers (Brynjolfsson and Hitt 2000). Improved flexibility and efficiency through suppliers can only be obtained using electronic platforms that are deployed as these platforms can connect suppliers, producers, distributors and customers (Jardim-Goncalves et al. 2007).

The PCS has been proven to be useful in distributed supply chains, where information from sub-suppliers is retrieved in the configuration processes. Ardissono et al. (2003) describe the development of configuration services which offers personalised user interactions as well as distributed configuration and services in the supply chain. The approach suggested is thought to help with further collaboration in which the exchange of orders, publishing of product catalogues and the billing processes could be supported (Ardissono et al. 2003). In another study, Zheng et al. (2017) addressed the challenge of having a centralised PCS constructed for a single company's product family. In that study, the proposed conceptual framework was based on an open architecture product platform that supports integrations to suppliers to allow for co-creation in the configuration process. Although the literature describes the importance of integrations across supply chains where a PCS can play an important role, the impact of the performance from establishing these integrations remains unaddressed.

3.5.2 Automatic identification of the most similar products in the configuration process

Engineering companies strive to increase the commonality between different projects and to reuse product-related information. Thus, the data of previously designed products are retrieved in order to identify parts of the design that can be reused. This enables companies to reduce the complexity of the product portfolio, decrease engineering hours, and improve the accuracy of the product specifications. To identify the similarities of previously designed products and new products, an automated IT system can be beneficial because such a system makes it possible to produce customised products while using the least amount of time and resources.

To estimate the price for highly complex products to be included in the PCS, Hvam (2006) suggested using a price curve based on previously made products. In Hvam's study, the price is calculated based on the product weight, which is plotted against performance. This formula allows for the price estimation of products that have not been previously made; it also allows for the adjustment in factors, such as the related cost of materials and currency exchange rates. This approach has limitations for highly customised and complex products, as there can be several dependent variables and a large number of similar dots on the curve. Another approach was suggested by Brunoe and Nielsen (2012) for addressing the challenges in the presale phase where incomplete product specifications are made available. In the approach, backward elimination is used to simplify a linear regression model based on historical data.

Another vital aspect of reusability of highly customised and complex products is related to the architecture of the product family and the level of modularisation. A *product family* can be defined as "a set of individual products that share common technology and address a related set of market applications," and a *product platform* is seen as "a set of subsystems and interfaces that form a common structure form which stream of derivative products can be efficiently developed and produced" (Meyer and Lehnerd 1997). *The product architecture* can be defined as (1) the arrangement of functional elements, (2) the mapping from functional elements to physical components, and (3) the specification of the interfaces among interacting physical components. (Ulrich 1995). Modularity has been defined as one of the most crucial aspects of product architecture (Eppinger and Ulrich 2000). The highest degree of modularity is seen when each functional requirement can be directly connected to one module and where there are few interactions between the modules, making it possible to change specific modules without affecting other parts of the design (Eppinger and Ulrich 2000). If an existing product has standardised and decoupled interfaces, the design of the next product can borrow heavily from the modules of the previous product (Ulrich 1994).

In engineering companies, a standardisation or system level configuration strategies can be applied (Kristianto et al. 2015). In the study by Thevenot and Simpson (2006), they developed a framework that uses commonality indices and is based on different parameters, such as the number of common components; these parameters are for redesigning the product families to adhere to cost reductions in the product development process. By having well-defined product architecture based on the modules, increased usability across different projects is supported.

Inakoshi et al. (2001) proposed a framework to support the PCS, which frames the integration of a constraint satisfaction problem with case-based reasoning (CBR). In engineering companies, the integration of existing PCS technologies with recommendation approaches is essential for supporting end-users in their configuration processes (Felfernig and Burke 2008; Felfernig et al. 2014b). Different recommendation technologies can be divided into collaborative filtering (CF), content-based filtering (CBF) and knowledge-based recommendations (KBR) (Felfernig et al. 2014b). The available recommendation technologies in e-commerce are potentially useful in helping customers choose a product's variables. Comparing the new project with previous ones could also result in developing a recommendation system that can be used in the configuration process.

3.5.3 SUMMARY: IMPROVED PERFORMANCE AND ACCURACY OF PCS WITH IT INTEGRATIONS

Based on the current literature in the field, the research has highlighted the importance of achieving higher integrations across the supply chains where an IT system plays a key role. Furthermore, for companies providing customised products, there is a need for having updates from sub-suppliers in the configuration process. Therefore, integrating PCSs across the organisational supply chains allows the company to integrate the flow of information further and at the same time solve some of the leading challenges concerned with PCS. However, the impact of interactions with multiple PCSs across a company's supply chains has not been addressed previously in the literature. Furthermore, identifying the most similar previously made project in the configuration process remains a challenge. This point is of great importance as it can save companies both resources and time by reusing previously made designs.

4 RESULTS

The importance of further studies addressing applications of a PCS in engineering companies is highlighted based on the literature review in Chapter 0. To address these challenges mentioned, this chapter presents the main findings of this project in relation to the research questions. The publications presented in this chapter are as follows.

A. Kristjansdottir, K., Shafiee, S. and Hvam, L. (2016). Industrial Application of PCS: From Motivations to Realised Benefits. Proceedings of 18th International Conference on Industrial Engineering, October 2016, Seoul.
B. Myrodia, A., Kristjansdottir, K., and Hvam, L. (2017). Impact of Product Configuration Systems on Product Profitability and Costing Accuracy. Computers in Industry, vol. 88, pp. 12–18.
C. Kristjansdottir, K., Shafiee, S., Hvam, L., Bonev M. and Myrodia, A. The Economic Value from Applying Product Configuration Systems – A Case Study. Submitted to ISI journal (second revision), November 2017.
D. Kristjansdottir, K., Shafiee, S., Hvam, L., Forza C. and Mortensen, N.H. The Main Challenges for Manufacturing Companies in Implementing and Utilizing Configurators". Submitted to ISI journal (second revision), November 2017
E. Kristjansdottir, K., Shafiee, S. and Hvam, L. How to Identify Possible Applications of Product Configuration Systems in Engineer-to-Order Companies, International Journal of Industrial Engineering and Management (Accepted).
F. Shafiee, S., Kristjansdottir, K., Hvam, L., Haug, A., Forza, C. and Sandrin, E. How to Frame Business Cases for Product Configuration Projects Success. To be submitted to ISI journal.
G. Hvam, L., Kristjansdottir, K., Shafiee, S. and Mortensen, N.H. The Impact of Applying Product Modelling Techniques in Configurator Projects. Submitted to International Journal of Knowledge Management.
H. Shafiee, S., Kristjansdottir, K., Hvam, L. and Forza, C. How to Scope Configuration Projects and Manage the Knowledge they Require. Submitted to International Journal of Knowledge Management.
I. Kristjansdottir, K., Shafiee, S., Bonev, M., Hvam, L., Bennick, M. H., & Andersen, C. S. (2016). Improved Performance and Quality of PCS by Receiving Real-Time Information from Suppliers. Proceedings of 18th International Configuration Workshop, September 2016, Toulouse.
J. Shafiee, S., Kristjansdottir, K. and Hvam, L. Automatic Identification of Products Similarities to Improve the Configuration Process in ETO Companies. International Journal of Industrial Engineering and Management (Accepted).
K. Katrin Kristjansdottir, Sara Shafiee, Lars Hvam, Loris Battistello and Cipriano Forza (2017). The complexity of Configurators Relative to Integrations and Field of Application. Proceedings of the19th International Configuration Workshop, September 2017, Paris.

4.1 THE MAIN BENEFITS OF IMPLEMENTING AND UTILISING THE PCS

This section investigates the main benefits in relation to implementing and utilising the PCS, and the section aims to answer RQ1. While the literature has mentioned a number of benefits from implementing and utilising PCS, there are still some unanswered questions as explained in Section 3.2.2. Thus, this section first analyses the primary motivations that companies have for investing in a PCS and their successfulness of achieving the initial motivations. Second, the impact of a PCS on the accuracy of cost calculations and product profitability is quantified. Finally, the economic value creation from implementing and utilising PCS is elaborated and quantified.

4.1.1 STUDY A: INDUSTRIAL APPLICATION OF PCS: FROM MOTIVATIONS TO REALISED BENEFITS

4.1.1.1 Research objective and research questions

This study analyses the relationship between the actual motivations for implementing PCS and the successfulness of the companies in achieving the initial motivations. In line with the focus of the study, the following research questions are developed:

> **RQ 1.1** What are the main motivations that companies manufacturing customized products have for implementing a PCS?
> **RQ 1.2** How successful are companies manufacturing customized products in achieving the benefits associated with the initial motivations?

To provide answers to these questions, the study uses the literature presented in Section 3.2, a survey (S1) as presented in Section 2.4.2.

4.1.1.2 Research contribution

First, this section describes each of the identified motivations categories based on the survey responses from the companies. The open questions in the survey are used for capturing the main motivations. The responses have been grouped into seven categories, which are (1) general competitiveness, (2) knowledge management, (3) efficiency in the sales and order processes, (4) efficiency of the production process, (5) accuracy of the products specifications, (6) management of products variants and complexity, and (7) other motivations. Second, 22 predefined benefits are listed in the survey; these are based on literature, and the respondent's experiences are rated on a five-point scale. The scale represents to which degree the companies agree with the different benefits being realised as a result of implementing and using a PCS. The benefits are grouped according to the categories of motivations; the grouping intends to measure the successfulness of the companies in achieving the initial motivations. Finally, the study also evaluates whether companies that expressed a motivation in a particular category are more likely to achieve the benefits. To do this, the average rating in each category is calculated based on all the benefits in the category, and the rating is then presented to companies expressing a motivation in the category and to the companies not expressing a motivation in the category. The following is a description of the individual categories of motivations and the successfulness of achieving the motivations based on the pre-defined benefits.

Motivation group 1: General competitiveness

Increasing general competitiveness was identified as one of the motivations in 27% of the companies. In terms of general competitiveness, two of the companies described that a use of a PCS was a market condition as they would not be in the market if they cannot deliver customised products efficiently. In another company, it was mentioned that the development of the PCS was supposed to enable greater automation of the sales and the order process; this implies the intention of improving overall competitiveness. Additionally, one of the companies intended to develop a PCS to be ahead of the market competition. Furthermore, respondent expressed that the PCS was designed to help the company reach more customers along with reducing orders that do not turn into an actual sale. Finally, it was mentioned that by implementing a PCS, the overall cost could be minimized.

The results show that out of the perceived benefits grouped into this category, 77% and 72% of the companies agreed that the increased satisfaction from customers and employees is realised as benefits from using the PCS, while only 32% of the companies agreed with more sales quotes resulting in actual orders. For the other benefits, between 68–41% of the companies agreed that the benefits were associated with the PCS. In this category, a significant difference of the companies that expressed a motivation in this category can be seen: roughly 79% agreed with those benefits, while for companies not expressing a motivation grouped into the category, only 53% agreed.

Motivation group 2: Knowledge management

Improving knowledge management was identified as one of the motivations in 36% of the companies. In terms of knowledge management, it was mentioned that preserving the knowledge within the companies is vital when experienced employees leave the company. Furthermore, by implementing a PCS, increased learning and knowledge sharing are supported. In this context, it was also said that knowledge held by a few experts at the companies should become available to an increased number of employees. As one company explained, the product knowledge needs to be more accessible so that the company is not constraint by a limited number of employees with specific product knowledge. Finally, by storing the knowledge and the product information in the PCS, there could be a better knowledge flow and documentation base, which is easier to maintain.

The results show that out of the perceived benefits grouped into this category, better accessibility to knowledge on product variants and product specifications was the most recognised benefit according to 73% of the companies. Meanwhile, improved documentation and maintenance of knowledge and reduction of redundant information were both recognised by 64% of the companies. However, no significant difference was found between companies expressing a motivation in this category and the ones not expressing a motivation in this category, as the average percentage of the companies agreeing to the benefits turned out to be 67% and 66%.

Motivation group 3: Efficiency in the sales and order processes

Increasing efficiency in the sales and order processes was identified as a motivation in 45% of the companies. It was mentioned that the salesperson should be able to handle all product configurations even for the complex products through the PCS, without compromising the qualities of a good seller. Furthermore, the companies described how they aimed to use the PCS as a tool, which should enable employees to make configurations where flexibility is provided without compromising quality. Another aspect was related to enabling all the customers' requirements to be efficiently captured and finding an optimal solution. It was also said that the PCS should be able to guide the sales process towards selling the right products based on the standard offerings while finding the optimal fit for the customers. Finally, by automating the sales and the order processes to a greater extent, some respondents hoped that the speed in the processes could be increased, leading to a reduction in routine work and in lead-time for fulfilling orders.

The results showed that out of the perceived benefits grouped into this category, 87% of the companies agreed that the benefits were a reduction of routine work; fewer transfers of responsibility and errors when generating the proposals and specifications; and a shorter time to generate proposals. Meanwhile, 77% agreed that the reduction of cost when of preparing proposals and specifications is a benefit. However, an interesting finding is that on average, 90% of the companies that did not express a motivation in this category also agreed with those benefits, while 78% of the companies expressing a motivation in the category agreed on average. Therefore, a higher percentage of companies not expressing a motivation grouped in the category agreed with achieving the associated benefits.

Motivation group 4: Efficiency in the production process

Increasing efficiency in the production process was identified as one of the motivations for 27% of the companies. Some companies mentioned that the PCS should improve on their overview of the different products variants, their connections and their effects on the production. Furthermore, the PCS should streamline the process of generating BOM and the production specifications, and this could increase speed and reduce errors. Finally, it was described that due to the variety of templates and different standards for generating the production specifications, errors would appear in the production, and therefore the specifications should become more homogenous through the implementation of the PCS.

The results showed that out of those two perceived benefits, 77% of the companies agreed that a reduction of cost in relation to construction and production is a benefit. Only 46% of the companies agreed that a reduction of cost in relation to production and procurement of materials is a benefit. In terms of companies that expressed a motivation in this category, a significant difference was found. From the companies expressing a challenge in this category, an average of 83% agreed with this being a realised benefit, while only 53% of companies not expressing a motivation in the category agreed on average with this being a realised benefit.

Motivation group 5: Accuracy of the products specifications

Improving accuracy of the product' specifications and the documentation associated with the product configuration was identified as one of the motivations in 41% of the companies. These companies explicitly explained that they aimed to eliminate errors and thereby improve the quality of the specifications. In this context, one of the companies expressed that they aimed to achieve increased uniformity of the generated quotations, seeing that the salespersons had different routines and preferences. As a result, the lack of uniformity led to errors in the quotations sent out to customers. Another company described how validating and ensuring the accuracy of the information modelled in the PCS should reduce the number of errors. Furthermore, it was said that the by implementing a PCS improved overview of the product parameters, the relationship between the different parameters and why certain combinations are not feasible, to reduce errors. Finally, when errors are discovered it is easier to communicate and correct them, as it only has to be changed in one place or in the PCS, and therefore the same errors should not occur repeatedly.

The results showed that out of the perceived benefits in this category, most companies—namely 86% of them—agreed with improved quality of the response to customer request. Meanwhile, 59% and 54% of the companies agreed with a reduction in the number of orders where there are deviations between the estimated and the actual cost, and less deviation (in percentages) between the estimated and the actual cost, respectively. In terms of companies that expressed a motivation grouped into this category, 71% of these companies agreed with those benefits being realised, while 64% of companies not expressing a motivation in the category agreed on average.

Motivation group 6: Management of products variants and complexity

Improving the management of variants and complexity was identified as one of the motivations for only 23% of the companies. It was mentioned that the PCS should help in the process of managing complex products' portfolio and the associated cost. Another company expressed that by use of a PCS, the number of items and structured BOMs needed should be minimized. This should result in reduced variant handling associated with long descriptions with a large number of different SKUs. Furthermore, it was expressed that by using the PCS, the PCS should help to standardise the way of offering individualised products, thereby reducing the overall cost. Finally, having an improved product overview, a standardisation of the product portfolio, and consistent configurations from time to time were to be achieved by the implementation of the PCS.

The results show that 91% of the companies agreed with the benefit of easier to identify and manage product variants, which makes is it the most realised benefit. The benefit of the increased use of standard modules/components also was agreed by 82% of the companies while only 32% agreed with a decreased number of product variants being benefits associated with using the PCS. An interesting finding is that on average 70% of the companies that did not express a motivation in this category agreed with those benefits, while only 50% of the companies expressing a motivation in the category agreed on average. Therefore, there are a higher percentage of companies not expressing a motivation in the category that agreed with achieving the associated benefits.

Motivation group 7: Other motivations

In terms of other motivations, responses from 23% of the total companies were grouped in this category. These responses include improved visualisation, security, innovation, and uniformity. Additionally, one of the companies explained that the ERP system used at the company included variant management but not financial management; this meant that it was not possible to calculate the production cost, and the problem motivated them to use a PCS. In terms of other motivations, no specific benefits could be grouped to the motivations listed in this category as they are too company specific. Therefore, it cannot be determined how successful the companies were in achieving the motivations listed in this category.

4.1.1.3 Conclusion

The aim of the study was to provide further insight into the relationship between the initial motivations that manufacturing companies have for implementing and using PCS, and the associate realised benefits after the implementation of the PCS. The study builds on the answers from 22 manufacturing companies and is presented in Paper A.

4.1.2 Study B: The PCS impact on product profitability and cost accuracy

4.1.2.1 Research objective and research questions

This study focuses on quantifying the impact of implementing and utilising a PCS on the company's ability to make accurate cost calculations in the sales phase and consequently the profitability of the products. More specifically, this study aims to provide answers to the following research question.

> **RQ 1.3** What is the impact on the accuracy of the cost calculations and consequently the impact on product profitability when supported with PCS?

To provide answers to the research question, this study was conducted in collaboration with a case company (C1), which is explained in Section 2.4.1

4.1.2.2 Research contribution

Analysis of the company's performance before and after implementation of the PCS

To compare the overall performance before the PCS was implemented (2009) and after the implementation (2011–2014), a contribution ratio (CR) is calculated for each project that was carried out by the company within the timeframe of the study. The CR represents the profitability of the projects and is calculated as the ratio of the sales price and the contribution margin (CM) (Farris et al. 2010). The deviation in the CR (DEV_{CR}) is calculated as the actual CR that is calculated after the project is closed when all expenses are known minus the estimated CR that is calculated in the sales phase. Any deviations in the CR must be attended to by the companies; if the cost is overestimated, the company might lose the customer, and if the cost is underestimated, profit is lost. The projects used for the comparison are from 2009—when only Excel was used to calculate the cost—to 2014. For the 2011–2014 period, the cost calculations were performed either in the PCS or with Excel. Due to organisational resistance, not all salespersons used the PCS. Table 4-1 illustrates the overall performance of the company in 2009 and in the 2011–2014 period in terms of a number of projects sold, CR and DEV_{CR}.

Table 4-1 Overall performance of the company before the PCS was implemented (2009) and after (2011–2014).

Year	No. of projects	Average DEV_{CR}	Average CR per project
2009	55	–1.5%	25.0%
2011	117	–3.5%	27.2%
2012	90	–1.1%	28.5%
2013	116	–1.0%	28.2%
2014	168	–0.8%	29.0%

In 2009, a strategic decision was taken to increase the CR from 25% to 30% for all of the projects sold at the company, and the PCS should help to achieve this goal. The analysis shows that the average CR steadily increased from 25.0% in 2009 to 29.0% in 2014. Furthermore, the analysis shows positive improvement in DEV_{CR} from 2009 to 2014—except for 2011 since that is the first year where the PCS was utilised and where DEV_{CR} increased considerably after that year. This increase in DEV_{CR} in the first year after the PCS was launched in 2011 can be traced to the system not being fully completed due to lack of testing and training before its launch. However, as the users became more experienced in using the PCS and errors were fixed, the PCS started providing valuable results. This analysis indicates that the cost calculations are now more accurate than before the implementation of the PCS, and the company is moving closer to the targeted CR. Consequently, the products' profitability is increasing.

Comparison of cost estimations and profitability between Excel and PCS

This section focuses on the period after the PCS was implemented (2011–2014). Specifically, the section compares the yearly turnover, the CR of the projects, and the DEV_{CR} based on whether the initial quotation created in the sales phase was generated by the Excel or by the PCS. This comparison is possible as the PCS is not accepted by all salespersons and thus both the PCS and the Excel are used simultaneously at the company.

The contribution to yearly turnover

To understand the extent to which the PCS is used at the company, the yearly turnover for the projects was compared based on whether the quotation was generated with the PCS or Excel. Figure 4-1 shows the yearly turnover from the quotations created by using the PCS and Excel.

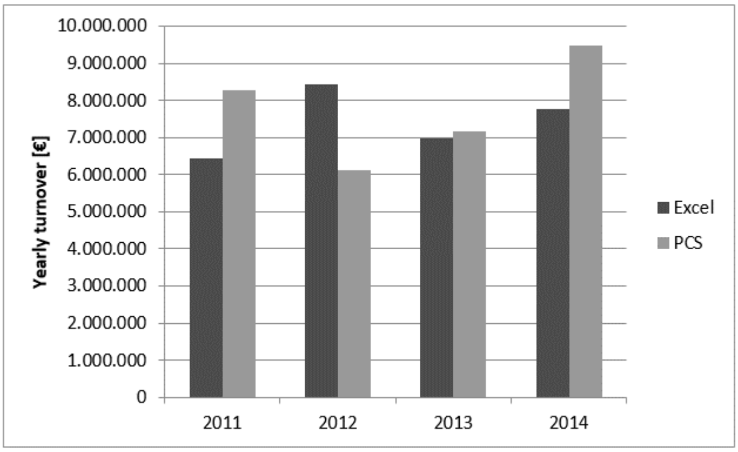

Figure 4-1 Comparison of turnover generated for quotations created in the PCS and Excel.

In the first year of using the PCS in 2011, the turnover for the products' quotations generated with the PCS was higher than the ones created with Excel. However, in 2012, the turnover for the products' quotations generated by using Excel spreadsheets was higher. In the first year when the system was running, the lack of training and errors in the system affected its functionality. However, in 2013, the quotations generated with the PCS contributed more to the yearly turnover, and in 2014, this difference increased even more, indicating that the salespersons were using the system to a greater extent.

The 2011–2012 period was the initial introduction of the PCS at the company, and the PCS did not include all products at that point; therefore, utilisation was limited. During the trial period, the turnover contributed by the projects handled in Excel was thus higher than the turnover from the projects handled in the PCS, but this changed over the following 2 years. Thus, in the 2013–2014 period, the company took greater advantage of the PCS and its utilisation was firmly established. As a result, the turnover of the projects done with the PCS outnumbered the ones generated with Excel. Overall, by comparing the yearly turnover of the projects handled through Excel and the PCS, no definite conclusion was reached, apart from showing how the utilisation of the system increased over the years. Thus, the next step of the analysis focused on identifying and comparing the CR for products sold via the PCS and Excel.

Comparison of project profitability

The analysis of the overall company's performance (Table 4-1) showed how the CR has increased from 25% to 29% since 2009. However, to confirm that this can be traced to the implementation of the PCS, a comparison of the CR of the quotations handled using the PCS and Excel is performed. Figure 4-2 shows the actual CR for the quotations created with the PCS and Excel.

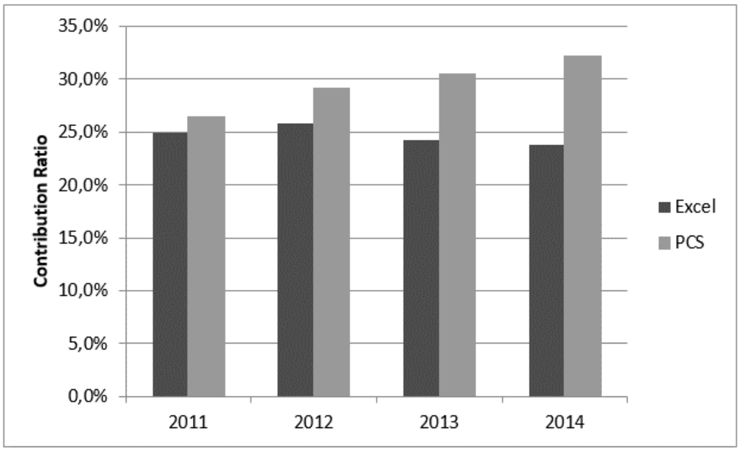

Figure 4-2 Comparison of the actual CR from quotations generated by the PCS and Excel

Salespersons who used the PCS contributed a higher CR than those who used Excel. Furthermore, the gap between the actual CR of the quotations generated by the PCS and Excel is increasing steadily over the years. In 2014, the average CR was 29.0%; salespersons who used the PCS had an average CR of 32.1% while salespersons who used Excel had 23.8%. The increasing gap between the CR for the quotations generated in the two systems can be explained as result of the increased utilisation of the PCS and the company's effort to update prices in the PCS instead of Excel. Finally, special products were not included in the PCS; therefore, to calculate the costs, Excel spreadsheets were always used. Although those products were omitted from the quotations made in Excel presented in Figure 4-2, they did not contribute significantly to the average CR. For example, for 2014 they affected the CR for the quotations created in Excel by only 0.2%. Therefore, the lower CR cannot be traced to special orders. This result supports the notion that product profitability is increased when the projects are handled through a PCS.

Comparison of the accuracy of the cost calculations

To compare the accuracy of the cost calculations generated in the PCS and Excel, the DEV_{CR} is calculated. The results are shown in Figure 4-3.

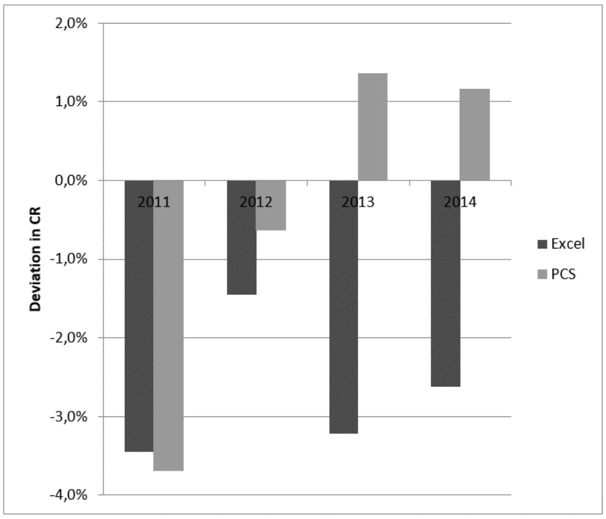

Figure 4-3 Comparison of DEV_{CR} *for salespersons who used the PCS and Excel*

The analysis shows less DEV_{CR} for the products where the salespersons used the PCS than for the products the salespersons used Excel, with the exception of 2011. In the following year of 2012, there was a significant reduction in DEV_{CR}, mainly for the ones created through the PCS. Moreover, in 2013 and 2014 the DEV_{CR} in the quotations created by the PCS were positive (1.4% and 1.2%, respectively), while the DEV_{CR} for the cost calculations generated with the Excel was negative and still quite high (–3.2% and –2.6%).

Another possible explanation for the increasing gap between the DEV_{CR} is a complete cost calculation via the PCS than Excel. All parts required for every product were included in the PCS; with cost estimates created in Excel, the salesperson might have forgotten to include all the parts. As a result, the estimated cost did not include all the required parts and was lower than the actual cost, which led to the negative DEV_{CR}. Therefore, the analysis of the performance of the salespersons who used Excel and the PCS implies that the PCS affected the accuracy of the cost estimates in terms of DEV_{CR} and the profitability in terms of CR positively.

4.1.2.3 Conclusion

The aim of this case study is to measure the impact of utilising a PCS on the accuracy of the cost calculations and consequently the impact on product profitability. The study is based on a case study where the company is analysed both prior and after implementation of a PCS. The findings of this study indicate that the contribution of the PCS is noteworthy; these findings are presented in paper B, and they provide an answer to RQ 1.3.

4.1.3 Study C: The economic value creation from using PCS – A case study

4.1.3.1 Research objective and research questions

This study analyses the cost factors and costs savings to provide a more fundamental understanding of the economic value creation in terms of the return on investment from implementing and using PCS.

> **RQ 1.4.** What is the actual economic value creation from implementing and utilising a PCS in companies manufacturing customized products?

To answer the question, this study was conducted in collaboration with a case company (C2), as explained in Section 2.4.1.

4.1.3.2 Research contribution

The case company produces both standardised and engineered products. Because the market environment is highly competitive, delivery time and cost are critical. The primary motivation for implementing the PCS was to reduce the time required to respond to customer inquiries and thereby increase the company's overall competitiveness. Both local sales offices (LSO) and the customer support unit (CSU) at the company's headquarters use the PCS. The LSO operate globally and are responsible for all interactions with customers during the sales process. In total, 43% of the LSO have access to the PCS, which allows them to configure products to a greater extent without having to contact the CSU at the company's headquarters. In cases where the LSO do not have access to the PCS, technical support performs the configuration while the local sales office interfaces with the customer.

Changes in the product specification process

The product specification process before PCS implementation

Before the PCS was implemented, the generation of product specifications involved two different scenarios.

The first scenario relates to standard products. In this case, customer orders the product that is available on the company's homepage; in the case of using different product catalogues, ordering is done through one of the local sales offices. If the customer is unable to find the desired product, the sales office makes recommendations. For standard products, all product specifications are available.

In the second scenario, customers order non-standard products, which are termed light and heavy ETO products depending on the level of customisation (Figure 4-4). This requires the involvement of a CSU in the sales process and where input from the engineering and the production department is required. This can lead to time-consuming interactions between the actors involved.

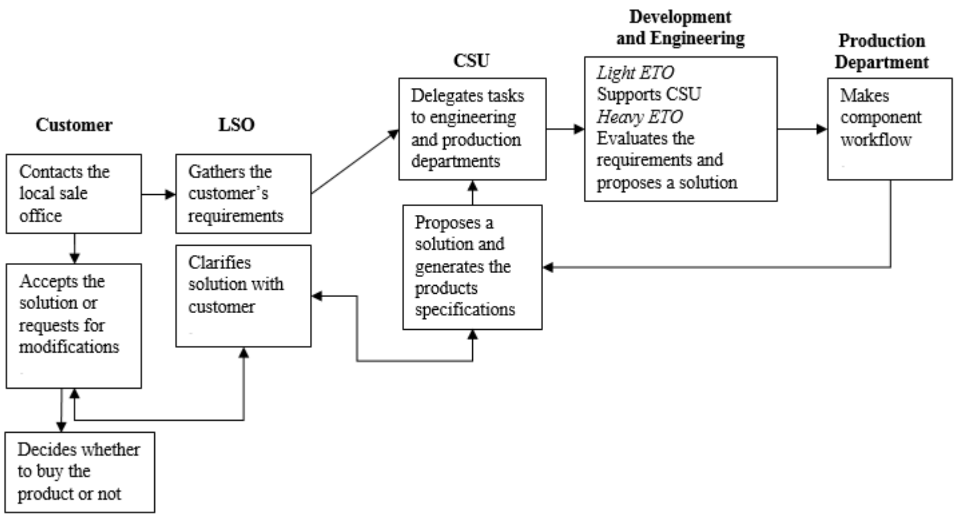

Figure 4-4 The product specification process for non-standard (light and heavy ETO) products before PCS implementation

The time taken to respond to the customer is one of the main criteria based on which customers decide whether to order a product. A large number of orders processed by the CSU department at the company's headquarters was causing a severe bottleneck in the product specification process, and consequently, customers had to wait up to weeks to receive a response. To address these challenges, the company decided to introduce a PCS to support the product specification process for light ETO products. Since the PCS did not affect the product specification process for standardized and heavy ETO products, the heavy ETO product type is not discussed in the study.

The product specification process after PCS implementation

The PCS aims to support the product specification process for light ETO products, which are further categorized into light ETO and CTO products. The CTO products were introduced to standardise the product range. This section presents two scenarios, namely the product specification process for CTO products and that for light ETO products.

CTO products are configured either by the LSO or by CSU. For the LSO that have access to the PCS, they can independently configure the products, generate product specifications, and send them to the customer. However, in cases where the LSO do not have access to the PCS, the customer's requirements are sent to the CSU, which configures the product via the PCS. The CSU then sends the product specifications back to the LSO, which forwards them to the customer. Figure 4-5 illustrates the product specification process for CTO products when supported by the PCS.

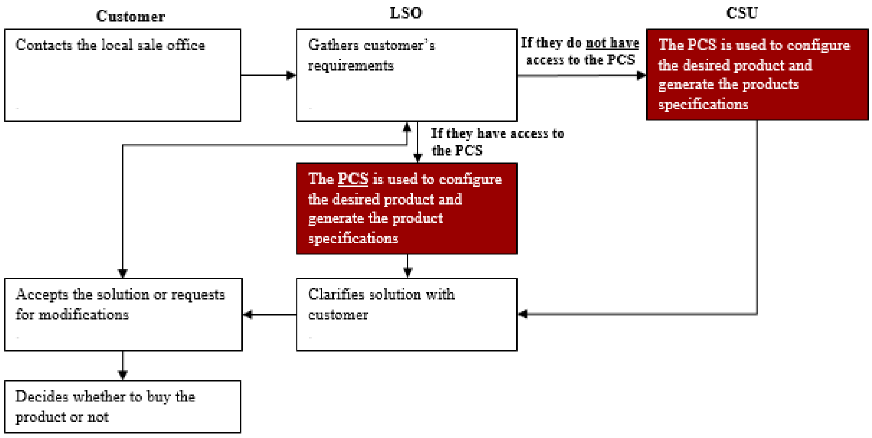

Figure 4-5 The product specification process for CTO products after PCS implementation

In the case of light ETO products, the customer requirements exceed the solution space of the PCS. In such cases, the LSO requires the assistance of the CSU, which can delegate the necessary tasks to other departments accordingly. The product specifications are created partly manually and partly automatically with the support of the PCS. Figure 4-6 illustrates the product specification process for light ETO products supported by the PCS.

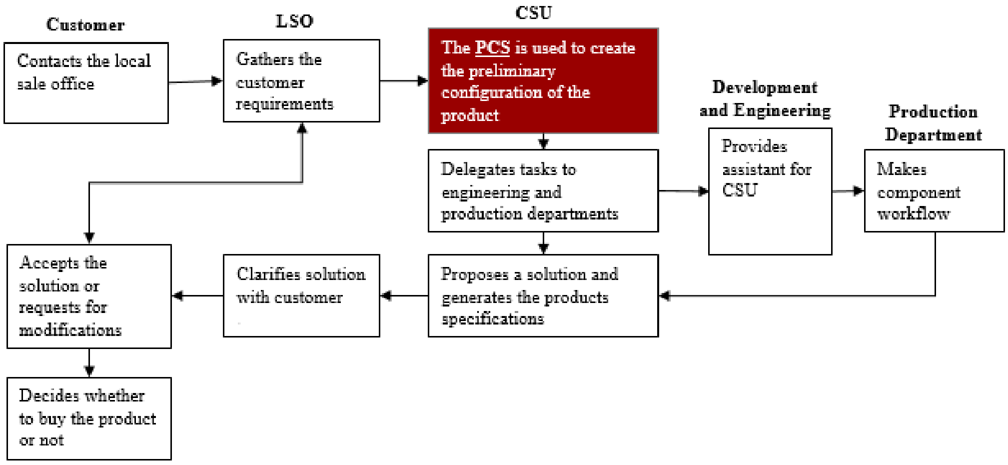

Figure 4-6 The product specification process for light ETO products after PCS implementation

Economic value creation from using the PCS

This section quantifies the cost savings factors and the cost factors in order to identify the economic value creation from using the PCS.

The main cost savings factors from using the PCS

This section quantifies the cost savings factors pertaining to resource consumption and lead-time over a five-year period. Additionally, indications of the improved quality of product specifications, and increased sales are analysed.

The impact of applying the PCS on resource consumption and lead-time. To estimate the impact of the PCS implementation, the products sold over a five-year period are compared to the resources consumption (work-hours) needed to generate the specifications when supported with PCS and when unsupported with PCS. The cost savings are calculated by comparing the time consumption of different products categories before and after PCS implementation. Since all CTO products were treated as light ETO products prior to implementing the PCS, the time required to generate specifications for these products is used to calculate how much time the product configuration for CTO would have taken when unsupported by the PCS. To make the calculations more conservative, the analysis assumes that no savings are gained in the case of light ETO products as there only partially supported by the PCS. Table 4-2 shows the total average resource consumption (work-hours) in the configuration process before and after PCS implementation.

Table 4-2 Work-hours required to respond to customer orders before and after PCS implementation (the calculation are based on a five-year period)

		With PCS		**Without PCS**
Product types	**CTO**	**CTO**	**Light ETO**	**Light ETO**
Responsible for the configuration	LSO	CSU	CSU	CSU
Average time per order (hours)	0.39	0.46	2.28	2.28
Total quantity sold over a five-year period (pieces)	175,699	66,553	23,960	266,212
Total time spent on orders over a five-year period (hours)	68,815	30,503	54,669	607,407
Weighted average of the total work-hours spent on orders over a five-year period (hours)		**153,988**		**607,407**

As Table 4-2 shows, the resource consumption for generating quotations reduced significantly; 453,419 work-hours (75%) were saved due to the implementation of the PCS over a five-year period. Assuming the average salary is 50 €/hour, the company saved 22,670,971 € in direct salary costs in the customer order process over the five-year period. PCS implementation also impacted the lead-time for generating quotations, as shown in Table 4-3.

Table 4-3 The quotation lead time (days) before and after PCS implementation

	With PCS			Without PCS
Product types	CTO	CTO –	Light ETO	Light ETO
Responsible for the configuration	LSO	CSU	CSU	CSU
Average lead-time (days)	2	5	9.5	9.5
Total quantity sold over a five-year period (pieces)	175,699	66,553	23,960	266,212
Weighted average of the quotation lead-time per order (days)		**3.4**		**9.5**

As shown in Figure 4-8, the average lead-time for generating quotations reduced from 9.5 days to 3.4 days, which means that an average of 6.1 days (64%) were saved for each quotation generated when the PCS was used.

Increased quality and sales from using the PCS. In addition to reduced resource consumption and lead-time gained from implementing, the PCS quality of the specifications and increased sales are analysed.

To measure whether the PCS had *increased the quality* of the product specifications, the errors were measured over a one-year period for all specifications generated by CSU using the PCS and without it. The analysis shows that fewer errors occurred in the specifications generated by the PCS. The errors are measure returns of the production line, which are dived into the following seven categories: test data, basis data, the error reported, name plate data, bill of materials, other errors, and operations. Each time an error is detected, the system registers whether the entry is created manually or by the PCS. However, when the requirements exceed the solution space in the PCS, the product specifications need to be generated manually. Therefore, this comparison does have limitations as the complexity of the products is higher when the specifications are generated manually. Specialists from the company confirmed through interviews that the PCS leads to higher data quality due to a standardised and guided structure. Moreover, the specialists explained that the errors in the product specifications generated by the PCS were not caused by the system itself but by the incorrect input in most cases. Thus, it can be assumed that if the PCS did not support generating specifications, the number of errors would be even higher.

Time and cost are critical factors that determine whether customers would make their purchase from a given company. Thus, it can be assumed that increased responsiveness in the customer order process can lead to *increased sales*. Increased responsiveness is measured by the productivity of employees and the lead-time in responding to a customer's order. Based on the saved work-hours, it can be assumed that productivity in of the company's employees is increased by a factor of 3.9. Consequently, it can be assumed that 3.9 times more resources became available to handle additional customer orders. As previously explained, before the implementation of the PCS, CSU became a bottleneck in the sales process due to the high number of orders being processed by the department. However, after the PCS was implemented, the number of orders that reached CSU reduced significantly, resulting in increased productivity. Furthermore, the time taken to respond to customer orders reduced significantly (from 9.5 days to 3.4 days, or by 64%). This should, in turn, lower the threat of losing customers to a competitor due to insufficient response time. In short, the findings show that the implementation of the PCS stimulated additional sales due to increased responsiveness. Even though there is no solid evidence to prove that PCS usage led to increased sales, this assumption is supported by the study findings. These findings were verified by specialists at the case company.

The main cost factors of the PCS

This section elaborates on the different cost factors associated with the development, implementation, and maintenance of the PCS. A number of different stakeholders are involved in development and implementation. After developing the PCS model, the model needs to be tested. Moreover, training sessions need to be held, and licenses must be bought in advance. Finally, both the system itself and the product data need to be maintained to ensure that they are up to date.

To render the calculations comparable with those previously described for cost savings, the maintenance cost was calculated over a five-year period. In addition to the maintenance cost, the development cost—which is spread over a two-year period—was also considered. Table 4-4 presents the individual cost factors in relation to the development, implementation, and maintenance.

Table 4-4 Cost factors associated with developing (over a two-year period), implementing, and maintaining the PCS (over a five-year period)

Cost components associated with the PCS		Amount	Unit
Development			
Weekly workload		88.8	Man-hours
Duration of development (over a two-year period prior to PCS implementation)		104	Weeks
	Total	9,235	Man-hours
	Total	461,760	€
Implementation			
Estimated total		300,000	€
Maintenance of the PCS			
Weekly workload		92.5	Man-hours
Duration of maintenance (over the five-year period)		260	Weeks
	Total	24,050	Man-hours
	Total	1,202,500	€
Maintenance of product data			
Weekly workload		34.0	Man-hours
Duration of maintenance (over the five-year period)		260	Weeks
	Total	8,840	Man-hours
	Total	442,000	€

4.1.3.3 Conclusion

The study's findings describe the economic value creation from using a PCS in the case company. By comparing the direct cost savings from the reduced work-hours to the direct cost of developing, implementing, and maintaining the PCS, it can be concluded that the PCS was highly beneficial for the case company over the five-year period analysed, or 842% return on investment for the five-year period analysed. Additionally, the study presented evidence supporting an increase in sales and in the quality of product specifications when products were generated with PCS. The findings of this study are presented in paper C, and they provide an answer to RQ 1.4.

4.1.4 Summary: Main benefits of implementing and utilising PCS

Section 3.2 elaborated on the different benefits explained in the literature from implementing and utilising PCS. As explained, there are still some unanswered questions regarding the benefits of PCS, which are described in Section 3.2.2. To provide answers to those questions, three studies (A, B, and C) were presented in this section.

First, the primary motivations that companies have for implementing and utilising PCS were analysed (RQ 1.1), and the successfulness of the companies in achieving the benefits related to the initial motivations (RQ 1.2) was addressed. The analysis reveals seven categories of motivations, and it is dependent on the category how successful companies are in achieving the benefits related to the initial motivations. Second, the impact on the accuracy of the cost calculations and consequently the impact on product profitability (RQ 1.3) was analysed. The analysis reveals that the impact of the PCS is noteworthy in a case company, as the products sold through the PCS have more accurate cost estimates and consequently improved profitability. Third, the economic value creation in terms of return on investment is analysed (research question 1.4). The analyses show the high return on investment of five-year period, which is calculated based on saved work-hours and the cost of development, implementation, and maintenance of the PCS. Furthermore, indications of the improved quality of the specifications and increased sales were identified.

It can be concluded that PCS can result in a number of benefits, which can improve the companies' competitiveness and profitability. Nevertheless, many PCS projects are not this successful. Thus, Section 4.2 provides some insight on the main challenges of implementing and utilising a PCS.

4.2 THE MAIN CHALLENGES OF IMPLEMENTING AND UTILISING PCS

This section investigates the main challenges in relation to implementing and utilising a PCS. In doing so, the section aims to provide an answer to RQ 2. While the literature explains a number of challenges from implementing and utilising PCS, there are still unanswered questions as seen in Section 0. Thus, this section aims to provide a more fundamental understanding of the main challenges that companies face when implementing and utilising PCS.

4.2.1 Study D: The main challenges for manufacturing companies in implementing and utilising PCS

4.2.1.1 Research objective and research questions

This study aims to provide insight on the main challenges of implementing and utilising a PCS with regard to the identification of the main challenges, the importance of the main challenges, and the specific challenges within each of the categories. More specifically, the study aims to provide answers to the following research questions.

> **RQ 2.1**. What are the *main categories* of challenges that companies manufacturing customized products face when implementing and utilising their PCS?
>
> **RQ 2.2.** What is the *importance* of each category of challenges that companies manufacturing customized products face when implementing and utilising their PCS?
>
> **RQ 2.3.** Which *specific challenges* within each category do companies manufacturing customized products face when implementing and utilising a PCS?

To provide answers to these questions, the study uses the literature presented in Section 3.3, along with a survey (S1) followed by interviews with 22 companies (Section 2.4.2).

4.2.1.2 Research contribution

First, the main categories of challenges based on the literature are presented; this is elaborated in Section 3.3 under the theoretical basis. Second, the categories identified from the literature are confirmed based on the response from the survey. Third, based on the answers from the survey, each of the main categories of challenges is explained in more details. Fourth, the perceived importance of the individual categories of challenges is presented.

Identification of the main categories of challenges

The literature review under Section 3.3 highlighted six main categories of challenges: IT, product modelling, organisational, resource constraints, product-related, and knowledge acquisition. Based on the answers from the company representatives, it was concluded that no additional categories of the challenges were required. Table 4-5 details the percentages of companies that referred to the different categories of challenges based on their answers to the survey's open questions.

Table 4-5 Companies expressing one or more challenges grouped into the main categories

The main categories of challenges	Companies (%)
IT-related	36.36%
Product modelling	40.91%
Organisational	68.18%
Resource constraints	22.73%
Product-related	22.73%
Knowledge acquisition	59.09%

The specific challenges within each category

The following is a detailed explanation of the answers given by the companies' respondents. This is used for describing the main categories of challenges.

IT-related

The reported IT challenges are grouped into two subcategories related to (1) software development and (2) system design to achieve user-friendliness.

With regard to *software development*, two of the respondents explained that the technical aspects of developing and implementing a web-based PCS had presented a significant difficulty. Two other respondents reported difficulties in integrating the PCS with other IT systems at their companies. One respondent also referred to challenges in exchanging information across different PCSs. Operating the database and developing customised functionalities had also caused problems for some respondents.

In addition, designing a *user-friendly* PCS was considered challenging. One respondent reported that salespersons' desire to use the PCS was proportional to the user-friendliness. The same respondent added that the sales PCS was launched and tested to achieve user-friendliness, and the PCS was later expanded to include technical configurations. One respondent said that maintaining the level of simplicity required for a user-friendly system had been a challenge, and another reported that the complexity of technical requirements and the product range had made it difficult to incorporate all the right product combinations in the configurator.

Product modelling

The reported product modelling challenges can be grouped into three subcategories related to (1) complexity due to lack of overview of product range, (2) correctness of specifications generated by the PCS according to product model, and (3) lack of knowledge related to product modelling.

Regarding *complexity due to lack of overview*, respondents highlighted problems caused by the complexity of the PCS for the users. For example, respondents noted that the lack of a product overview made it difficult to formalize the questions asked in the configuration processes logically. Another respondent referred to difficulties in maintaining an overview, and another said that it was difficult to ensure the PCS ease of use with increasing complexity. These answers confirmed the need for modelling techniques to establish an overview of a company's product ranges and to reduce the complexity of linkages between offered solutions and customer needs. Product models also need to be regularly updated to provide an overview and to reflect the product knowledge incorporated in the PCS.

The *correctness of specifications* generated by the PCS depends on the underlying product model. One respondent reported a constant need to test whether parts were properly configured, owing to a lack of product modelling and validation. Another respondent stated that in addition to ensuring that the PCS was capable of generating BOMs in the configuration process, it was also important to verify that the individual parts or components fitted together and that instructions were provided for setting up the individual parts or components. This highlights the importance of a product model that accurately represents the different relationships in the product structure to ensure the correctness of configurations.

Regarding *unfamiliarity with product modelling*, one respondent reported challenges in establishing knowledge and acquiring information on how a PCS works and how to build the underlying product model.

Organisational challenges

Organizational challenges refer to (1) a lack of support from management, (2) resistance to using the PCS, and (3) disagreements about the scope of the PCS.

Two respondents reported a *lack of support from management*. As implementation of a PCS is usually cross-functional and affects multiple stakeholders, increased support from management promotes project success. This support can ensure that critical activities are prioritised and that resources are assigned to the project. As one respondent explained, key individuals at the company have the necessary knowledge to develop and validate the system. To secure access to this professional knowledge, PCS projects must be prioritised by management. One respondent said that the PCS team found it challenging to keep itself updated with product development because the team is usually the last to know about new products. Failing to involve the configuration team in the early stages of product development can cause delays in releasing new products because those products are not included in the PCS and are therefore not available to salespersons. Finally, two respondents referred to the lack of documentation and ongoing training as organisational challenges when resources and central activities are not prioritised.

One respondent mentioned the challenge posed by *resistance to using the system*, emphasising the difficulty of changing employees' habits to adapt to the use of the PCS as part of a new work procedure. Another respondent stated that this resistance might stem from employees' reluctance to abandon the comfort of the old system—for example, employees who were used to working alone experienced difficulties in adjusting to a system that required them to work on the same things in client mode. Increased standardisation of products and processes was also mentioned as a source of organisational resistance. One respondent explained that the PCS marked a move toward a more standardised and structured sales process, thereby limiting individual freedom and shifting the focus from prices to customer value creation. Furthermore, one respondent explained that sales representatives used the PCS only in special cases while continuing to use the old system in other cases, indicating that sales representatives were not committed to the new procedure, even in cases that could be handled by the PCS. In addition to this internal resistance, four respondents reported difficulties in convincing their sales agents or customers to use the PCS despite offers of training and discounts for using the systems in the sales process.

Disagreement about *PCS scope* was also reported as a source of organisational challenge. Not all products are supported by the PCS, which means that employees may lack experience in using it. One respondent mentioned that all products need to be supported by the PCS if salespersons were to recognise the system's usefulness. However, another respondent explained that resistance to using the PCS depended on usability—that is, the system needs to cover all needs and product variations adequately. To ensure successful implementation and acceptance, it is essential that the system meets all requirements while avoiding increased complexity. Finally, one respondent noted a challenge in agreeing on the PCS content and scope. According to the companies, not all products were included in the PCS because that would result in considerable complexity. It follows that in supporting a configuration for a greater variety of products, the system can compromise user-friendliness.

Resource constraints

The main challenges related to resource constraints were described in terms of (1) lack of resources, (2) vulnerability if key personnel leave.

With regard to challenges related to *lack of resources* in PCS projects, two respondents highlighted the lack of resources for the configuration team and the release of resources from the business (e.g., product experts). Another respondent explained this in terms of capacity planning difficulties; another said that a lack of resources meant that not all products were included in the PCS and thus increasing resistance to using the system. In terms of vulnerability, if *key personnel leave*, one respondent indicated that a lack of resources made it difficult for anyone other than key personnel to gain an overview of the PCS and the knowledge embedded in the system. Confining all of the valuable knowledge to a small number of employees puts the company at risk if these key personnel leaves the company; it can be difficult for another person to become familiar with the system because this requires knowledge about both products and software.

Product-related challenges

The main challenges related to the products were described in terms of (1) complexity of product structures and (2) rapid product development.

One respondent explained that as *complex products* entail more options, rules, and dependencies, more decision making and more complex PCSs are required. In this sense, managing complexity is a challenge. Another respondent emphasised that proceeding with the PCS requires a high level of standardisation of the product range. This corresponds to how a PCS requires components or modules to be defined with constraints that determine how different parts and components can be combined. Another respondent explained these challenges in relation to the generation of BOMs enabling individual parts and components to fit together and setup instructions to be generated.

With respect to both the challenges related to product range and *rapid product development*, one respondent pointed out that PCSs must be capable of rapid updating to be aligned with product offerings. Another respondent expressed the view that to keep the PCSs updated and to ensure that they reflect product offerings, the configuration team needs to be at the forefront of new product development.

Knowledge acquisition

The main challenges relating to knowledge acquisition were characterized as (1) difficulties in acquiring the correct knowledge, (2) a lack of knowledge to meet users' and customers' needs, and (3) failure to communicate knowledge in the maintenance phase.

The process of *acquiring product knowledge* was considered critical in ensuring the quality of the PCS. One of the interviewees explained this in terms of the need to transfer specifications to the PCS without misinterpreting or losing knowledge. Other problems arose regarding requirement specifications, which should be as accurate as possible so all personnel would have the same starting point. Other respondents explained that incomplete product definition made it difficult to keep track of products and their variants. Finally, it was also observed that organizations had different approaches to validating the correctness of the PCS and the generated product specifications. While some organizations started out with the product model, others went through an extensive testing phase to eliminate errors, and others relied on feedback from installation and error correction as an input for correcting the configurator. As knowledge acquisition challenges can lead to a PCS generating inaccurate specifications, the focus should be on ensuring that the correct information is retrieved the first time. This may be difficult if only a few people are in possession of the requisite knowledge.

Another challenge related to knowledge acquisition was expressed in terms of understanding the *needs of customers and users* to ensure that these can be fulfilled in the configuration process. As PCS are commonly used to guide sales processes, it is critical to gather sufficient information to capture the needs of users and customers' needs. As in the case of organisational challenges, if the system lacks the necessary scope to address users' needs, resistance to the use of the system is likely to increase. This was also expressed as a problem of knowledge acquisition; one respondent noted that the PCS could not meet all salespersons' needs and all product variants because of a lack of knowledge. Another challenge was expressed by respondents in two companies in terms of acquiring knowledge of the customers' needs to be reflected in the PCS setup. A respondent from a company specialising in engineered solutions for individual customers referred to challenges resulting from an inadequate product program structure, which made it difficult to capture the required knowledge and expand the PCS. Similarly, another respondent noted challenges in relation to parameters of each variant requested by the customer and another described the lack of knowledge of how different parts can be combined as a critical challenge. In this way, knowledge acquisition challenges can be related to the product types offered—that is, companies providing more engineered solutions may have less product knowledge because each product is engineered for a specific customer. For that reason, these companies may encounter more knowledge acquisition difficulties.

Issues related to *knowledge acquisition in the maintenance phase* were also considered a challenge. This relates to a lack of troubleshooting knowledge, which is why certain configurations are unfeasible and why error messages are generated. Two other respondents stated that new options were not being updated in the PCS because product knowledge was not being communicated in the maintenance phase. Finally, it was also seen as challenging that new products had to be approved each time because of a lack of validation and information from product experts.

The perceived importance of the main categories of challenges

The second part of the research focuses on assessing the importance of the challenges encountered when implementing and managing the PCS. Table 4-6 sets out the main categories of challenges in terms of their importance as measured on a five-point scale, ranging from 1 (*not important*) to 5 (*very high importance*). The results are synthesised into three groups: not important (1), low importance (2–3), and high importance (4–5) and show the percentages of companies' ratings of the different groups.

Table 4-6 Perceived importance of the main categories of challenges when implementing and utilising the PCS

	Quantitative results		
	Not important	**Low**	**High**
IT-related	9.09%	54.55%	36.36%
Product modelling	9.09%	40.91%	50.00%
Organizational challenges	13.64%	36.36%	50.00%
Resource constraints	18.18%	36.36%	45.45%
Product-related	22.73%	50.00%	27.27%
Knowledge acquisition challenges	18.18%	31.82%	50.00%

Based on these results it can be observed that challenges relating to knowledge acquisition, organisational and product modelling are rated with high importance by 50% of the companies. However, the overall importance is determined by comparing the results based on the qualitative and the quantitative part the following section elaborates on.

Importance of the main categories of challenges

The overall importance of the main categories of challenges is determined based on the qualitative and the quantitative results (Table 4-7).

Table 4-7 Importance of the main categories of challenges when implementing and utilising the PCS

Main categories of challenges	Qualitative results	Quantitative results	Overall importance
1. Organizational challenges	Ranked number 1 (68.18% of companies)	Rated as of high importance by 50.00% of companies	Significant importance
2. Knowledge acquisition	Ranked number 2 (59.09% of companies)	Rated as of high importance by 50.00% of companies	High importance
3. Product modelling	Ranked number 3 (40.91% of companies)	Rated as of high importance by 50.00% of companies	Medium importance
4. Resource constraints	Ranked number 5-6 (22.73% of companies)	Rated as of high importance by 45.45% of companies	Medium importance
5. IT-related	Ranked number 4 (36.36% of companies)	Rated as of low importance by the most companies (54.55%)	Low importance
6. Product-related	Ranked number 5-6 (22.73% of companies)	Most often rated as not important (22.73%) and of low importance (50.00%)	Low importance

Overall, organisational challenges were of significant importance. Where companies rated organisational challenges as highly important, other challenges also became more significant, indicating that this type of challenge is an underlying factor in other challenges. Knowledge acquisition is rated as of high importance and product modelling as of medium importance. While both are among the highest scorers in the quantitative part of the study, knowledge acquisition is mentioned by more companies in the qualitative part of the study, and its impact is therefore considered higher. Although least often mentioned in the qualitative part of the study, resource constraints are rated as of medium importance, given the observed dependency between these and the organisational challenges. This indicates that the presence of both organisational and resource-related challenges makes other challenges more significant —in other words, these are underlying factors in other challenges. IT challenges and product-related challenges are rated as of low importance.

4.2.1.3 Conclusion

The findings from the study address the main challenges of implementing and utilising PCS. First, the main categories of challenges are identified based on literature and confirmed with the grouping of the answers from the survey's open question. Second, the challenges within each category are elaborated. Third, the importance of the main categories of challenges is assessed. The findings of this study are presented in paper D, and they provide answers to RQ 2.1, 2.2 and 2.3.

4.2.2 SUMMARY: THE MAIN CHALLENGES OF IMPLEMENTING AND UTILISING PCS

Section 3.3 elaborated on the different challenges explained in the literature from implementing and utilising a PCS. As explained, there are still some unanswered questions regarding the challenges, which are addressed in Paper D under Section 4.2.

First, the main categories of challenges were identified both with a literature review and by using a survey (RQ 2.1). The analysis revealed six main categories; even though additional challenges are identified in the literature, these were the most commonly expressed. Second, the perceived importance of those categories was determined (RQ 2.2). Third, based on the responses of the survey, each of the main categories of the challenges was elaborated in more detail (RQ 2.3).

It can be concluded that the implementation and utilization of PCS are not without challenges. By identifying firstly the main challenges and categories, then according to the importance, the study aimed to provide valuable information both to the research community and to practitioners. To address some of the challenges described, the following sections focus on providing improved tools and methods to apply PCS, specifically with how to identify and evaluate potential PCS projects, how to improve the development and maintenance of PCS projects, and how to have improved performance and accuracy of a PCS with IT integrations.

4.3 IDENTIFICATION AND EVALUATION OF PCS APPLICATIONS

This section investigates identification and evaluation of PCS projects with particular focus on engineering companies. While the literature explains different strategies for improving the efficiency within different PCS projects, this section focuses on the effectiveness of PCS projects by providing answers on how to identify and evaluate the different applications PCS.

4.3.1 STUDY E: HOW CAN ENGINEERING COMPANIES IDENTIFY AND EVALUATE POSSIBLE APPLICATIONS OF PCS

4.3.1.1 Research objective and research questions

This study aims to contribute to the literature and help practitioners by providing a framework that engineering companies can use to identify different applications of a PCS. More specifically, this study aims to answer the following research question:

> **RQ 3.1** How can possible applications of PCSs be identified in engineering companies?

To provide answers to this question, the research method in this paper is structured in two phases. The first phase is concerned with the development of the framework that aims to provide a structured approach to identify different applications of PCS in engineering companies. The second phase explains the validation of the framework that was done in collaboration with an engineering company (C3). The setup of the case study is explained in Section 2.4.1.

4.3.1.2 Research contribution

This research proposes a three-step framework that should help companies to identify different applications of PCS in engineering companies. The framework builds on related research fields and attempts to include the main aspects that should be considered when identifying possible applications of PCS (Figure 4-7).

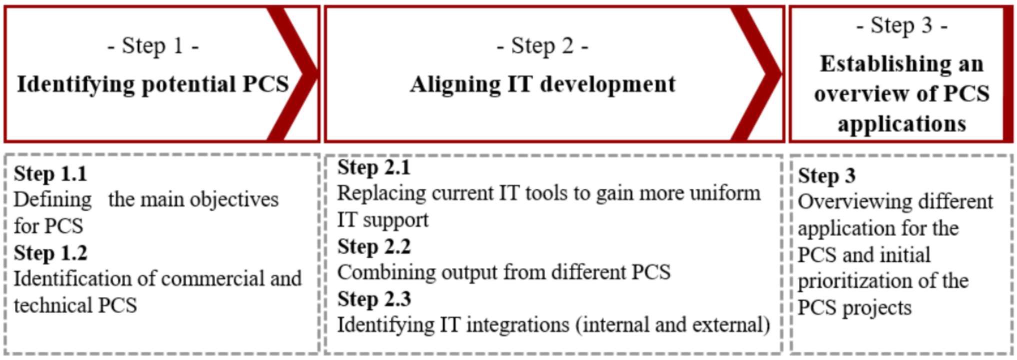

Figure 4-7 The proposed framework to identify applications of PCSs.

Step 1: Identifying potential PCS

Step 1 aims to identify a potential PCS. This step is divided into two sub-steps: defining the main objectives for PCS (Step 1.1) and identifies potential PCSs, both commercial and technical (Step 1.2).

Step 1.1: Defining the main objectives for PCS

The literature describes numerous benefits achieved from using PCS, including reduction of work-hours and lead-time when making product specifications, improved quality of product specifications and products, more on-time delivery, improved control of product variants and improved accuracy of cost calculation and thus increased profitability (e.g. Forza and Salvador 2002a; Heiskala et al. 2005b; Forza et al. 2006; Hvam, 2006a; Haug et al. 2011; Trentin et al. 2012; Myrodia et al. 2017). It is essential that the objectives or the benefits to be achieved are clear from the start, as they influence decision-making when evaluating commercial and technical PCS separately (Step 2.1) and when evaluating the complete overview of different PCS applications (Step 3). Furthermore, the main objective of the implementation should be aligned with the company's strategy.

Step 1.2: Identifying commercial and technical PCS

In this step, potential PCS to support both the sales and engineering processes—or in other words, commercial and technical PCSs (Forza and Salvador 2007) are identified. The objectives determined in Step 1.1 serve as guidelines in this process. The following questions can be used as guidelines, but they can change depending on the objectives defined.

- Where are a considerable number of work-hours used when making product specifications?

- Are there quality issues related to specific product specifications?
- Where are the long lead-times or bottlenecks? (For example, long waiting times can result from lack of work on product specifications, redesign loops, and lack of information).
- When are critical decisions made to avoid unnecessary complexity and increased cost?
- When are there delays (e.g., late delivery)?
- Where are there deviations between estimated and realised costs?

Step 2: Aligning IT development

Step 2 aims to provide an understanding of current IT systems used to generate product specifications, interactions across PCS, and other IT system interactions with a PCS. This step is divided into the following three steps: replacing current IT tools to gain more uniform IT support (Step 2.1); combining output from different PCSs (Step 2.2); and identifying IT integrations, both internal and external (Step 2.3).

Step 2.1: Replacing current IT tools to gain more uniform IT support

This implies a more standardised way of applying the IT systems that are needed for generating proposals and other product specifications. Actions can include replacing current tools or IT systems (e.g., Excel-based tools) to create more uniform IT support for generating product specifications. This, in turn, allows for interactions across PCSs used in different departments, as explained in Step 2.2. More uniform IT support can also be valuable in terms of maintenance, user acceptance, and quality (Myrodia et al. 2017).

Step 2.2: Combining output from different PCS

Combining different PCSs means that different PCS within a company can interact. This helps to avoid data redundancy, as the same information does not have to be included in multiple PCSs. Combining different PCSs also streamlines the communications across different departments, where the PCSs are used as platforms to exchange data and to give input (e.g., sales to engineering, and vice versa). This also implies that the outputs from one PCS are used as inputs for the other (e.g., sequential processes such as pre-sales, sales and engineering).

Step 2.3: Identifying IT integrations (internal and external)
The configuration process is highly dependent on retrieving information from both internal and external IT systems. Redundancy can be avoided by having integrations with other IT systems (Blecker et al. 2004). This step is thus concerned with identifying required IT integrations—both internal and external aspects—in the configuration processes. Internal integrations include IT systems used within the company. These can include CAD, ERP,CRM, PDM, and PLM (Felfernig et al. 2000a; Blecker et al. 2004; Forza and Salvador 2007; Hvam et al. 2008). External IT systems integrations can retrieve the information needed during the configuration process from a supplier's database or even a PCS (Ardissono et al. 2003; Zheng et al. 2017). Such information can include prices and sizing parameters.

Step 3: Establishing an overview of PCS applications
Step 3 draws on the analysis of the previous steps to establish an overview of different applications for PCS and create an initial prioritisation of the identified PCS. This step takes into account the analysis performed in the previous two steps. The company's complete specification process is mapped based on the analysis performed in Steps 1 and 2. This should provide a clear overview of how the specification process can be supported with PCS. After the overview is established, the overall specification process is evaluated based on the overall objectives (Step 1.1). This provides initial input for the prioritisation of the identified PCS.

4.3.1.3 Framework validation
In the case company that is used for framework validation, the first PCS was launched in 2013, and since then, five new PCS have been introduced. The PCS covers some of the primary product categories offered, such as catalysts, equipment, and processing plants. The approach of expanding the application of PCS has focused primarily on implementing new PCSs with little consideration for creating an optimised workflow based on overall objectives and aligning the different stakeholders with one another. This approach served its purpose by quickly establishing the application of PCS and demonstrating the benefits the company can achieve. As the company recognised its expansion of PCS applications, an overview of the specification process was required where the potential application of PCS are listed. The results of implementing the individual steps of the framework are presented in the following sections.

Step 1: Identifying potential PCS

Step 1.1: Defining the main objectives for PCS

This step provides an understanding of the main objectives to be achieved from implementing and using a PCS. The objectives are based on discussions with different stakeholders in the company and their experiences from using PCS.

The case company has a high-level focus on increased digitalisation and automation of the sales and engineering processes. The following are the primary objectives the company aims to achieve from the increased use of PCS:

- reducing routine work in the sales and engineering processes
- decreasing the lead time to generate proposals and other specifications
- increasing the hit rate as a result of shorter lead time to respond to customers' requests
- improving the quality of the product specifications by reducing errors and increasing accuracy, and
- empowering the global sales offices to generate product specifications.

The importance of these individual objectives differs from project to project. For instance, a processing plant with a meagre sales rate would invest in a PCS to empower sales offices around the world and extract implicit knowledge from employees to make the information more explicit. The objectives are determined at the company level. However, since the following analysis was conducted on the business unit level, the following examples from the case study are based on one of the company business units.

Step 1.2: Identifying commercial and technical PCS

In this step, the sales and engineering processes are analysed, based on the objectives described in Step 1.1 to identify processes where PCS can add value. The business unit already uses one commercial PCS that supports the sales process. The analysis revealed three potential new PCSs, namely one commercial PCS and two technical PCS. Using both commercial and technical PCSs enables the engineers to base their work on the output from the commercial PCS and to further work with the data inside the technical PCS. This optimisation of workflow means that the relevant data for configuration is stored in a single system: a setup that allows both salespersons and engineers to work in a more optimal way. Figure 4-7 summarises the setup of the users, output documents, and interactions between the commercial and technical PCS identified. The interactions between the PCS are further discussed in step 2.2.

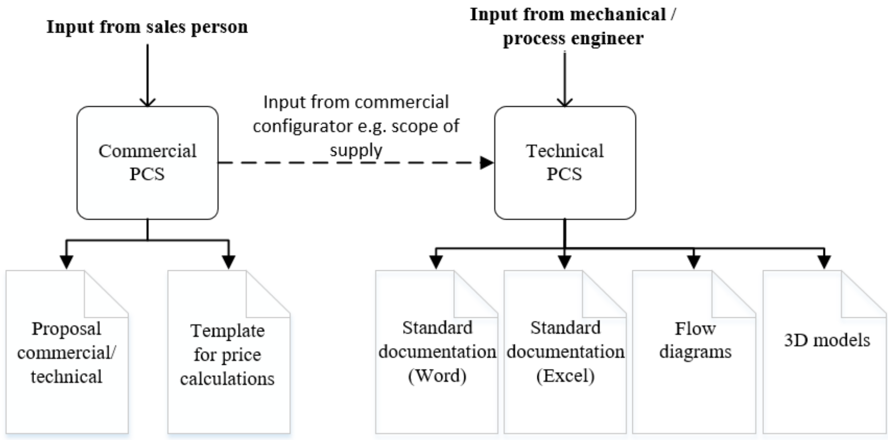

Figure 4-7 Setup for the identified commercial and technical PCSs.

Step 2: Aligning IT development

Step 2.1: Replacing current IT tools to gain more uniform IT support

This step establishes an overview of different IT systems used to create product specifications with the aim of gaining more uniform IT solutions to support the sales and engineering processes. The analysis revealed three Excel-based tools used in the sales process to generate quotations. There are more than 30 of these tools in the engineering processes. The reason for so many Excel-based tools is that specification processes are designed on a component level. In almost all cases, the Excel-based tools used by the engineers have interfaces to interact with other IT systems (e.g., calculation and simulation tools, CAD). They require expert users and are very department specific. This means that cross-department input requires an expert user in that department to operate the Excel-based tool. The identified PCS from Step 1.2 can replace some of the Excel-based tools used to generate product specifications. The commercial PCS can replace the three Excel-based tools used in the sales process. The two technical PCS are not able to replace all Excel-based tools, but they can reduce them by about 80%. The reason for incomplete replacement is that the requirements in about 20% of the cases are too complicated to include in the PCS.

Step 2.2: Combining output from different PCS

This step focuses on listing dependencies across departments, data sharing, and identifying how PCS support that process. The analysis revealed high dependency across the different departments. When a project/plant is sold, input data for different equipment are required from the relevant sales departments. This requires stakeholders to attend time-consuming meetings; often, the input data is received late. In response, a project/plant commercial PCS that can retrieve information from the other departments was identified**.** Figure 4-8 shows the interactions between the identified project/plant PCS and the other commercial PCS used for equipment configurations.

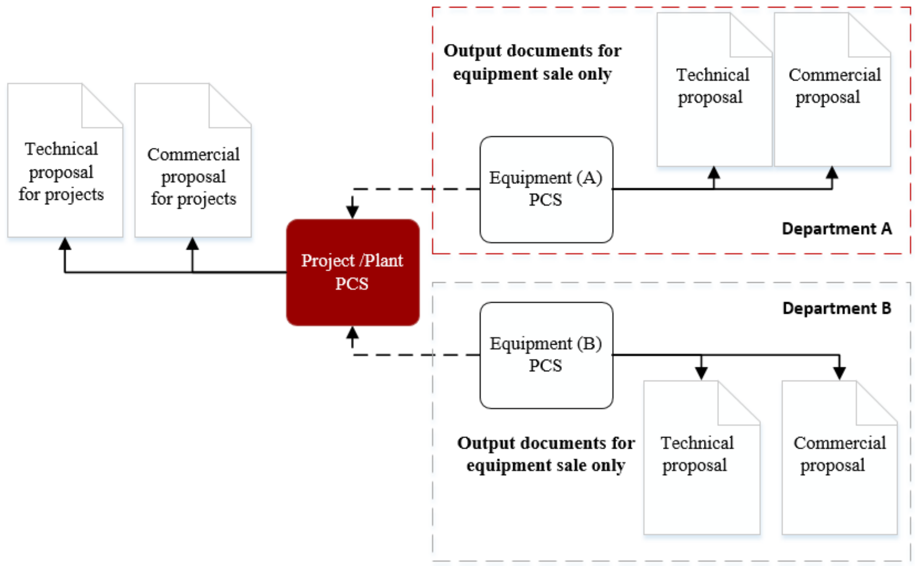

Figure 4-8 Generating output documents using information from PCS across departments.

Step 2.3: Identifying required IT integrations (internal and external)

This step lists the different IT systems used in the business unit and includes descriptions of how those IT systems are used. The company has already established some essential integrations for the commercial PCS in use. These include integrations to databases storing information related to previously sold equipment and software performing both complex calculations and simulations. Other minor integrations are also established (e.g., to retrieve an updated currency rate). The analysis in this step reveals the following IT system requirements for interacting with the PCS:

- Integrating the commercial PCS to an ERP system to retrieve information related to customers and cost
- Integrating the technical PCS to a CAD system to generate 3D models
- Integrating the commercial PCS in the company with the suppliers' systems to ensure that information is up-to-date and to eliminate the need for manual adjustments

Step 3: Establishing an overview of PCS applications

The overview to demonstrate the different application of PCS was generated in a workshop where the results of the previous steps were presented to the managers of the business unit. The results provided a guideline to draw up a figure that the managers could agree on. Figure 4-9 shows a simplified version of the overview. Additionally, based on how the PCS contributed to the overall objectives, the business unit managers could make the initial prioritisation of the different PCS.

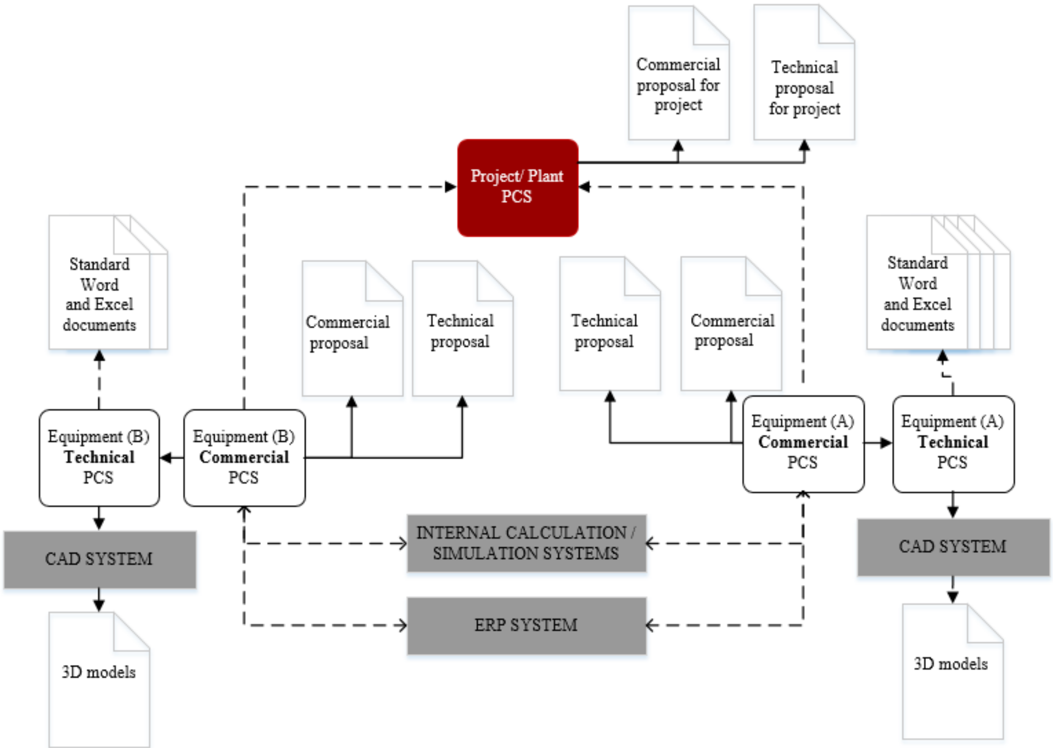

Figure 4-9 Simplified overview of how the sales and engineering processes could be supported by PCS and other IT systems.

By involving the managers from the business unit in the process of creating the overview, a common understanding and ownership were established regarding the application of PCS. Having managers within the business units on board is defined as a critical success factor in achieving the objectives of the PCS. The results of applying the framework in the company and establishing an overview of different PCS applications led to additional work to support the expansion of the PCS. This included defining how testing, maintenance, and user support should be designed. Furthermore, recourse was considered for the configuration team to ensure they would have the capacity to implement the potential PCS identified. A governance structure and a commitment of business resources were also defined. Finally, collaborations with external actors were discussed to share knowledge across engineering companies and to stay up-to-date on the newest developments in the area.

4.3.1.4 Conclusion

The aim of the study is to provide a more structured approach for engineering companies to identify possible applications of PCS. This should give companies an overview of the different applications, align different stakeholders and make the initial prioritisation. The findings of this study are presented in paper E, and they provide an answer to RQ 3.1.

4.3.2 Study F: How to frame business cases for product configuration projects success

4.3.2.1 Research objective and research questions

This study aims to contribute to the literature and help practitioners by providing a framework that companies can use to evaluate different applications of PCS by constructing business cases. More specifically, this study aims to answer the following research question:

> **RQ 3.2**. How can business cases be framed in order to evaluate the potential applications of PCSs?

To answer the research questions, a framework is proposed to make business cases for PCS projects. The proposed framework is then tested on three PCS projects in two engineering companies as explained in Section 2.4.1.

4.3.2.2 Research contribution

The proposed framework builds on both literature for general IT projects (sequence of the individual steps) and literature for PCS projects (proposed tools within the individual steps) as further explained under Section 3.4.2.

First, the study analyses frameworks for constructing business cases for IT projects, in general. The intention is to find similarities of the identified frameworks where the main steps are listed in terms of (1) a benefit analysis, (2) a stakeholder's analysis, (3) IT requirements, and (4) risk and cost analysis (e.g. Ashurst et al. 2008; Häkkinen and Hilmola 2008; Gambles 2009; Bechor et al. 2010; McNaughton et al. 2010; Taylor et al. 2012; Nielsen and Persson 2017). For the framework development of business cases for PCS projects, the same steps are used with the following exceptions. In PCS projects, there is a need for comprehensive process evaluation so that accurate cost analysis can be made. In most cases, the IT structure and platform of the PCS projects is decided for the first time when the PCS is introduced in a company (Hvam et al. 2008). Thus, when making a business case for different PCS projects the IT architecture does not have to be specified each time. Hence, based on the literature, discussions and initial testing, the IT requirement step is substituted with the process and gap analysis, which can also include analysis of the IT architecture if required. Furthermore, a sensitivity analysis is presented to make the cost analysis more realistic. Figure 4-10 shows the main steps of the proposed framework, which are then explained in the following sections.

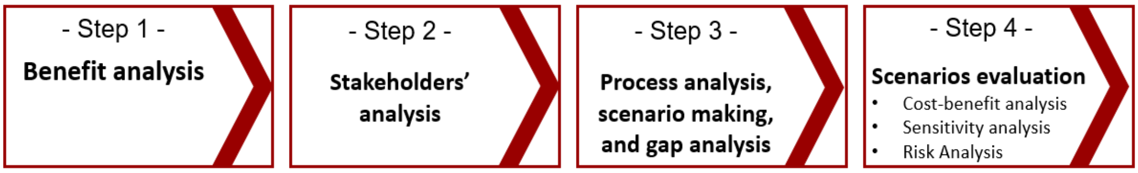

Figure 4-10 Proposed framework for making business cases for PCS projects

Step 1: Benefit analysis

The literature emphasises on the various benefits gained by using PCS in different organisational settings. There are a number of benefits commonly found with using PCS, including a reduced lead-time, reduced resource consumption, higher quality of specifications, higher independency from domain experts, better decision making in early phases of sales, accurate and free of errors quotations, less rework, and higher customer satisfaction (Barker et al. 1989; Forza and Salvador 2002a, 2007; Ardissono et al. 2003; Petersen 2007; Hvam et al. 2008; Tenhiälä and Ketokivi 2012; Trentin et al. 2012). The goals of the implementation of the PCS have to be aligned with the current company's strategy. Identifying the goals and the desired benefits to be gained from the implementation of the PCS is essential as it will influence decision making in the following steps.

Step 2: Stakeholders' analysis

Identification of the primary stakeholders' requirements enables understanding of the project (Basili and Weiss 1984). The literature reflects both on stakeholders' analysis in IT projects (Ebert 1997; Bittner 2002a; Jiao and Chen 2006; Lim et al.

2011) and PCS projects (Nellore et al. 1999; Hvam et al. 2008; Mortensen et al. 2008; Friedrich et al. 2014a). For both IT and PCS projects in general, the categorisation of requirements can be divided into two types of requirements: functional and non-functional. A non-functional requirement is one that describes not *what* the software will do, but *how* the software will perform the task (Ebert 1997). A functional requirement then specifies each of the functions that a system must be capable of performing (Ebert 1997). A use case diagram is the means of expressing the requirements and the actors involved in the project (Kruchten 1998). Using a case diagram to visualize stakeholders' requirements has proven to improve communication with the main stakeholders in PCS projects (Hvam et al. 2008; Shafiee et al. 2014). Furthermore, the requirements have to be prioritised based on their importance. The MoSCoW rule can be beneficial when prioritising the stakeholders' requirements: Must have (Mo), Should have (S), Could have (Co), Want to have (W) (Bittner 2002a).

Step 3: Process analysis, scenario making, and gap analysis

The specification process at the company is analysed in order to get an overview of the essentials activities, their sequences, and connections, list up the persons responsible for the different activities, information flows and the processes' inputs/outputs (Hvam et al. 2008). Understanding the current processes is a fundamental step to design how the future processes should look like when supported with PCS. There are a number of tools used for this purpose, such as the flowcharts with Business Processes Modelling Notation (BPMN) (White 2004). A gap analysis is the recommended way to compare the operational performance to the target goals and identify the gap that needs to be bridged (Hvam et al. 2008). Based on this, different scenarios can be generated to demonstrate how a PCS can be used to support the current situation to a different extent so that the targeted performance can be reached (Hvam et al. 2008).

Step 4: Scenarios evaluation

The last step of the framework is concerned with evaluating the proposed scenarios based on the cost-benefit, sensitivity and risk analyses (Hvam et al. 2008; Shafiee et al. 2014; Kristjansdottir et al. 2016b).

Cost-benefit analysis should be clear from the beginning, and cost evaluation is one of the fundamental purposes of the business case. A cost-benefit analysis is carried out to compare the expected costs and benefits of the different scenarios (Haddix et al. 2003). Return on investment (ROI) is commonly used as a cost-benefit ratio, which is a performance measure used to evaluate the efficiency of a number of different investment (Phillips and Phillips 2010), and it has been used in PCS projects to determine the profitability of these projects (Kristjansdottir et al. 2016b).

Sensitivity analyses are used to prepare for uncertainty or changes in different parameters to increase the accuracy of the cost analysis. A sensitivity analysis is concerned with representing the certainty, which can be apportioned to different sources of uncertainty in its output (Saltelli 2002). Sensitivity analysis is grouped into the following main categories: (1) decision making or development of recommendations for decision-makers, (2) communication, (3) increased understanding or quantification of the system, and (4) model development (Pannell 1997). In this research, sensitivity analysis is used to improve the decision-making where the uncertainty of the cost calculation is considered.

Software project *risk analysis* aims at improving the chances of achieving a successful project outcome and/or avoid project failure by identifying, analysing and handling risk factors (Boehm 1991). Mathematically, $R = P*I$ where R is the risk exposure attributable to a particular risk factor, P is the probability the undesirable event will be realised, and I is the impact or magnitude of the loss if the event occurs (Boehm 1991). Four inter-related approaches to risk analysis are: checklists (Boehm 1991; Johnson et al. 2001), analytical frameworks (Cule et al. 2000), process models (Boehm 1991) and risk response strategies (DeMarco and Lister 2003). In PCS projects, the risk can be divided into the following categories: (1) development of the PCS system, e.g., knowledge management, system ownership, and modelling issues, (2) deployment and uses of the PCS (e.g., lack of training, inadequate testing, and lack of motivation for users), and finally (3) maintenance and further development of a PCS (e.g., neglecting in documentation, lack of commitment for further developments, and outdated PCS) (Hvam et al. 2008).

4.3.2.3 Framework validation

To validate the usability of the framework, it was tested in two engineering companies on three projects in total. The results from testing the framework in the case studies and the observations show the interest between the configuration team—

and especially the managers—to gain a deeper understanding on the unclear points in the projects before initiating and estimating the cost and risks for PCS projects. The framework proved to provide a structured approach for framing business cases in PCS projects.

4.3.2.4 Conclusion

In order to avoid failure of IT projects, it is of high importance to frame business cases where both cost, benefits and risk are highlighted as they all have a remarkable effect on decision-making regarding prioritising different projects and aligning stakeholders' expectations. To address these challenges, this study proposed a framework for business cases that can be used in PCS projects, which is evaluated in two engineering companies. The findings of this study are presented in paper F, and they provide an answer to RQ 3.2.

4.3.3 Summary: Identification and evaluation of PCS applications

This section analysed how to identify and evaluate different applications of PCSs. This is especially important in engineering companies where often a number of PCSs are implemented as a result of having vast products and processes complexity. While the literature has described a variety of tools and methods to increase the efficiency in PCS projects, the identification of the different application of a PCS has not yet been addressed in the literature. Furthermore, a systematic way to evaluate the projects in terms of business cases is needed to compare and prioritise the different projects. This is an important topic as the successfulness of the PCS is highly depended on the most beneficial projects to be selected.

First, the study examined how engineering companies can identify possible applications of PCS (RQ 3.1). To achieve this goal, a three-step framework was proposed. Second, the study how to construct business cases for PCS projects in a systematic way to evaluate the identified applications of PCS (RQ 3.2). To address this research question, a four-step method was proposed. The following section focuses on how to improve development and maintenance of PCS by focusing on product modelling and knowledge management.

4.4 IMPROVED DEVELOPMENT AND MAINTENANCE OF PCS

This section aims to analyse how to improve development in PCS projects by both analysing the impact of using product modelling techniques proposed for PCS projects and by proposing a framework for knowledge management in PCS projects. This is aligned with the primary challenges of PCS projects as described in Section 4.2.

4.4.1 STUDY G: THE IMPACT OF APPLYING PRODUCT MODELLING TECHNIQUES IN CONFIGURATOR PROJECTS

This section focuses on the impact of using structured product modelling methods in PCS projects.

> **RQ 4.1** What is the impact of using formal modelling techniques in PCS projects?

To analyse the impact of applying different types of modelling techniques in PCS projects, the research method in this study includes a survey (S1) and interviews, as explained in Section 2.4.2.

4.4.1.1 Research contribution

To examine the impact of using formal modelling techniques in PCS projects, this study focuses on three different representations product modelling techniques used in PCS projects. First a UML based modelling techniques where the phenomenon model and information model are considered in a visual way, second non-UML based modelling techniques where only the phenomenon model is considered (e.g. structured BOM), and third non-formal modelling techniques (e.g. making a list of features in Word or Excel without any formal structure or modelling directly in the PCS). The impact is analysed in terms of control of product variants and increased availability of product knowledge in the organisations. This comparison is valuable not only for academia but also for practitioners when it comes to justifying resources spent on modelling and documenting knowledge of the PCS. This section presents the primary results of the study in terms of the modelling techniques used by the companies and what characterises the companies and the PCS they have in operation.

Modelling methods used at the companies and characteristics of the PCS and companies

The companies were divided into three groups according to the modelling technique applied: users of a UML based modelling technique (Group 1), users of a non-UML based modelling technique (Group 2), or users of a non-formal modelling technique (Group 3).

In Group 1, six companies using a UML based modelling method are identified; they used the CPM procedure, which is based on UML notation (as explained under Section 3.4.3.1). The companies in this category used either PVM, class diagrams and CRC cards altogether or at least either PVM or class diagrams. Group 2 consists of six companies that utilized non-UML based modelling techniques or structured BOM in addition to Excel spreadsheets, Word documents and the modelling tools provided by the PCS software. Finally, the remaining six companies form Group 3; these companies claimed they did not use any formal modelling technique outside of PCS software besides Excel spreadsheets and Word documents.

To determine the characteristics of the companies and the PCS used at the different companies, the respondents were asked about the number of employees, the size and complexity of the PCS in terms of the number of attributes and rules in the system, the number of PCS, and the integration of the PCS with other IT systems. In Table 4-8, this information is provided for the companies and grouped according to the approach used for the product modelling.

Table 4-8 Use of different types of modelling techniques related to size and complexity of the PCS

	No. of employees	No. of PCS	No. of attributes	No. rules	No. of integrations
Group 1 (Companies using UML based modelling techniques)					
Average	7833	4.2	2725	2391	3.2
Group 2 (Companies using non-UML based modelling techniques)					
Average	4600	2.3	720	730	1.7
Group 3 (Companies using non-formal modelling techniques)					
Average	370	1.3	1000	708	1.7

According to the results presented in Table 4-8, companies in Group 1 are characterised as having more employees than companies listed in other groups. Furthermore, these companies also have more PCSs in operation, and the PCSs are characterised as being more complex regarding the number of attributes, rules and integrations with other software applications. In three of the six companies in Group 1, the respondents reported that they started to model their PCS using non-formal modelling techniques. However, as the PCS grew bigger and the number of people involved in the configuration projects increased, the companies realised that it was necessary to be able to work in a more structured way and be in more control of the models implemented in the system. Therefore, in these cases, UML based modelling techniques were applied at a later stage in the companies.

Comparing the companies in Group 1 with those in Groups 2 and 3 reveals that the latter groups are smaller companies in terms of the number of employees and users of the systems. Moreover, the PCSs in these groups are also less complex with respect to numbers of rules, attributes and integrations. However, the result shows that companies in Group 2 were larger and had more PCS users than those in Group 3, but the PCSs of the two groups were similar in terms of complexity. These results could indicate that with a minor configuration project not involving too many employees, the modelling can be managed by using non-UML based or non-formal modelling techniques.

The impact of applying an IT formal modelling technique (CPM procedure)

The impact of using a UML based modelling technique compared to non-UML based or non-formal modelling techniques is analysed concerning the availability of product knowledge and control of product variants. The respondents rated the impact on a five-point scale, with one indicating they strongly disagree and five indicating they strongly agreed with the statement. Table 4-9 provides the results concerning the impact of using the different modelling techniques on increased availability of product knowledge and improved control of product variants.

Table 4-9 Comparison of the impact of using different types of modelling techniques in configuration projects

	Increased availability of product knowledge		**Improved control of product variants**		
	Improved documentation of knowledge	**Improved availability of product knowledge**	**Reduction of product variants (item numbers)**	**Increased use of standard parts**	**Improved quality of products**
	Group 1 (Companies using UML based modelling techniques)				
Average	**4.7**	**4.7**	**4.0**	**4.7**	**4.4**
	Group 2 (Companies using non-UML based modelling techniques)				
Average	**4.3**	**4.5**	**2.5**	**4.3**	**4.2**
	Group 3 (Companies using non-formal modelling techniques)				
Average	**3.7**	**3.8**	**2.2**	**4.0**	**3.8**

The companies not using a UML based modelling technique gave higher ratings to improved documentation of knowledge and enhanced availability of knowledge. However, there was little difference between the three groups concerning documentation and the accessibility of product knowledge. The reduction of product variants (item numbers) refers to the ability to eliminate unnecessary product variants from the product assortment. The companies using a UML based modelling technique claimed to have better ability to reduce the number of product variants than in the other companies not using UML based modelling technique, which may be related to an increased ability to document and access to product knowledge. Furthermore, the companies using UML based modelling techniques rated slightly higher with respect the benefits of increased use of standard part and improved product quality.

4.4.1.2 Conclusion

The study explored the impact of using different product modelling techniques in PCS projects. Three different types of modelling techniques are analysed, namely a UML based modelling technique, a non-UML based modelling technique, or a non-formal modelling technique. The impact is then analysed in terms of increased availability of product knowledge and improved control of product variants. From the study, it can be concluded that the impact differs from the different modelling techniques used where the perceived benefits are notable from applying UML-based modelling techniques in PCS projects. The findings of this study are presented in paper G, and they provide an answer to research question 4.1.

4.4.2 Study H: How to scope configuration projects and manage the knowledge they require

4.4.2.1 Research objective and research questions

The lack of knowledge management framework in PCS projects can lead to faulty knowledge management processes. Thus, this study focuses on how to acquire and manage knowledge in PCS projects to provide an answer to the following research question.

RQ 4.2. How is knowledge acquired and maintained in PCS projects?

To answer the research questions, this study proposes a framework to improve the knowledge management in PCS projects. The proposed framework is tested on four PCS projects in two engineering companies as explained in Section 2.4.1.

4.4.2.2 Research contribution

The proposed framework for managing knowledge in PCS projects is based on the available frameworks IT projects in general (Basili and Weiss 1984; Kucza and Komi-Sirviö 2001; Komi-Sirviö et al. 2002; McGinnis and Huang 2007; Gemino and Sauer 2012; Lech 2014). According to the level of abstraction, the frameworks range from three phases/actions to six phases/actions, and some of the frameworks focus more on acquisition (e.g. Basili and Weiss, 1984), whereas others consider the entire knowledge management lifecycle, including maintenance (e.g. Kucsa and Komi-Sirviö, 2001). Different terms are also often used in the frameworks, which can be a source of confusion. Even though the frameworks use different terms for the various phases of knowledge management in IT projects, they have a number of similarities (Rubenstein-Montano et al. 2001). In general, the frameworks begin by forming the scope of the project, following by a phase of knowledge collection. After this, knowledge acquisition takes place, which involves communicating, modelling and clarifying the knowledge. Most authors consider the collection, validation and documentation of the knowledge as separate steps, and the majority of the frameworks end with a step for maintaining the knowledge.

However, owing to the general differences between IT systems in general and PCS systems, the individual steps of the framework are supplemented with tools and method explicitly aimed at PCS projects. The framework was improved in an iterative process using a case company. Additionally, the users' expectations and requirements for the PCS increases as they become more successful (Barker et al. 1989). Thus, it is essential that the PCS can be further developed. The proposed framework, therefore, includes the possibility of iterations in the knowledge management process to allow for further development. Figure 4-11 illustrates the individual steps of the framework and shows the relations between the steps. The following sections describe the individual steps of the framework in more details.

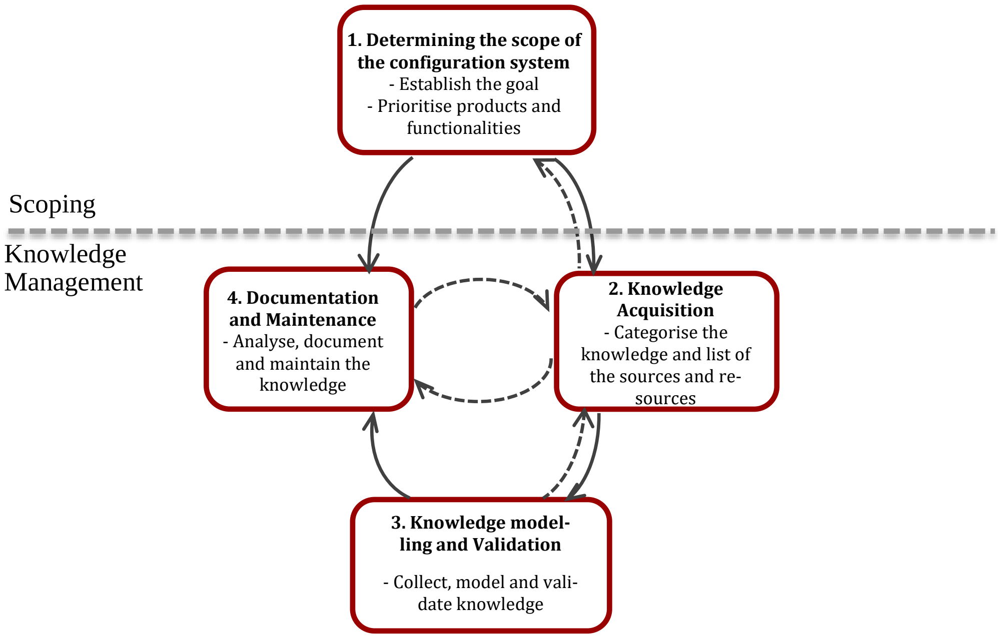

Figure 4-11. The proposed framework for knowledge collection in configuration projects.

Step 1: Determining the scope of the PCS

Establishing the goal of the project

Project goals are determined by identifying stakeholders' functional and non-functional requirements. This step aims to improve the understanding of the project by identifying the primary stakeholder requirements (Basili and Weiss 1984). The requirements can be classified into functional and non-functional requirements (Ebert 1997).

The stakeholders and their requirements can be drawn up using process flowcharts based on rational unified process (RUP) methods (Compton and Jansen 1990) as well as use-case diagrams. Process flowcharts can be used to describe the current situation and different scenarios for future work (Hvam et al. 2008), whereas use-case diagrams can illustrate the requirements and the actors involved in the project (Kruchten 2007). Finally, The MoSCoW rules are commonly used when prioritising stakeholder requirements (Bittner 2002a). Stakeholders' analysis is further described for IT projects in a number of studies (Ebert 1997; Bittner 2002b; Jiao and Chen 2006; Lim et al. 2011) as well as for PCS projects (Forsythe and Buchanan

1989; Nellore et al. 1999; Hvam et al. 2008; Mortensen et al. 2008; Felfernig et al. 2014c)

Prioritising products and functionalities to be included in the system
In this step, the products or product features and functionalities to be included in the PCS are prioritised. The purpose of using a component-based structure, based on RUP methods, is to break down a large and complex project into smaller pieces (Briand 2003). This makes the development less complicated, which is especially important when dealing with highly engineered projects (Felfernig et al., 2014). After breaking down the project, the team can start developing one of the components or products, depending on the size of the project. The recommended tool for this step is a weighting table, in which each of the components is rated against several specific weighted project success criteria, and a score is computed to rank the priority of the components (Wiegers 1999).

Step 2: Knowledge acquisition
Data clustering is a multivariate analysis technique that assigns observations (objects) of a population to clusters (groups) so that observations within the same cluster have a high degree of similarity; observations from different clusters have a high degree of dissimilarity (Kaufman and Rousseeuw 2009; Tsai et al. 2009; Anzanello and Fogliatto 2011). Based on observations in the knowledge sharing between the software design team and customers, Waltz et. al (1993) makes the following recommendations (1) the amount of application domain knowledge can be increased, (2) knowledge acquisition can be promoted by facilitation techniques; these activities can be formally recognizing by allocating time to them, (3) recognize that the information needs to become part of the team's memory is not captured formally, particularly in standard documentation. According to Walts et a. (1993), experienced designers recognised that customers may not understand the true nature of the requirements and the expectations from the results at the beginning of a project. Some knowledge acquisition tools are intended for a wide variety of contexts. For example, a card sorting tool should, in theory, be of value in any domain where objects, concepts or even processes can be named, shuffled about and sorted (Shadbolt et al. 1999). Some knowledge acquisition tools belong to specific domains; for instance, Compton et al. (1990) rejected the need for modelling and focused instead on the evaluation of prototypes developed on the basis of an

increasing number of test cases. The questions about knowledge are designed to reveal the expert's recommendations and hence strategies for how to deal with a variety of conditions, such as how to identify current conditions and which conditions warrant which actions (Woodward 1990).

The process of knowledge acquisition in PCS projects includes the following activities where the configuration team (1) communicates techniques for eliciting knowledge from relevant experts, (2) interprets this knowledge in order to draw conclusions about the reasoning process of the product experts and what may be the underlying knowledge, and (3) uses the conclusions to direct the construction of the product model (Byrd 1992). While these activities are common in configuration teams, there is a risk that the activities would lower the quality of acquired knowledge and consume time and resources that could be devoted to validation (Shafiee et al. 2017). One method of clustering in PCS is to determine output knowledge according to stakeholder requirements and subcategorise them systematically. Listing the sources and resources of the knowledge creates value in categorising the knowledge, and it also helps delegate the tasks to different resources (Tiihonen et al. 1996b). Organisations have two types of knowledge—explicit and tacit. Explicit knowledge is formal and systemic, whereas tacit knowledge is highly personal and difficult to formalise. Depending on the resources, the knowledge might be explicit, and it may come from the company's internal documentation systems; it may also be tacit and come from domain experts (Nonaka 1994).

Step 3: Knowledge modelling and validation

One of the steps of knowledge management in PCS projects relates to modelling the knowledge inside the system, which requires validation typically from domain experts. Communication between IT personnel (software developers and modellers) and domain experts is an essential factor for PCS projects (Stelzer and Mellis 1998).The knowledge modelling of a PCS—known as the product (phenomenon) model structure—is one of the significant challenges in PCS projects (Sabin and Weigel 1998; Hansen et al. 2012). Product models are also used for communicating with people outside the IT field, which is required to validate the knowledge (Duffy and Andreasen 1995). Many researchers have developed product modelling techniques to meet this challenge (e.g. Aldanondo et al. 2000; Chao and Chen

2001; Hvam 2001; Magro and Torasso 2003; Jinsong et al. 2005; Tseng et al. 2005; Hvam et al. 2008; Yang et al. 2009). This paper recommends using PVM along with CRC cards (Hvam 2001; Hvam et al. 2008).

Step 4: Documentation and maintenance of knowledge

This step addresses how to document and maintain the knowledge to ensure that the PCS remains up-to-date. Studies of companies using PCS have revealed that without a documentation system, companies are unable to develop and maintain their PCS (Haug et al. 2009a). The iterative process of testing enables feedback in the early phases of a project (Kruchten 2007). Reaching the feedbacks require a proper communication and maintenance tool. Numerous methods exist for conducting iterative testing and validation in projects, which eliminates unnecessary debugging at the end of the project (Hirsch 2002). Modelling techniques are used as documentation tools alongside the task of communication and validation. Research supports the modelling process by adding software support and integrating these different modelling techniques (PVM and CRC) (Haug and Hvam 2007; Shafiee et al. 2017). Selic (2009) explained agile documentation by elaborating different steps for design and development. Avoidance of duplicate knowledge is critical in documenting IT systems (Selic 2009). The automatic agile IT system proposed by Shafiee et al. (2017) involves two steps. First, the initial product model (PVM or any modelling technique) is built, which is then used for the programming of the PCS. Second, the product model is generated directly from the PCS and is based on the structure, attributes and constraints inside the PCS, which makes it possible to maintain the product model directly from the PCS. This approach meets the demand for agile documentation and efficient communication with domain experts; it also uses the fewest resources possible (Shafiee et al. 2017).

4.4.2.3 Framework validation

To evaluate the usability of the framework, it was tested in two engineering companies on four PCS project in total. The testing of the framework demonstrated both its applicability in different industrial settings and its potential to enhance the quality and speed of the implementation of the PCS.

4.4.2.4 Conclusion

The challenges of knowledge management and the ability of the organisations to handle knowledge have been thoroughly considered based on both research and practice. The present study proposed a knowledge management framework for projects aimed at PCS projects. The findings of this study are presented in paper H, and they provide an answer to research question 4.2.

4.4.3 Summary: Of improved development and maintenance of PCS

Section 3.4 describes the theoretical background for managing PCS projects. In line with the main challenges of PCS projects as described in Section 4.2, this section examines how to improve management in PCS projects by focusing on the impact of using different product modelling techniques and how to improve the knowledge management process.

First, the study analysed the impact in terms of increased availability of product knowledge and improved control of product variants from using different modelling techniques in PCS projects (RQ 4.1). The analyses reveal that there are considered more perceived benefits of applying formal modelling techniques than for the less formal (non-UML based and non-formal) modelling techniques. Second, the study examines how to improve knowledge management in PCS projects (RQ 4.2). To address this, a four-step framework is proposed.

Integrations to other IT systems is also an influencing factor for successful applications of PCS, as knowledge duplications can be avoided while performance and accuracy can be increased. Thus, Section 4.5 focus on increased performance and accuracy of PCS with integrations to retrieve information in the configuration process. In addition, the complexity of having different integrations is addressed.

4.5 IMPROVED PERFORMANCE AND ACCURACY OF THE PCS WITH IT INTEGRATIONS

This section investigates whether the performance and accuracy of PCS can be increased by retrieving information in the configuration process. In engineering companies, the accuracy of the product specifications is highly depended upon the ability to retrieve the correct information. To improve the accuracy of the product specifications, this section explores two different methods, or the impact from receiving information from sub-suppliers in the configuration processes and how to identify the most similar previously made product. Finally, the impact on the PCS complexity is examined with respect to different applications and different integrated IT systems.

4.5.1 Study I: Improved performance and quality of PCS by receiving real-time information from suppliers

4.5.1.1 Research objective and research questions

This study analyses the impact of integration PCS across the supply chain in companies to retrieve up-to-date information in the configuration process. The technical setup of this approach is described in the literature is elaborated, but the impact has not been addressed. Aligned with the focus of the research, the following research question is developed.

> **RQ 5.1:** What is the impact of integrating multiple PCS across supply chains to retrieve product information in the configuration processes?

To provide answers to the research question, this study was conducted in collaboration with a case company (C5), which is explained in Section 2.4.1.

4.5.1.2 Research contribution

Background information

The case company has a number of sub-suppliers providing customised products to be used in the overall design. Thus, there is a high dependency on receiving relevant product information and prices from the sub-suppliers in the configuration process. In many cases, products are sourced from several suppliers, and it has to be considered which supplier is the most suitable one for a particular project. To include the suppliers' information in the internal PCS used at the case company, three different methods have been used over the years. The method selected to document the supplier's information each time depends on the product complexity and the availability of the product information. The following is a brief description of those methods.

- The first method includes making *a list of all possible configuration of the supplied product*. In cases of producing a highly complex product with a high number of possible configurations, it would become impossible to map down all different configurations.

- The second method includes *building a PCS model based on the supplier's documentation*, which could cover all different configurations even for complex products. However, the main limitations can be traced to lack of knowledge regarding the supplier's product for the programmers of the PCS.
- Finally, the third method is to *integrate with .DLL files provided by the supplier*. The .DDL files can contain both codes and data, which enables the program division into separate modules. Therefore, the .DDL files from the suppliers can be incorporated into the PCS as separate components of the program.

Even though these approaches have been used at the company to include the suppliers' information, they are not without limitations. The main limitation is the insufficient level of detail of the included product specification and its availability in an up-to-date form. In order to overcome these limitations, the suppliers can be contacted every time an input or a proposal from them is required. However, this would delay the overall process, as the lead-time for receiving input or proposal can take weeks. Furthermore, this requires resources being available at the company and at the supplier so that information could be requested and sent. This scenario is therefore regarded as being unfeasible or impractical.

An alternative approach to receive up-to-date and accurate products' information from sub-suppliers is to establish a system that allows data exchange in an automatic and efficient way. In this case, the case company has decided to integrate its internal PCS via API web services to the supplier's PCS. During the configuration process, input parameters configured in previous steps are sent to the supplier's PCS, which calculates possible solutions within the given criteria in 0,1 - 0,2 seconds and sends back the requested product specifications. This setup enables the company to use the correct and up-to-date designs. Aside from this, suppliers have the ability to optimise the design for the particular customer requirements with a higher level of detail instead of using a fixed range of pre-calculated calculations.

The technical setup and the protocols at the case company

The case company and the supplier both had an operational PCS used for the internal operation to support the sales and engineering processes. The technical setup allows the PCS at both companies to interact (B2B communication) in order to retrieve real-time and accurate product configuration from the supplier. The company has currently established integration with one of their suppliers but has planned to expand the number of suppliers in close future as is shown in Figure 4-13. Expanding the number of suppliers allows for an expansion of the parts that can be configured via the integration. By including a number of suppliers providing the same product, the most desirable supplier can be found each time in an automatic way, which is done manually today.

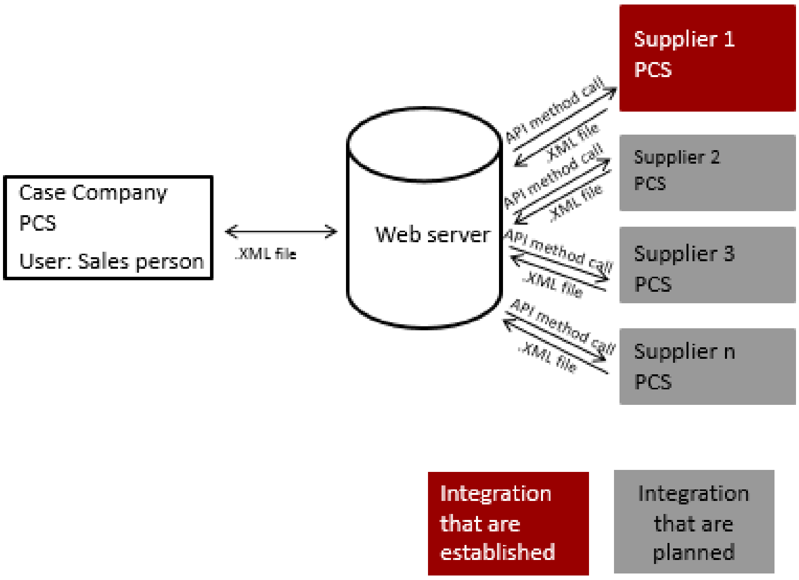

Figure 4-12 The technical setup at the case company: the setup for transferring data from one system to another system

Confidential data are transferred among the companies, and therefore particular security methods are required. In this specific case, the confidential part is limited to the pricing logic as different product designs are already accessible for customers in product catalogues. Therefore, by establishing the integration, the supplier does not have to revile the logic behind the pricing as only the final price for the specific configuration are reviled. In order to reduce the risk from the supplier's site of sharing confidential information, several methods are established. Those methods are not only limited to the prices but also to the overall access of the information that can be gathered from the supplier's PCS.

To prevent spying collection, data tracking and Men-in-the-Middle attack, a third party is not used for transferring the data, and the data communication is directly established between the two companies. The case company has special access rights to the supplier's server, which can be used without identification after login. The initial login therefore only enables persons having access to the PCS at the case company to access the supplier's PCS. At the case company, the access rights are not shared with the whole company; they are only available for the employees who need to work with the specific configuration/product model. These security methods should protect the supplier from misuses of the integration both from the case company and from other external threats.

Input and output parameters

The data exchange between the case company and the supplier is done via .XML files. The case company sent 20 design parameters (such as min/max torque, what the reduction should be in the gearbox, gear factors), which are defined in the previous steps of the configuration process. The request was to (1) find a design within these parameters, where the supplier's PCS is based on their logic and business rules; (2) find all possible design solutions, which can be around 100; and (3) find the prices for the different designs. It is highly unlikely that the supplier's PCS would not be able to find a feasible solution. However, if this situation occurs, either parameters would have to be changed in the configuration at the case company, or the supplier has to be contacted. The design solutions are sorted according to prices (from lowest to highest) and sent back on an .XML format via the web API web services. For this specific product, the prices are the most important, and therefore the cheapest solution is automatically selected by the case company's PCS. It should though be noted that other parameters (e.g., quality or lead-time) can be used for sorting afterwards. The information retrieved from the supplier is then used in the further steps of the configuration as the dimensioning of the product will affect the overall design being configured at the case company.

The impact of integrating PCS across the supply chains

Reduced complexity of the configuration model

The PCS operated at the case company contains a number of sub-models that in turn include parts and modules bought from suppliers as previously described. By outsourcing these sub-models reduces the complexity of the PCS. By reducing the complexity in terms of business rules, tables, parts and values of the PCS, the development and maintenance effort can simultaneously be reduced as the supplier's

PCS is accessed in the configuration process. In this way, the supplier becomes responsible for developing and maintaining his own products' information. Table 4-10 summarises how the supplier integration affects the complexity of one of the PCS operated at the case company and the impact on the development time.

Table 4-10 Summary of the reduced PCS complexity

Characteristics of the PCS	**Before the supplier's integration**	**After the supplier's integration**
Business rules	86	0
Tables	13	0
Parts	17	1
Values	18.836	20
Development time of the system	8+ days	2 days
Specialist time spent on the development	8+ days	0 days

Improved quality of the specifications in terms of updated and more detailed product information

An essential aspect of the proposed approach is the improved quality of the products' specification as they are based on real-time, optimised and more detailed information. This would guarantee that all necessary components—a valid solution, the right dimensioning of the product under question, and exact and up-to-date prices—are used in the overall configuration process.

For the product provided by the supplier addressed in this case study—that is, gears—the number of possible configurations for a product are 25-26 million. When having so many possible combinations, it is not feasible to include them all using Excel sheets or preliminary databases. It would be too time-consuming to look up the information, and this would affect the time it takes to start up the PCS. Therefore, for the product in question in this case study, only 20 different configurations were included in the PCS prior the integration. As a result, the company was not using the most optimal design of the supplier's product, since as the feasible solution is selected based on a limited number of configurations. The solution that was chosen was always scaled up to the predefined range, which means that the surrounding systems also needed to be scaled up. If one part of the design is over-dimensioned, other parts have to be adjusted accordingly, which would cause a snowball effects in the overall design.

Figure 4-13 demonstrates this point where the blue line represents the predefined configuration that would have been selected prior to the supplier integration. The red line represents the exact configuration, which can be selected as a result of more detailed information retrieved after the supplier integration was established. The product' dimensions for this specific product are determined based on required kilowatts (kW).

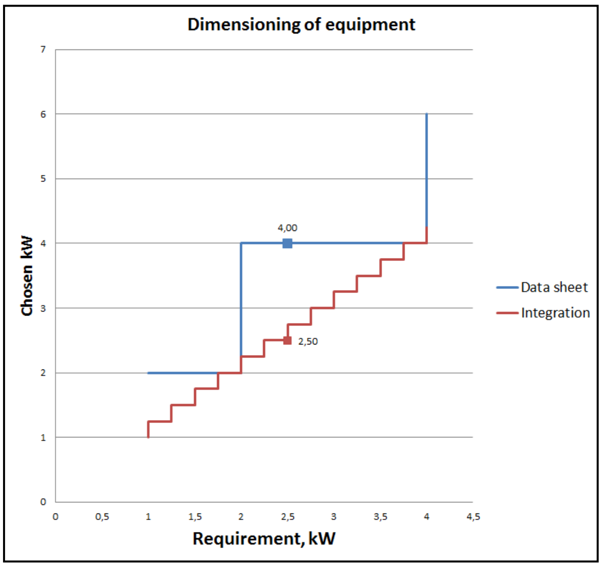

Figure 4-13 Dimensioning intervals of the equipment before and after the supplier integration

Having the precise dimensions of the supplier's product in the configuration process has proven to improve the accuracy of the generated specifications and reduce over-dimensioned surrounding systems. Therefore, the company has achieved both immediate and indirect cost savings as a result of having more detailed product information. The immediate cost saving for this example is presented in

Figure 4-13, which is the difference between the 4,00 kW and 2,50 kW gear. The in-direct cost savings represent the related systems or the frame as the gear is positioned, which do not need to be scaled up. It is estimated that the company saves up to 20% in material cost in the overall design by having more detail information in the design phase.

4.5.1.3 Conclusion

This study describes the impact of having integrated PCS across supply chains in a case company. The impact is analysed in terms of the complexity of the system and development effort, the accuracy of the configuration and the impact on the overall design. The findings of this study are presented in the Paper I, and they provide an answer to RQ 5.1.

4.5.2 Study J: Automatic identification of products similarities to improve the configuration process in ETO companies

4.5.2.1 Research objective and research questions

For identifying the similarities of previously designed products and new products, an automated IT system can be beneficial, as it allows companies to produce customised products using the least possible amount of time and resources. With this point in mind, this study aims to provide an answer to the following research question.

> **RQ 5.2:** How to automatically identify the most similar previously made products to improve the configuration process?

To provide an answer to the research question, a framework based on literature and experience is proposed and validated in an engineering company. The setup of the case study is explained in Section 2.4.1.

4.5.2.2 Research contribution

The proposed framework builds on previous research that covers subjects such as identifying product variables, clustering the data for the comparison purpose, creating an IT system, and integrating it with the PCS. Figure 4-14 shows the individual steps of the framework and the following sections explain the individual steps in more details.

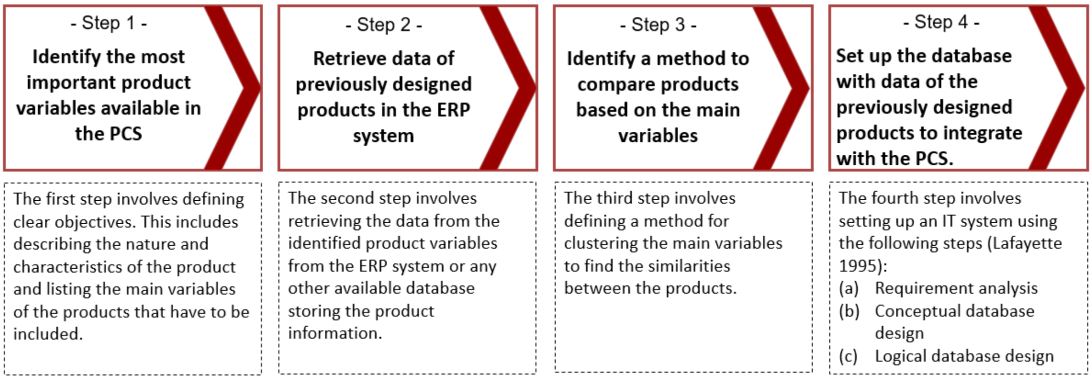

Figure 4-14 Proposed framework to identify previously made products in the configuration process

Step 1: Identify the most important product variables available in the PCS

A company's product range is often vast, with a great number of variants. Therefore, it is essential in the first step to obtain an overall view of the products, or the product range. For this purpose, different techniques can be used to demonstrate, identify, and communicate product structure and variables, such as the PVM (Hvam et al. 2008). In this study, the PVM is used for breaking down the components of the product into a tree structure and for identifying the primary product variables.

Step 2: Retrieve data from previously designed products in the ERP system

Database systems are designed mainly to support business applications, and most of these systems offer discovery variables using tree inducers, neural nets, and rule discovery algorithms (Imielinski and Mannila 1996). One of the fundamental problems of information extraction from ERP systems is that the format of the available data sources is often incompatible, requiring extensive conversion efforts (Bendoly 2003). Knowledge discovery in databases represents the process of transforming available data into strategic information, which is characterised by issues related to the nature of the data and the desired features (Davies 1989; Ho 1997). The knowledge discovery process can be broken down into three following steps: (1) task discovery, data discovery, data cleansing and data segmentation; (2) model selection, parameter selection, model specification and model fitting; and (3) model evaluation, model refinement and output evaluation (Brachman and Anand 1996). In this study, the specific steps of knowledge discovery are followed to retrieve the data from an ERP system. To decode the high-level data from the ERP system, a commonly used technique named “British classification” is used when naming different components according to the product variants (Burbidge 1975).

Step 3: Identify a method to compare products based on the main variables

Clustering techniques can be used to identify and to cluster relevant products variables. Burbidge (1975) describes how to cluster the product components and code them by introducing the Group Technology (GT) method. Martines et al. (2000) provided an example of using the GT technique in a manufacturing plant to minimise unnecessary diversity by informing designers about existing components. Simpson (2005) used GT for adding, removing, or substituting one or more modules to a product platform that should improve the design of the product platform and the customisations. Leukel et al. (2002) discussed the design and components of product clustering systems in B2B e-commerce and suggested a data model based on XML. Fairchild and De Vuyst (2002) elaborated on the application of clustering systems and their requirements, and they suggested an automated clustering system for the specialisation of the life cycle assessment. Software Product Line Engineering (SPLE) has also been introduced to represent the combinations of features that distinguish the system variants using feature models (Lopez-Herrejon et al. 2015).

A commonly non-hierarchical clustering method is the k-means, which is recognised for its efficiency (Taboada and Coit 2008). This method aims to minimise the k-means algorithm by considering the squared differences between considering the squared differences between the observational data vectors and the cluster centroids overall observations and k-clusters (Taboada and Coit 2008). A method proposed by Ansanello and Fogliatto (2011) is based on six steps: (1) obtaining experts’ variables, (2) modelling the variables, (3) defining bounds, (4), selecting the variables, (5) checking whether the upper bound is selected, and (6) identifying the best variables and clusters. Euclidean distances are typically used to calculate the distance between observations because a Silhouette Graph can be generated for displaying the performance of a clustering procedure (Rand 1971). For each observation *j*, the method provides the SIj, which can vary from –1 to +1. The closer

SIj is to one, the smaller the distance is within a cluster, meaning that it is appropriately assigned to the correct cluster (Kaufman and Rousseeuw 2009). After testing multiple clustering methods, this study uses k-means and Euclidean distance measurement methods.

Step 4: Set up the database with data of the previously designed products to integrate with the PCS

Database design includes the following three steps (Ramakrishnan and Gehrke 2003):

1. *Requirement analysis*: Understand what data are to be stored in the database, what applications must be built on top of it and what operations are most frequent and subject to performance requirements.
2. *Conceptual database design*: The information gathered in the requirements analysis step is used to develop a high-level description of the data along with the constraints to be stored in the database.
3. *Logical database design*: The Database Management System (DBMS) has to be chosen to implement the database design, and the conceptual database design must be converted into a database schema in the data model of the chosen DBMS.

In this study, the database design instruction proposed by Ramakrishnan and Gehrke (2003) is used. First, requirement analysis is performed in Step 1. Second, the conceptual database design is built, based on the analysis of Step 1 and the retrieved data based on Step 2. Finally, the logical design of the database is conducted, and the logics are built upon the selected clustering method.

4.5.2.3 Framework validation

The proposed framework was tested in an engineering company by developing the IT system, which was developed based on Excel. Following is a description of the results of the individual steps of the framework.

Step 1: Identify the most important product variables available in the PCS

The first step involves selecting the main product variables to be compared across new and previously made products. The PVM is used as the tool to identify the primary product variables (Hvam et al. 2008). The tree structure of the PVM is then used to structure the entire product and to break the overall product structure down into sizes that can be analysed.

Step 2: Retrieve data from previously designed products in ERP system

In the second step, all the product variables and data are retrieved from the company ERP system using the knowledge discovery process described by Brachman and Anand (1996). The primary product variables are determined based on the selected products (e.g. weight and cost). Based on these selected product variables, one specific component with different variables is selected, and the IT department helps to retrieve the cost documents from the ERP system into Excel. The retrieved data is then divided into subparts (based on the specific variables from the PCS), and the project numbers are decoded to make the deliverables more generic.

Step 3: Identify a method to compare products based on the main variables

The first objective of this step was to select the most suitable set of clustering variables leading to an optimised product grouping. Thus, the k-means procedure was run for every combination of the variables. Each one belonged to a different Excel sheet. In this case, there were four sheets for each cluster: x-y, x-s, y-s and x-y-s. Following this, an assessment is done to determine the number of processes, namely which sheet would lead to the optimal clustering, where the average Silhouette Index (SI) for all the analyses is stored, and where a higher SI means more accurate clustering. The next step was to calculate the distance between the previously designed and the new product based on the Euclidean distance. This distance was calculated for all combinations of the variables—three variables (x, y, s) and six possibilities (xys, xy, xs, ys, x, y, s). A small distance between the new product and the previously designed product indicated a high similarity. The final step of the comparison platform is to list the products based on similarity.

Step 4: Set up the database with data of the previously designed products to integrate with the PCS

The PCS used at the case company is based on a commercial platform, where the integration with Excel is part of the standard platform. For this project, it was decided that Excel would be used for the prototype, as integration to ERP was evaluated as being too time-consuming and expensive. However, it is anticipated that this integration would be established in the future.

The aim of the user interface is to return the most similar previously made products when the user configures a new product. Based on this idea, the user can use product-relevant information from previous projects. The system, which was developed based on the proposed framework, was tested in the case company with one of the current PCSs. Figure 4-15 shows the simple user interface after the Excel sheet is generated from the PCS, where the primary product variables are exported to MS Excel. Furthermore, Excel is integrated with the PCS, and it also receives the relevant input from the PCS.

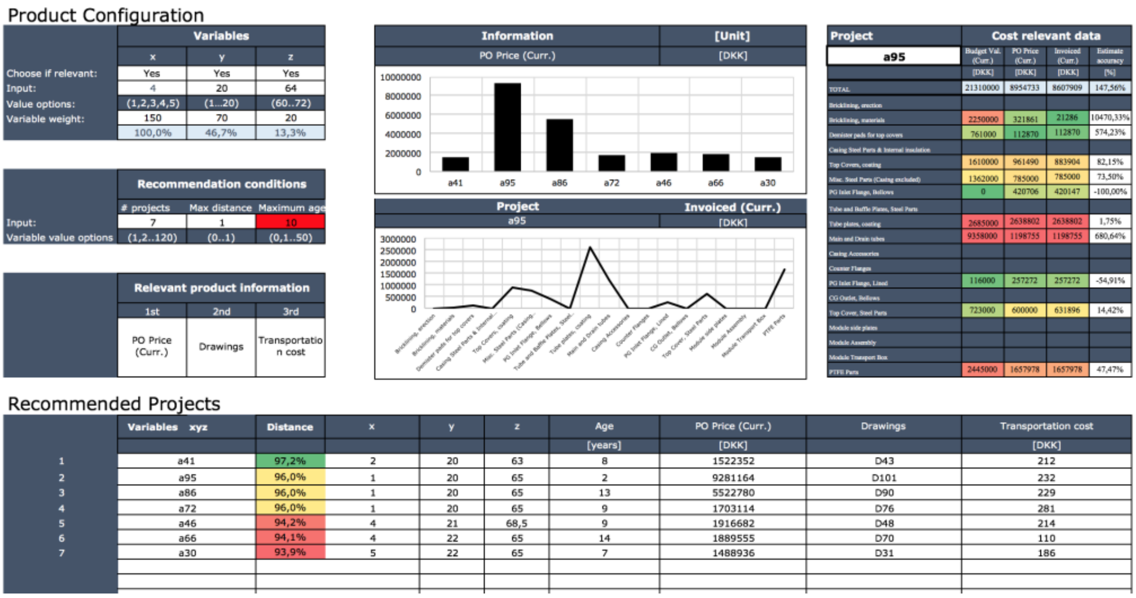

Figure 4-15 Final user interface of the IT system

4.5.2.4 Conclusion

This study analysed how to identify similar previously made products in the configuration process. This is of great importance since product designs in engineering companies often need to have their consistency checked, and usually parts of the designs can be re-used. The challenge arises in identifying the most similar product. With this point in mind, this study proposed a four-step framework to set up an IT system that can automate this process when a new product is being configured. The findings of this study are presented in paper J, and they provide an answer to RQ 5.2.

4.5.3 PAPER K: THE COMPLEXITY OF PCS RELATIVE TO INTEGRATIONS AND FIELD OF APPLICATION

This study aims to analyse the factors influencing the complexity of a PCS where the complexity of the PCS in this study is determined based on the number of rules and attributes or based on parameters complexity. The complexity is analysed both regarding the users of the system and integrated IT systems. Thus, this study aims to provide answers to the following research questions:

> **RQ 5.3:** What is the relationship between the complexity of the PCS and the users of the system??
> **RQ 5.4:** What is the relationship between the complexity of the PCS to integrated IT systems?

To answer the research questions, the study uses a survey (S2) followed with interviews. The setup of the survey (S2) is explained in Section 2.4.2.

4.5.3.1 Research contribution

Complexity in relation to the users of the PCS

This section provides the results in relation to the complexity based on sales and engineering PCS. Figure 4-16 shows the percentages of using the PCS to support (1) sales, (2) sales and engineering, (3) engineering, and (4) other activities.

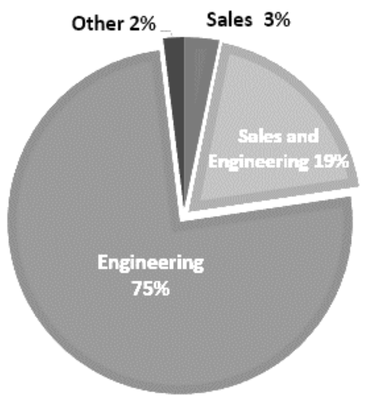

Figure 4-16 Percentages of using the PCS to support different activates at the company.

As seen in Figure 4-16, only 3% of the total PCS is used by the sales team, while 19% of the PCS is used by both salespersons and engineers. Moreover, 75% of the PCS is used to support only engineering, and 2% support other employees. The complexity of the PCS used for the different activities is shown in Figure 4-17; this complexity is seen in the average number of rules and attributes, and the overall complexity factor is calculated based on the sum of a number of rules and attributes.

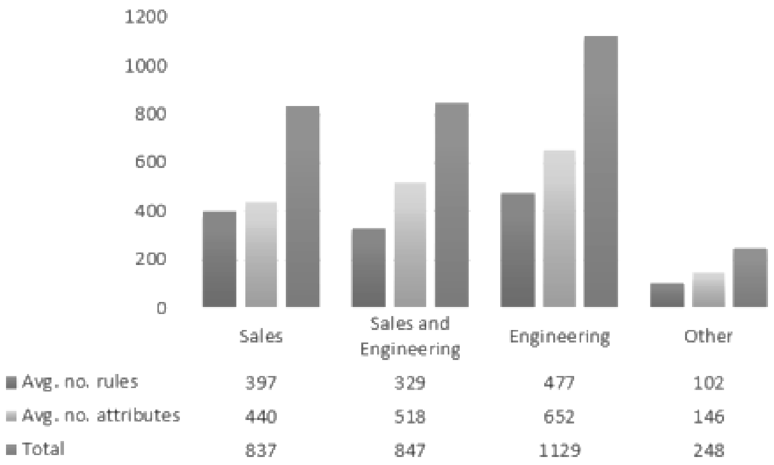

Figure 4-17 Complexity of using the PCS to support the different activities at the company.

Figure 4-17 shows that in terms of the rules used by in the PCS, by engineers have 477 rules on average, while sales have 397. The PCS used by salespersons and engineers have 329 rules on average. In terms of attributes, the PCS used by engineers have 652 on average, which is the most number of attributes. Meanwhile, the PCS used by salespersons and engineers have 518 attributes on average, and sales have 440. As previously defined, the complexity of the PCS is determined based on parameters or the sum of attributes and rules. Thus, a PCS supporting only engineers have the highest total score of complexity, or 1129. For a PCS only supporting salespersons or salespersons and engineers, the total score is 837 and 847 respectively. Other PCS supporting simpler tasks at the company have the lowest rate of complexity, or only 248.

Complexity of PCS in relation to integrated systems

The application of the PCS was divided according to the integrations in the company used for this study. The integrations included the following IT systems: (1)

ERP, (2) CAD, (3) calculation systems, (4) combination of the above-mentioned systems, and (5) other systems, in a few cases. Only 4% of the PCSs used in the company did not have any integration, while 70% of the PCSs were integrated to one of the above-mentioned systems, and 26% were integrated into one or more of the systems. Figure 4-18 shows the percentages of how the PCSs are integrated to different IT systems.

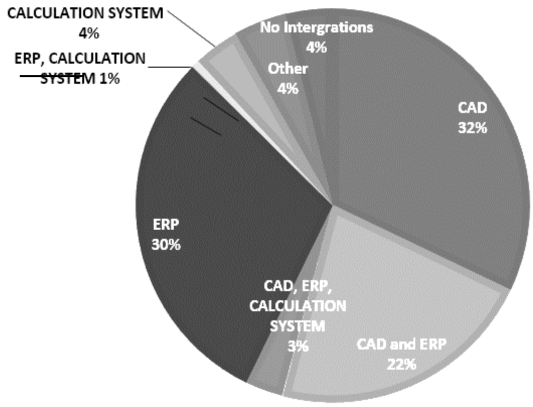

Figure 4-18 Percentages of IT integrations and combinations of integrations to the PCS used at the company

As can be seen in Figure 4-18, the majority of the PCSs are intergraded to the CAD and the ERP systems used at the company, or 32% and 30% respectively. Only 4% are integrated to calculation systems or other IT systems used at the company. Finally, 26% of the PCSs are integrated to more than one of the above mentioned IT systems. Figure 4-19 shows the complexity of the PCSs with respect to the IT systems they are integrated to in terms of an average number of rules, attributes, and then the sum of the average rules and attributes.

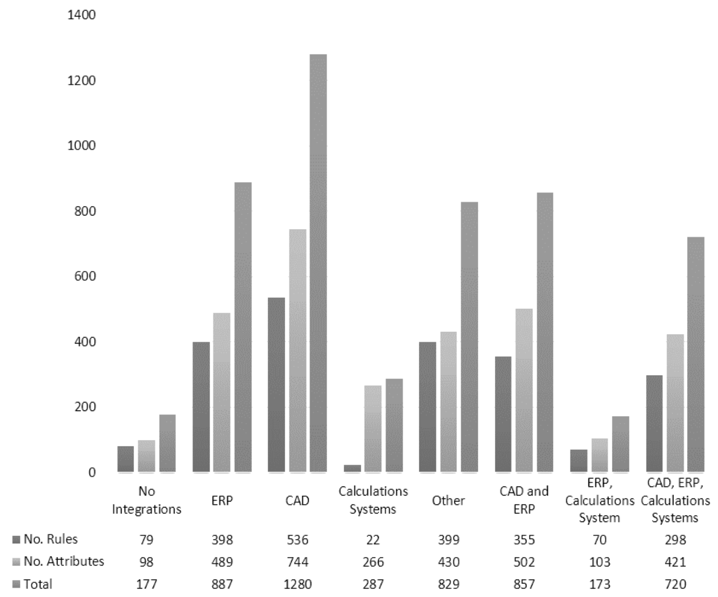

Figure 4-19 The main characteristics of the PCS integrated to different IT systems at the company.

In Figure 4-19, it can be seen that in terms of both attributes and rules, the PCS integrated to CAD system scored the highest in terms of complexity. PCSs that have combinations of integrations, or more than one integration, has the second highest score. This can be explained by the fact that in most cases, the category of combined IT systems includes integration to a CAD system. By looking into PCSs that have integrations with calculation systems, it can be seen that they have the fewest rules, which can be explained by the fact that the calculations are performed within the calculation system (i.e., not the PCS). Finally, it can be seen that PCS with no integration has the lowest complexity factor.

4.5.3.2 Conclusion

This study analyses the parameters complexity of PCS, which is calculated based on a number of attributes and rules, the field of application (sales or engineering), and integrations to other IT systems. The findings of this study are presented in paper K, and they provide an answer to RQ 5.3 and 5.4.

4.5.4 Summary: Improved performance of PCS with IT integrations

Two studies were introduced to analyse the improved performance of a PCS being integrated to retrieve information in the configuration processes. The first study examines the impact of integrating PCS across supply chains in organisations to retrieve product information in the configuration process on the PCS performance (RQ 5.1). The analyses showed that by retrieving information from sub-suppliers in the configuration process has a positive impact in the company. The second study investigated using an automatic way to identify the most similar previously made product to improve the configuration process (RQ 5.2). This can give valuable information on both the sales and the design phase in cases where designs can be re-used, either partially or entirely. To achieve this goal, a four-step framework was proposed. To analyse the complexity of the PCS with respect to the field of application (RQ 5.3) and integrated IT systems (RQ 5.4), the study uses a survey followed up with an interview. This is important as the complexity of the PCS can be used to determine development and maintenance effort; even though integrating PCSs to different IT systems is highly beneficial, there would also be an impact on the complexity.

5 DISCUSSIONS

This chapter discusses the research questions of this PhD thesis in relation to the literature and the limitations of the studies. The overall objective of the PhD project is to facilitate successful application of PCS in engineering companies. To achieve this objective, five research questions were introduced, along with relevant sub-questions.

5.1 THE MAIN BENEFITS OF IMPLEMENTING AND UTILISING THE PCS

The first research question (RQ 1) discussed in this section was formulated as follows: *What are the main benefits of implementing and utilizing PCS in companies manufacturing customized products?* This research question consists of four sub-questions; the discussion of each question provides an overall answer to RQ 1.

5.1.1 THE MAIN MOTIVATIONS AND REALISED BENEFITS OF PCS

The first two research questions under the benefits are focused on the main motivations that companies have for investing in PCS and how successful they are realising the benefits related to the initial motivations and are addressed in Study A. The analysis reveals six main categories of motivations, based on the answers provided by the companies' representatives. The categorisation of the main motivations is supported by realised benefits reported in the literature as listed in Table 5-1.

Table 5-1 The identified motivations categories in relation to the literature

The identified main categories of motivations	**Related literature of the benefits of implementing and utilizing PCS**
General competitiveness	Barker et al. 1989; Heatley et al. 1995; Fleischanderl et al. 1998; Heiskala et al. 2007
Knowledge management	Slater, 1999; Forza and Salvador, 2002a; Hvam, 2006b
Efficiency in the sales and order processes	Sviokla 1990; Ariano and Dagnino 1996; Slater 1999; Forza and Salvador 2002a, b; Ardissono et al. 2003; Hvam et al. 2004, 2011, 2013; Heiskala et al. 2005a; Petersen 2007
Efficiency in the production processes	Barker et al. 1989; Sviokla 1990; Hvam 2006a
Accuracy of the products' specifications	Sviokla 1990; Forza and Salvador 2002a, b; Heiskala et al. 2005a
Management of products variants and complexity	Forza and Salvador 2002a, b, 2008; Tenhiälä and Ketokivi 2012

Furthermore, the findings of the study give a valuable insight to the extent that companies realise the benefits of implementing and utilising the PCS. In the study, 22 benefits are analysed. Table 5-2 summaries to what extent the companies agreed with the benefits being realised from implementing and utilising PCS.

Table 5-2 The extent companies agree with the identified benefits being realised from utilising PCS

Grouping of the companies	**The benefits and the extent companies agree with them being realised**	
100-80% of the companies agree with the following benefits	•Easier to identify and manage product variants (91%) • Reduction of routine work (87%) •Fewer transfers of responsibility and errors when generating the proposals and specifications (87%) •Shorter time to generate proposal (87%) •Improved quality of the response to customer request (86%) •Increased use of standard modules or components (82%)	•Reduction of cost when of preparing proposals and specifications (77%) •Reduction of cost in relation to construction and production preparation (77%) •Increased customers' satisfaction when the configurator is used (77%) •Better accessibility of knowledge about product variants and product specifications (73%) •Increased employees' satisfaction (72%)
80-60% of the companies agree with the following benefits	•Increased gross margin for the products included in the configurator (68%) •Larger share of products that meet the quality objectives (64%) •Increased sales revenues for the products included in the configurator (64%)	•Better documentation and maintenance of knowledge (64%) •Reduction of redundant information (64%)
60-40% of the companies agree with the following benefits	•Reduction in the number of orders where there are deviations between the estimated and the actual cost (59%) •Less deviation (in percentages) between the estimated and the actual cost (54%)	•More on-time delivery resulting in an increased number of orders (41%) •Reduced cost in relation to production and procurement of materials (46%)
40-20% of the companies agree with the following benefits	•More sales quotes result in actual orders (32%) •More on time delivery result in increased number of orders	•Decreased number of product variants (32%)

The analyses reveal that even though a company expresses certain motivations, they are not necessarily more likely to achieve the associated benefits than companies not expressing the same motivation. The findings presented in this study thus raise further questions regarding the relationship between the planned benefits prior to the implementation of the PCS and the side benefits that are realised without being planned. Analysing this relationship would require further studies. This present study is of an explorative nature, where the sample design consists of 22 manufacturing companies providing customised products. To increase the generalisability of the findings, the sample size should be increased, which should allow for improved analysis of the relation between the initial motivations and the realised benefits. Furthermore, the benefits are measured on a five-point scale indicating to what extent the company's respondent agrees with this being a realised benefit. Further studies should include more objective measurements to quantify the impact; these can include the percentages of reduction of variants, the number of product modelling/coding errors or corrections, and product modelling workload.

5.1.2 The PCS impact on the accuracy of cost calculations and profitability

The third research question under the benefits focuses on the PCS accuracy of the cost calculations and product profitability.

Study B, shows that positive impact on both accuracy of the cost calculations and the product profitability when supported by the PCS, which have not been previously discussed in the literature. However, the results are aligned with studies that have shown that by using a PCS increased quality of the product specification can be realised (e.g. Sviokla, 1990; Heatley, Agarwal and Tanniru, 1995; Ariano and Dagnino, 1996; Tiihonen et al., 1996; Yu and Skovgaard, 1998; Slater, 1999; Forza and Salvador, 2002a, 2002b; Hvam et al., 2004, 2011). The study also revealed the importance of testing before realising the system and the PCS ability to support the relevant functionalities for the complete companies' product offerings. Resulting from lack of testing and the system scope the PCS was not accepted by all employees. Thus, the case study reveals the importance of organizational challenges and proper testing in PCS projects.

The relations of the PCS and increased product profitability require further research, which can be done by adding more case companies to confirm the underlying correlation between PCS utilisation and an increase in products profitability. By examining more cases, a deeper understanding can be gained, and a more detailed explanation of the correlation between the PCS and product profitability can be provided. Additionally, other lifecycle processes of the product can be taken into the calculations of the actual product profitability when supported with PCS (e.g., cost related to design, manufacturing and installations), as this study only focuses on the accuracy of the cost calculations as a contributing factor to the product profitability.

5.1.3 THE ECONOMIC VALUE CREATION FROM USING PCS

The fourth research question relating to benefits focuses on the economic value creation from implementing and utilising PCS.

Study C, analysis the economic value creation from implementing and utilising the PCS, which are calculated based on saved work-hours and compared to the cost of development, implementation and maintenance. The findings show 75% reduction of work-hours used in the sales process. This is aligned with other research, which has reported significant time reduction of manned activities (Forza and Salvador 2002b; Hvam et al. 2004, 2013; Haug et al. 2011). Furthermore, the lead-time for responding to the customer is reduced by 64%. Other researchers have also quantified this, where a significant reduction of lead-time is reported (Forza et al. 2006; Haug et al. 2011; Hvam et al. 2013). Over the five-year period analysed, the PCS has been very beneficial for the company, where a positive return on investment is achieved within the first year. However, the calculations are based on the assumption that fewer resources are needed to prepare the specifications in the sales phase. It should be noted that the implementation of the PCS is not necessarily intended to reduce the number of employees. Instead, PCS implementation should increase the efficiency and allow resources to focus on more value-adding activities (e.g., on more complex sales or R&D). Thus, it can be argued that the savings presented in the study are indirectly achieved in the company, as the numbers of employees are not reduced. Nevertheless, the finding represents the work-hours used in the sales phase and a better utilisation of resources, which means a reduced cost in the sales phase as presented in the results. Additionally, if the previously described benefits of using PCS are analysed interdependently, even more significant value creation might be identified.

The findings of this research provide a more fundamental understanding of the value creation process and offer a method to evaluate the value creation; as such, they are significant not only for the research community but also for practitioners. Companies with a product portfolio comprising of the standard to highly engineered products can therefore potentially achieve significant economic value creation by using PCS, and by improving the standardisation of their product range by supporting the product specification processes for CTO products. The generalisability is however limited, as the findings are based on a single case company. Thus, to increase the understanding of the economic value creation, studies in other companies would be beneficial.

5.1.4 The main benefits of implementing and utilising PCS - Overall discussion

To identify the benefits of implementing and utilising PCS, the first step was to analyse the literature as presented in Section 3.1. Furthermore, the presented findings show that other benefits can be realised in terms of the accuracy of the cost calculations and product profitability, in addition to economic value creation. However, PCS implementation often involves companies improving their product designs with a particular focus, increased standardisation, and predefined product architecture. Thus, the benefits from applying the PCS are not only gained from the implementation of the PCS but also from other initiatives required to make the implementation possible. These initiatives include improving the product architecture and modular design and re-designing the business processes. Furthermore, as explained in the introduction, PCS are often associated with mass customisation strategies; thus, it could be difficult to identify the initiatives that bring about the actual benefits (Petersen 2007). However, this PhD project focuses on PCSs and their application, and thus it does not distinguish between these concepts even though they can be a contributing factor.

5.2 THE MAIN CHALLENGES OF IMPLEMENTING AND UTILISING PCS

The second research question discussed in this section is as follows: *What are the main challenges that companies manufacturing customized products face in relation to the implementation and utilization of their PCS?* The research question consists of three sub-questions; each of those questions are discussed to provide an overall answer to RQ 2. The results presented in relation to these questions are based study D.

5.2.1 Identification of the main categories of challenges

To identify the main categories of challenges of PCS this project reviews the literature. Based on the literature review, the main challenges are identified and categorised into the following categories: (1) IT related, (2) product modelling, (3) organizational, (4) resource constraints, (5) product-related, and (6) knowledge acquisition. While the literature also describes other managerial challenges, this categorization encompasses the most commonly reported challenges in relation to PCS. The qualitative part of the study confirmed that these six categories all remain relevant and that no additional categories are required. Thus, validation of the categorization is achieved based on the empirical data gathered as part of exploring the main challenges. The identification of the main challenges in the literature gives the foundation for exploring the main categories concerning the overall impact on the PCS success and to analyse the specific challenges within each of the main category identified.

5.2.2 Importance of the main categories of challenges

Studies analysing the impact of the different challenges from implementing and utilizing PCS are mostly based on case studies (Barker et al. 1989; Ariano and Dagnino 1996; Forza and Salvador 2002a, b; Haug and Hvam 2007; Haug et al. 2012; Myrodia et al. 2017; Shafiee et al. 2017). This makes it difficult both for research and practitioners to identify the main challenges and prioritize them according to the challenges' overall impact. Thus, to focus managerial attention and research efforts on the most important categories of challenges, supporting strategic prioritization of investment, to address these challenges this study sheds light on the importance of the challenges. The findings of the study show the importance of the main categories of challenges, which are rated based on a five-point scale (1 not important and 5 very important). The findings show that organizational challenges are rated with the highest importance, knowledge acquisition of high importance, product modelling and resource challenges of medium importance, and finally, IT challenges and product-related of low importance. Further, companies rated organizational challenges as highly important, other challenges also became more significant, indicating that this type of challenge is an underlying factor in other challenges.

5.2.3 The specific challenges within the main categories of challenges

To provide insight on the specific challenges within each of the categories, the answers to the survey's open questions were grouped into the main categories identified in the literature. Based on these analyses, each of the main categories of challenges can be described in more details, based on the 2 or 3 sub-categories. To validate the existence of the sub-categories they are compared to the literature as illustrated in Table 5-3.

Table 5-3 The sub-categories of the main challenges in relation to the literature

Main categories of challenges	**The specific challenges within each category of challenges**
1. IT realted	1.1 Software development Barker et al. 1989; Tiihonen et al. 1996, 1998; Felfernig et al. 2000; Forza and Salvador 2002a, 2007; Heiskala et al. 2007
	1.2 Systems design for user-friendliness Barker et al. 1989; Aldanondo et al. 2000; Ardissono et al. 2003; Blecker et al. 2004; Heiskala et al. 2007; Zhang and Helo 2016
2. Product modelling	2.1 Complexity due to lack of overview of the product range Tiihonen et al. 1996, 1998; Aldanondo et al. 2000; Felfernig et al. 2000; Forza and Salvador 2002a, b; Hvam et al. 2006; Haug and Hvam 2007; Petersen 2007; Shafiee et al. 2017
	2.2 Correctness of specifications generated by the PCS Heiskala et al. 2005b; Haug et al. 2012; Shafiee et al. 2017
	2.3 Lack of knowledge related to product modelling None
3. Organizational	3.1 Lack of support from top management Barker et al. 1989; Ariano and Dagnino 1996
	3.2 Resistance to use of the configurator Ariano and Dagnino 1996; Tiihonen et al. 1998; Forza and Salvador 2002a; Hvam et al. 2006; Myrodia et al. 2017

	3.2 Disagreements about the scope of the configurator Forza and Salvador 2007; Haug et al. 2012; Myrodia et al. 2017
4. Resource constraints	4.1 Lack of resources Ariano and Dagnino 1996; Forza and Salvador 2007; Haug et al. 2012; Zhang and Helo 2016
	4.2 Vulnerability if key personnel leave Barker et al. 1989; Ariano and Dagnino 1996; Aldanondo et al. 2000; Heiskala et al. 2005b
5. Product related	5.1 Product complexity Forza and Salvador 2002a, b, 2007; Ardissono et al. 2003; Forza et al. 2006; Hvam et al. 2006; Petersen 2007; Zhang and Helo 2016
	5.2 Rapid product development Barker et al. 1989; Tiihonen et al. 1996; Felfernig et al. 2000; Heiskala et al. 2005b; Zhang and Helo 2016
6. Knowledge acquisition	6.1 Difficulties in acquiring the correct knowledge Tiihonen et al. 1996, 1998; Aldanondo et al. 2000; Felfernig et al. 2000; Ardissono et al. 2003; Heiskala et al. 2005b, 2007; Hvam et al. 2006; Forza and Salvador 2007; Zhang and Helo 2016
	6.2 Lack of the requisite knowledge to meet users' and customers' needs Tiihonen et al. 1996; Blecker et al. 2004
	6.3 Failure to communicate knowledge in the maintenance phase Tiihonen et al. 1998; Heiskala et al. 2005b, 2007

As can be seen in Table 5-3 the sub-categorization of the challenges when implementing and utilizing PCS is supported by the literature. Out of the identified challenges, only lack of knowledge related to product modelling was not identified in the previous literature. This specific sub-challenge is only mentioned by one company and might therefore not appear in many other companies. The importance of the sub-categories is not in the scope of this study, as this study focuses on the overall importance of the main categories. Therefore, in this study, it cannot be determined if the importance of the sub-categories varies within the main categories. Further, studies should aim to include that analysis, in addition, to verify the existence to a greater extent of the described sub-categories based on larger surveys. This could also give valuable information about how to prioritize attention of both researchers and practitioners to the challenges on a lower-level to the different challenges.

5.2.4 THE MAIN CHALLENGES OF IMPLEMENTING AND UTILISING PCS – OVERALL DISCUSSIONS

The findings of this study are of explorative nature where the main challenges from implementing and utilizing PCS are based on answers from 22 manufacturing companies making customized products. The findings presented in the current study do not only provide valuable insight into the main categories of challenges but can also be used to guide further studies where larger surveys (descriptive or explanatory) should in more detail validate the results presented in this study. Thus, this information is not only of interest to practitioners and research by providing increased understanding of the main categories of challenges and their importance but also give important guidelines for further studies.

5.3 IDENTIFICATION AND EVALUATION OF PCS APPLICATIONS

The third research question discussed in this section is formulated as follows: *How can engineering companies identify and evaluate possible applications of PCS?* The research question consists of two questions, and each of those questions will be discussed to provide an overall answer to RQ 3.

5.3.1 IDENTIFICATION OF PCS APPLICATIONS

Study E analysed how to identify possible areas of applications for PCS in engineering companies, and a three-step framework was proposed. This type of framework is especially vital in engineering companies because projects with high complexity that require gradual implementation of PCS (Petersen 2007; Hvam et al. 2008). The framework builds on the literature in the field of PCS (e.g. Ardissono et al. 2003; Blecker et al. 2004; Forza and Salvador 2007; Hvam et al. 2008).

The results of the case study show that the framework provided a structured approach for this purpose. The framework also gave the main stakeholders a shared understanding of the overall objectives of PCS in terms of implementation and the initial prioritisation of projects. The process of creating this overview proved beneficial, as the stakeholders were able to express their opinions and take ownership in the projects. The involvement of relevant people thus led to strategic and smart decisions. Even though the proposed framework is successfully validated in an engineering company, the limitation of having only one case study is recognised.

Further studies should include testing the proposed framework in other engineering companies. This should also include companies that have not introduced PCS. In this study, it was decided to focus on engineering companies to cover both process and product complexity. Future studies could also analyse if the proposed framework can be used in companies with different manufacturing strategies and degree of customisation.

5.3.2 Evaluation of PCS applications

Study F analysed how to structure business cases for PCS projects, and a four-step framework is proposed. The framework build on both literature for IT projects in general (Gambles 2009; McNaughton et al. 2010; Nielsen and Persson 2017) to determine the main steps and their sequence and specific tools for PCS projects (e.g. Felfernig, Hotz, et al., 2014; Heiskala et al., 2007; Hotz et al., 2014; Salvador and Forza, 2007)

The proposed framework was tested in two engineering companies on three projects in total. These multiple cases proved the application of the framework in different projects as well as in different companies. The cross-case comparisons showed that the framework has different effects the two companies, which could relate to the different companies' cultures. Nevertheless, there are some limitations on the case studies, as it was limited to engineering companies. Further studies should, therefore, aim to validate the framework within other industries. Additionally, to provide a benchmark for the expected return on investment and/or risks in PCS projects, further studies should address these issues. Aspects related to more qualitative benefits from implementing the PCS should also be taken into consideration along with the net value of the investment. As discussed in the benefits section, even though significant savings in work-hours can be achieved by implementing and utilising PCS—which can be capitalised—the actual realisation of the benefits can be even more significant, such as determining whether the PCS can lead to increased sale due to faster response time (e.g. Hvam 2006b). Thus, even though the return on investment is a useful measurement to set the investment into perspective, other benefits should also be considered.

5.3.3 Identification and evaluation of PCS applications - Overall discussion

This part of the PhD project addresses how to identify and evaluate the different application of PCS. This is important to align different stakeholders concerning the application of PCS and prioritise the PCS projects. Furthermore, if the right projects are not identified, there would be a significant impact on the overall success of the PCS applications. Thus, this part of the study seeks to increase effectiveness by focusing on the selection of the most beneficial PCS projects to pursue.

5.4 IMPROVED DEVELOPMENT AND MAINTENANCE OF PCS

The fourth research question discussed in this section formulates as follows: *How to improve the development and maintenance of a PCS regarding product modelling and knowledge management in engineering companies?* The research question consists of two sub-questions each of those questions will be discussed to provide an overall answer to RQ 4.

5.4.1 Impact of using formal modelling techniques in PCS projects

The impact from applying the modelling methods are analyzed regarding the improved availability of knowledge (Tiihonen et al., 1996; Slater, 1999) and improved control of product variants (Forza and Salvador 2002, Tenhiälä and Ketokivi 2012). These are commonly described benefits from utilizing PCS and can be directly linked to the product modelling method used to represent the knowledge of the PCS. The findings show that companies utilizing UML-based modelling techniques perform better, concerning knowledge availability and control of product variants than the ones using non-UML based modelling methods and non-formal modelling methods. These findings indicate that investing time in structuring the knowledge using formalized modelling methods can bring additional benefits apart from the PCS. The ability to keep down the number of product variants in the product assortment is claimed to be an important enabler for reducing complexity and thus keeping down costs in the company (Hvam et al. 2008; Lindemann et al. 2008).

As this is an explorative study, more focus is set towards gathering in-depth information from the companies instead of having a more extensive sample of companies. Thus, both survey and interviews methods are used as part of the survey to assure a high quality of the data. The results presented in this study are based on responses from 18 companies. However, in order to provide a solid proof of the impact of using the different modelling techniques based on statistical analysis, a larger sample of companies is required. Further studies should address this to increase the generalisability of the findings and to prove the relations between the constructs. Finally, the impact of using the different modelling techniques is based on the preserved benefits using a five-point scale, and are therefore based on the respondent judgement of to what extent the benefits are achieved. This is aligned with the explorative nature of the study, which aims to explore whether there are any relations between the constructs and thereby provide direction for further studies.

5.4.2 Knowledge management in PCS projects

Study H analysed how to acquire and manage the required knowledge in PCS projects, and a four-step framework is proposed. The framework integrates both knowledge management in general and from IT projects (Basili and Weiss 1984; Rodriguez and Al-Ashaab 2005; Reich et al. 2012) to determine the primary steps and their sequence. Furthermore, this study takes advantages of proposed tools and methods for PCS projects (e.g. Forza and Salvador 2007; Hvam et al. 2008; Haug 2010, Shafiee et al. 2014, 2017).

The suggested framework is tested in two engineering companies on four projects in total where the proposed framework helped the companies address the main challenges of knowledge management in the PCS projects. The configuration teams involved in the development and testing of the framework expressed a willingness to use the framework in future projects to save both time and resources. Involved employees at the company also appreciated their involvement in knowledge verification. These results indicate both the effectiveness of the framework and its positive involvement effects on the people engaged in the PCS project. The main obstacle for the configuration team's use of the framework was their lack of familiarity with the suggested tools. Thus, an introduction to the tools in workshops significantly reduced their resistance to the framework. The use of cases allowed in-depth validation of the framework effectiveness. However, the limited number of cases used in the study influence the generalisability of the results. The ability of the framework to cope with highly customised, complex products in engineering companies indicates that it could also be used in configuration projects of less complexity. The necessity of applying such a structured framework in smaller projects is questionable and needs further testing. Future research should, therefore, test the framework in various industrial setups and identify more efficient and simpler tools and techniques for use in each step of the framework.

5.4.3 Improved development and maintenance of PCS - Overall discussions

This part of the PhD project addresses how to manage knowledge in PCS project and structure the knowledge by using formalised modelling methods. These are central activities in the development and the maintenance phase of the PCS; they are also a highly contributing factor on the quality of the system, as the system is only as good as the knowledge it includes. Thus, by addressing the knowledge management and validation, the study contributes to the successfulness of the PCS application in relation to the knowledge that needs to be communicated and validated, both in the development and in the maintenance phase of the PCS.

5.5 IMPROVED PERFORMANCE AND ACCURACY OF THE PCS WITH IT INTEGRATIONS

The fifth research question discussed in this section formulates as follows: *How can engineering companies increase the performance and accuracy of a PCS with integrations of product information retrieval in the configuration process?* The research question consists of four sub-questions; each of those questions are discussed to provide an overall answer to RQ 5.

5.5.1 Retrieving information from suppliers in the configuration process

Study K, analysed the impact of retrieving product information from suppliers in the configuration process on the complexity of the PCS and the accuracy of the generated product specifications.

The technical setup of the supplier integrations corresponds to proposed methods in the literature (Ardissono et al. 2003). The study shows that based on more detailed and up-to-date information from the supplier, the case company can save up to 20% of the overall material cost for the overall design, and the complexity and the development effort of the PCS are significantly reduced. As the application of the PCS is continually increasing, this integration to a supplier's PCS has become more realistic. The requirement for making the integration is limited to the suppliers having operational PCS and their willingness to develop a PCS which is capable of covering the required configurations. Finding suppliers capable of establishing this type of integration can though proven to be a challenge (Tiihonen et al. 1998). The case company has identified that this integration can be established with increased number of suppliers where comparisons capabilities of the PCS can be used to identify the most suitable supplier for each bid. Additionally, the company has plans to increase the number of documents retrieved from the suppliers in the configuration process, such as 3D models and technical specifications, as now only prices and dimensions of the product are received. Furthermore, currently the integration is only used to receive data as input in the configuration process, where the procurement would then contact the supplier to make the actual order purchase. In the near future, it is anticipated that this step will be automated as well so that the products can be requested from the supplier via the integration.

The analysis presented in this study are based on a single company where an integration to one of their suppliers is analysed. Thus, to increase the generalisability of the findings presented, a study of a greater number of companies is required. Nevertheless, the findings indicate that by increasing integrations of PCS across companies, high benefits can be achieved.

5.5.2 AUTOMATIC IDENTIFICATION OF MOST SIMILAR PRODUCTS IN THE CONFIGURATION PROCESS

Study J, analyses how to automatically identify the most similar products in the configuration process. The framework builds on the literature in the field of PCS and related areas of data based design and clustering methods (e.g. Burbidge 1975; Lafayette 1995; Brachman and Anand 1996; Inakoshi et al. 2001; Ramakrishnan and Gehrke 2003; Hvam et al. 2008; Kaufman and Rousseeuw 2009).

The framework was validated in an engineering company. The result showed that the IT system, which was developed based on the proposed framework, helped the users of the PCS to manage the high number of previously designed products and the high level of customisation. The users of IT system did not have to overcome any challenges related to training or system changes because the engineers were familiar with the setup of Excel and it had a friendly user interface. In the study, IT system is developed in Excel based on data retrieved from the company's ERP system. The reason for developing the system in Excel is mainly based on time and cost restriction for the research project. However, by integrating the PCS directly to the ERP system, data redundancy can be avoided. Therefore, in the future, it might be more beneficial to integrate the PCS directly into the ERP system. The proposed framework has only been tested in one company. Further research should thus include validation of the framework in different case companies to increase the generalisability. Additionally, the focus of further research can be directed on clustering and integrate the IT systems with the ERP system to update the knowledge automatically.

5.5.3 The complexity of PCS

Study K, provides an insight into the complexity of the PCS where the complexity is analysed based on a number of attributes and rules, or parameters complexity (Brown et al. 2007).

The results presented in relation to the research questions are based on answers to a survey (S2) and interviews from one company, where the unit of measurement is defined as operational PCS. The company has 159 PCS in operation, which the results are based on. This is thought to provide valuable insight as by studying one company an in-depth knowledge about the configuration setup could be accessed. Furthermore, it allows comparison of the complexity as all the PCS are developed based on the same commercial configuration platform. Limitation of the dataset can be explained as the majority of the PCS are used to support the engineering processes. More companies could be contacted in the future to enable cross-functional comparison. To allow comparison across different commercial configuration platforms, additional criteria needs to be defined that takes into the account how attributes and rules are defined as the modelling language can affect the number of rules and attributes. Furthermore, additional classification of rules and attributes could be beneficial (e.g., some rules are directly related to the product configuration while others are more related to the PCS setup or the user interface).

5.5.4 Improved performance of PCS with IT integrations - Overall discussion

This part of the PhD project has demonstrated how IT integrations can be used to both improve performance and accuracy of the PCS. Both methods provide highly beneficial results and can also be used together. While the information is up-to-date when retrieved from suppliers this approach can be more difficult to establish, as both the suppliers need to have a PCS and be willing to provide access, which has proven to be a challenge. While the method of identifying the most similar previously made products can more easily be established—as approval is only dependent internally at the company—some risk is still involved as a small modification for the new product can have a significant impact on the overall cost and work-hours required for the updates. Furthermore, procedures to correct pricing to make it aligned with the current market price is required if the main intention is to reuse the cost calculations. Finally, the complexity of the PCS is addressed both with respect to the users of the systems (sales, engineering, or both) and integrated IT systems. The complexity of the PCS is of importance as it directly influences both the development and maintenance effort (as also demonstrated in study J), and in some cases also the performance concerning the speed of the system.

6 CONCLUSION AND FUTURE RESEARCH

This chapter concludes with the findings from this PhD project. First, the contribution to the research is discussed using the different research questions. Contribution to the practice is also elaborated. Finally, direction for further studies is given.

6.1 CONTRIBUTION TO RESEARCH

The key findings are summarised in this section based on the research aim and the research questions presented in Section 2.3.

RESEARCH OBJECTIVE:
To facilitate successful application of PCS in engineering companies by providing theoretical and empirical based evidence of the impact from applying PCS and methods to improve the implementation, development and maintenance of the PCS.

The overall research objective is broken down into five research questions, which are then further broken down into sub-questions for specificity. Following is a description of the research questions and the result obtained from studies introduced in this thesis.

6.1.1 THE MAIN BENEFITS OF IMPLEMENTING AND UTILISING PCS

The benefits of PCS are analysed to understand what can be achieved by implementing and utilising a PCS. Successful PCS applications from the 1980s are highlighted in the literature where various benefits are described in relation to PCS. Based on a literature review, the main categories of benefits are identified and categorised (Section 3.2). The realisation of the benefits helps to identify where companies can apply a PCS to receive the greatest gain from their investment; it also provides more understanding of the value that companies can gain from implementing and utilising these systems. Building on the literature review, the sub-questions are developed, which are not addressed in the current literature as explained under Section 3.2.2. This section concludes the findings related to RQ 1 that is presented as follows:

RESEARCH QUESTION 1:
What are the main benefits of implementing and utilizing PCS in companies manufacturing customized products?

RQ 1.1 What are the main motivations that companies manufacturing customized products have for implementing PCS?
RQ 1.2 How successful are companies manufacturing customized products in achieving the benefits associated with the initial motivations?

The results presented to answer this research questions are based on Paper A and the method adopted is an explorative survey. Based on the survey's open questions seven categories of motivations are identified, which are listed as follows (in the order of the most expressed motivation to the least expressed):

1. Efficiency in the sales and order processes (45%)
2. Improved accuracy of the products specifications (41%)
3. Improved knowledge management (36%)
4. Improved general competitiveness (27%)
5. Efficiency in the production processes (27%)
6. Management of products variants and complexity (23%)
7. Other motivations that are company-specific (23%)

Building on the above-described results, pre-defined benefits are then grouped into the identified categories of motivations to analyse the successfulness of the companies of achieving the initial motivations described. For the motivation categorises, *general competitiveness, efficiency in the production process* and *accuracy of the products specifications*, companies expressing a motivation grouped into these categories agreed to a greater extent with the associated benefits being realised. This means that companies that have plans from the beginning to achieve those benefits are more likely to accomplish them. For the motivation categories *efficiency in the sales and order processes* and *management or product variants and complexity*, the companies that expressed a motivation grouped into these categories agreed to a lesser extent than those without a motivation in the categories with the realised benefits. Finally, for the category *knowledge management*, no significant difference between the companies expressing a motivation in the category and those without motivation. This highlights that there is a need for the plan prior to investing in the PCS what should be the benefits. This benefit realisation can also be used as an input when making identifying and formulating business cases for PCS applications.

RQ 1.3 What is the impact on the accuracy of the cost calculations and consequently the impact product profitability when supported with PCS?

The results presented to answer this research question are based on Paper B and the method adopted is a case study. The findings show that when support is done with a PCS, an improved accuracy of the cost calculations and the increased profitability of the products. The analysis leads to the conclusion that the contribution of the PCS is noteworthy as the performance of the products included in the PCS improved in terms of more accurate cost estimates and improved profitability. This could be explained by the fact that the data used in the PCS is updated, and all possible solutions are validated before making an offer; therefore, the generated quotations include fewer errors and the price estimates are more accurate than the quotations for products not included in the PCS. However, this study also highlights the importance of fully testing a PCS before making it operational. To this end, as can be seen from the results, the implementation had a negative impact in the first year due to insufficient testing. This also highlights that the performance of the PCS is aligned with the quality of the system.

RQ 1.4 What is the actual economic value creation from implementing and utilising PCS in companies manufacturing customized products?

The results presented to answer this question are based on Paper C, and the method adopted is a case study. The results from the study show that by comparing the direct cost savings from the reduced work-hours to the direct cost of developing, implementing, and maintaining the PCS, it can be concluded that the PCS is highly beneficial for the case company across the five-year period analysed. The analyses reveal that the case company reduced work-hours used in the sales process of 75%

and where the lead-time to respond to customer orders is reduced by 64%. Additionally, evidence of improved quality of the specifications when supported by PCS and increased sale is identified as a result of utilizing the PCS. Furthermore, by comparing the cost savings (based on reduced work-hours) to the cost of development, implementation and maintenance the return on investment is calculated. Based on the findings presented in this study, it can be concluded that the PCS is highly beneficial for the two product families analyzed in this study—the company saved 20,264,711€, with an 842% return on investment for the five-year period. Furthermore, if the previously described benefits of using PCS were interdependent, even greater value creation would be possible.

6.1.2 The main challenges of implementing and utilising PCS

This part of the project aims to highlight the main categories of challenges companies face when implementing and utilising PCS. This should inform companies regarding challenges on the way so that they can successfully implement and utilise a PCS. Furthermore, by identifying the importance of the challenges, the study helps to prioritise both research and practitioners according to the overall impact on the success of the system. To identify the main challenges that companies face when implementing and utilising PCS, both literature and explorative survey are used, and the results are based on Paper D. This section concludes the findings related to research question 2 that is seen as follows:

RESEARCH QUESTION 2:
What are the main challenges that companies manufacturing customized products face in relation to the implementation and utilization of their PCS?

RQ 2.1 What are the main categories of challenges that companies manufacturing customized products face when implementing and utilising PCS?

Research question 2.1 sought to identify the main categories of challenges faced by companies when implementing and utilising PCS. Six main categories were identified from the literature review (Section 3.2), and these are (1) IT related, (2) product modelling, (3) organisational, (4) resource constraints, (5) product-related, and (6) knowledge acquisition. Based on the survey's open questions, these grouping is also confirmed.

RQ 2.2 What is the importance of each category of challenges that companies manufacturing customized products face when implementing and utilising their PCS?

Research question 2.2 addresses the importance of the identified categories representing the main challenges when implementing and utilising PCS. The results show that the importance of the challenges varies among the identified categories and can be listed as follows.

- Organisational challenges were of significant importance as when companies rate organisational challenges as highly important other challenges also became more significant, indicating that this type of challenge is an underlying factor in other challenges.
- Knowledge acquisition is rated as of high importance
- Product modelling and resource constraints are rated of medium importance
- IT challenges and product-related challenges are rated as of low importance

The importance of the challenges faced when implementing and utilizing PCS should both help companies and researchers to prioritise the attention to the different challenges to allow for successful applications of PCS.

RQ 2.3 Which specific challenges within each category do companies manufacturing customized products face when implementing and utilising PCS?

Finally, research question 2.3 sought more in-depth knowledge about *the specific challenges* within each category that manufacturing companies face when implementing and utilising PCS. *IT challenges* were divided into two subcategories: software development, and systems design for user-friendliness. *Product modelling* challenges were divided into three subcategories: (1) complexity due to lack of overview of product range, (2) correctness of specifications generated by the configurator according to product model, and (3) lack of knowledge related to product modelling. Reported *organizational* challenges were described as (1) lack of support from management, (2) resistance to use the PCS, and (3) disagreements about the scope of the PCS. *Resource constraints* related to (1) a lack of resources, and (2) companies' vulnerability if key personnel leave. *Product-related* challenges concerns (1) product complexity, and (2) rapid product development. Finally, the main *knowledge acquisition* challenges were difficulties in (1) acquiring the correct knowledge, (2) a lack of the requisite knowledge to meet users' and customers' needs, and (3) failure to communicate knowledge in the maintenance phase. This provides a valuable insight into the main categories of the challenges.

6.1.3 Identification and evaluation of PCS applications

The complexity in engineering companies often results in having multiple PCSs. This highlights the importance of having a structured framework to identify and evaluate the different applications to both align different stakeholders and prioritise the PCS projects. This section concludes the findings related to RQ3 that formulates as follows:

RESEARCH QUESTION 3:
How can engineering companies identify and evaluate possible applications of a PCS?

RQ 3.1 How can possible applications of PCSs be identified in engineering companies?

Paper E provides answers to RQ 4.1. The study proposes a framework that allows systematic identification of PCS the applications. The proposed framework consists of three steps, which are (1) identifying potential PCSs, (2) aligning IT development, and (3) establishing an overview of PCS applications. The execution of each step is supported by relevant tools and methods identified in the literature.

RQ 3.2 How can business cases be framed in order to evaluate the potential applications of PCSs?

Paper F provides answers to RQ 3.2. The study proposes a business case framework for PCS projects success by addressing the main challenges of the business case framing for PCS projects. The suggested framework includes the following steps: (1) benefit analysis, (2) stakeholders' analysis, (3) analysis of the current processes and design of the future processes where PCS is used, and (4) evaluation of scenarios based on a cost-benefit analysis, sensitivity analysis and risk analysis. The execution of each step is supported by relevant tools and methods identified in the literature.

6.1.4 Improved development and maintenance of PCS projects

This part of the study focuses on improved the development and maintenance of the PCS. By improving those phases development time and reliability of the PCS can be improved. Two commonly described challenges concerning the development and the maintenance are product modelling and knowledge management, which are addressed in this part of the project. Furthermore, those challenges are especially important in engineering companies resulting from specialized and complex knowledge of the company's product offerings, which is often spread around the company in its tactic and explicit forms.

RESEARCH QUESTION 4:

How to improve the development and maintenance of a PCS regarding product modelling and knowledge management in engineering companies?

RQ 4.1 What is the impact of using formal modelling techniques in PCS projects?

Paper G provides answers to RQ 4.1. In this study, the impact of using UML-based modelling techniques is compared to that of non-UML based modelling techniques and non-formal techniques. The study illustrates that UML-based modelling techniques are used in larger companies and in PCS projects where the system includes a higher number of rules, attributes and integrations. The impact of using the different modelling methods is analysed in terms of the increased availability of product knowledge and improved control of product variants. In the study, the relation between the use of more formal modelling methods (UML-based and non-UML based) has a positive impact on those aspects and thus justify the resources spent on making these models, especially in larger companies that have more complex PCS.

RQ 4.2 How is knowledge acquired and maintained in PCS projects?

Paper H provides answers to RQ 4.2. The study proposes a knowledge management framework where the main challenges of knowledge management in PCS projects are considered. The proposed framework consists of four steps, which are (1) determining the scope of the project, (2) acquiring knowledge, (3) modelling and validating knowledge and (4) documenting and maintaining the system. The execution of each step is supported by relevant tools and methods identified in the literature.

6.1.5 Increased performance and accuracy of PCS with IT integrations

In engineering companies, it is of importance to retrieve accurate data in the configuration process. Two different methods are analysed where the first aims to retrieve information from suppliers PCS in the configuration processes and second to identify the most similar previously made product in the configuration process. Finally, the impact on the PCS complexity is analysed with both respect to different applications and with respect to different integrated IT systems. This section concludes the findings related to research question 5 that is formulated as follows:

RESEARCH QUESTION 5:

How can engineering companies increase the performance and accuracy of a PCS with integrations of product information retrieval in the configuration process?

RQ 5.1 What is the impact of integrating multiple PCS across supply chains to retrieve product information in the configuration processes?

Paper I provides an answer to this research question based on a case study. The approach suggests the involvement of a PCS to retrieve accurate product information in real-time from suppliers during the customisation process. The impact is analysed in terms of complexity and development effort, quality of the specifications, and optimisation of designs.

First, in terms of the *complexity of the PCS and development effort*, the result shows complexity reduction of the PCSs—which is defined using the number of business rules, tables, parts and values—is reduced to almost zero. This also affects the development time of the system, which is reduced from over 8 days to 2 days and the specialist time spent on the development has been reduced from over 8 days to zero. Second, in terms of the improved *quality of the specifications* generated by the PCSs, the quality of the information retrieved via the supplier integration is optimised, more detailed and up-to-date. The findings support this as over-dimensioning of different parts is not required as a result of improved quality of the products' specifications. Third, in terms of *optimisation of designs*, the findings indicate that the company can save up to 20% of material cost as a result of immediate and in-direct savings gained from over-dimensioning both the supplier's product and the surrounding systems.

RQ 5.2 How to automatically identify the most similar previously made products to improve the configuration process?

This research question is addressed in Paper J. This study proposes a framework to for development of an IT system, which should enable identification of the most similar previously made products in the configuration process. The proposed framework includes three steps, which are (1) identifying the most important product variables available in the PCS, (2) retrieving data of previously designed products in the ERP system, (3) identifying a method to compare products based on the main variables, and (4) set up the database with data of the previously designed products to integrate with the PCS. The execution of each step is supported by relevant tools and methods identified in the literature.

RQ 5.3 What is the relationship between the complexity of the PCS and the users of the systems?
RQ 5.4 What is the relationship between the complexity of the PCS to integrated IT systems?

Research questions 5.3 and 5.4 are addressed in paper K. The study provides insights into the complexity of the PCS where the complexity is analysed based on parameters, which consists of a number of attributes and rules.

Research question 5.3 analysis the relationship between the complexity of the PCS and the field of applications. The analysis shows that PCS used to support engineers have the highest parameters complexity. However, there was only a slight difference between the complexity factor of the PCS only used by sales, and the PCS used to support both sales and engineering. Research question 5.4 analysis the relationship between integrations and complexity of the PCS. In this study integration to CAD, ERP and calculation systems are analysed. The result shows out of the above mention IT systems, the complexity of the PCS integrated to CAD systems is the highest. This can be supported by the fact that in order to generate CAD files from the PCS, greater details needs to be supported. PCS integrated to ERP systems scored as the second highest while PCS integrated to calculation systems scored the lowest out of those systems. When PCS are integrated to calculation system, the reason is usually that the calculations being too complicated or specialised to handle within the PCS. This supports the fact that PCS integrated to calculations systems have low parameters complexity. Thus, it can be concluded that IT integrations and application have an impact on the PCS complexity.

6.2 CONTRIBUTION TO PRACTICE

This PhD project aims to support the more efficient application of PCS in engineering companies. To achieve that goal, eleven studies are conducted, where seven are based on case studies and four on survey research.

The first part of the PhD project aims to identify the main benefits of implementing and utilising PCS. This is intended to help companies understand the benefits that can be realised from implementing and utilising PCS. This is also helpful when formulating business cases and justifying the investment in PCS. Furthermore, the research highlights the importance of setting clear goals prior to the implementation, which should reflect on the company's strategy.

The second part of the PhD project aimed to identify the main challenges from implementing and utilising PCS. Based on the literature, different challenges are identified and further insight into the main categories of challenges is provided using a survey. Finally, to focus managerial attention, the impact of the challenges is assessed. This should make companies more aware of the different challenges associated with PCS to reduce the overall impact on the project success and to increase awareness. Finally, the presented result should help companies to prioritise their attention towards the different challenges.

The third part of the PhD project aims to support engineering companies to identify and evaluate applications of PCS. In this part of the study, two frameworks are proposed in order to support companies in this process. First, a framework to identify different applications of PCS is proposed. Second, a framework to construct business cases for PCS projects is proposed to evaluate the different applications. By constructing a business case, the benefits and the potential savings of the system can be identified to justify the investment in the system. The frameworks proposed in this part of the study should enable companies to identify and prioritise different PCS projects to align different stakeholders while gaining the most out of the investment in PCS.

The fourth part of the PhD project aims to improve the development and maintenance in PCS projects. First, the impact of using different product modelling techniques in PCS projects is evaluated. This is an important topic for companies when justifying the resources spent on making and maintaining the documentation of their PCS. The analysis highlights the circumstances where it is essential to use formal modelling techniques; this would be relevant for larger companies with more complex PCS. Second, to cope up with the complexity of knowledge in the different phases of PCS projects, a knowledge management framework is proposed, which should help companies to have a more structured approach to the knowledge management process through different lifecycle's of PCS projects.

Finally, the fifth part of the PhD project focuses on the increased performance of PCS by integrated IT systems to retrieve product information in the configuration process. This is especially important for engineering companies where there is uncertainty in the sales phase and high dependency to retrieve information from sub-suppliers. First, the focus is set on retrieving information from sub-suppliers in the configuration process by integrating PCSs across companies. In the study, both the technical setup of the integration is elaborated. Additionally, the impact from establishing such integration is assessed, which shows that both complexity and development time can be significantly reduced along with more optimised designs. Second, the focus is on automatically identifying the most similar previously made product in the configuration process. This study provides guidelines for companies to design an IT system that allows for automatically identification of the most similar made products, which should enable increased re-usability of previously made products that should reduce work-hours in the design phase. Finally, this part of the studies analysed the complexity of PCS with respect to supporting processes and IT integrations. This is also an essential aspect for companies both to predict development and maintenance effort required.

By covering the different aspects of the application of PCS, this PhD project aims to give companies the right tools and methods to successfully apply PCS, with a particular focus on engineering companies. With increasing competition, companies continuously need to be ahead of their competitors, which requires rapid development and introduction of new products and at the same time, the efficiency of the specification process needs to be assured to keep down prices and lead-time and at the same time guaranteeing a high quality of the product deliveries. For these reasons, PCS can be very beneficial for companies providing customised and engineered solutions in a smarter and more efficient way.

6.3 FURTHER RESEARCH

Through this PhD project, several opportunities for further research subjects can be considered. Reflecting on the methods, the results and the conclusions of this research project the following areas of interest for future research are identified.

The interdependence between the described benefits (e.g., less error in the product specifications lead to reduced work-hours as error do not have to be corrected) is an area that would be interesting to study further. By taking into the account the interdependence of the benefits, even higher economic value creation could be identified from implementing and utilising PCS. Furthermore, a more standardised way of quantifying the overall benefits from implementing and utilising PCS is required in order to both help companies to justify the investment before and after implementation of the systems.

Furthermore, with respect to the challenges, the correlation between the different categories could provide further insight into how to prioritise attention to reduce impact in PCS projects. The finding from this PhD project shows how organisational challenges are the most significant in PCS projects when it comes to the successfulness of implementing and utilising them. When implementing PCS to support different processes in companies, it will have a direct impact on the employees and change the current work habits. Thus, it is essential to pay attention to these challenges early in the PCS project. Studies on how to manage this would increase the acceptance of the systems and render the overall change management process. Furthermore, studies reflecting on the identified sub-categories of challenges would be interesting and analyse their internal impact towards the main category. Since, this project only concerns the overall impact of the main categories of challenges. Aligned with the focus of this study the challenges of implementing and utilising PCS are explored, thus PCS projects that fail before implementation are not considered. Furtherer, studies should, therefore, explore the challenges leading to companies abounding PCS projects. Finally, both for the benefits and the challenges addressed in this PhD project, studies based on a higher number of companies are also required to increase the generalisability of the findings.

With increased attention to industry 4.0, it should be analysed in more details what role PCS will play in the next industrial revolution. Industry 4.0 supports further automation in the manufacturing, where cyber-physical systems, internet of things (IoT) and big data play an essential role. IoT and smart products allowing interoperability of different devices and real-time configurations will call for new methods of handling the configuration task. Also aligned with the increased use of sensors and big data, allowing to make real-time configuration would call for new methods of the PCS to be able to process configurations and analyse the data. In engineering companies, this could allow real-time configurations based on operational data from plants and/or equipment to optimise the performance and while the customer can have prices for the needed updates. Finally, with increased use of 3D printing and smart factories, PCSs can streamline the complete order to the manufacturing process, where a 3D model generated based on the user's input in the configuration processes can be directly printed from a 3D printer.

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APPENDIX A

INDUSTRIAL APPLICATION OF CONFIGURATORS: FROM MOTIVATIONS TO REALIZED BENEFITS

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Abstract. Manufacturing companies are increasingly seeking to gain the benefits of mass customization strategies as a response to increased customers' demand for customized products. To automate the process of generating products' specifications and guide the sales process, configurators are commonly used to support companies applying mass customization strategies. This articles analysis the relationship between the initial motivations manufacturing companies have for implementing configurators and the realized benefits from the application of configurators. The results presented in this paper are based on a survey followed by interviews in 22 industrial companies. The findings show that the main motivations can be grouped into seven categories, where the successfulness of achieving the targeted benefits varies between the individual categories. Furthermore, the results highlight that substantial benefits can be achieved when applying configurators in manufacturing companies.

Keywords: *Configurators, Process optimization, Information systems, Product and process designs*

1. INTRODUCTION

The ability to provide customized products has become more important across industries over the past years (Salvador & Forza 2004). In order to cope up with increasing demand for customized products, mass customization strategies have received greater attention both from practitioners and researchers over the years. Mass customization outlines how companies can make customized products and services, which fit every customer through flexibility and integrations with a cost similar to mass-produced products (Pine 1999). Configurators are one of the key enablers of mass customization strategies (Pine II *et al.,* 1993)(Piller & Blazek, 2014) and one of the most successful systems of artificial intelligence (Blecker *et al*., 2004). Configurators are used to guide the communication with the customer and automate the generation of the product specifications, where product variants are defined within the chosen scope of variety (Forza & Salvador, 2008). Such systems utilize formally expressed product architectures, i.e. knowledge bases, consisting of a set of components, their relationships, and constraints to prevent infeasible designs (Felfernig *et al*., 2000).

The literature describes the various benefits that can be achieved by utilizing configurators. However, the motivation behind the implementation and how successful companies are in achieving the benefits that can be related to the initial motivations has not been addressed to a great extent in the literature. Besides, the majority of the literature describes the motivations and the realized benefits based on single case company, which makes it difficult to generalize.

This paper aims to capture that research opportunity by analysing the relationship between the actual motivations for implementing configurators and how successful companies are in achieving the benefits in relation to the initial motivations. In addition, the results provide insight into the main challenges companies face in the process of providing customized products and how those challenges can be addressed by implementation of configurators. Aligned with the focus of the study the following research questions were developed:

RQ. 1. What are the main motivations manufacturing companies consider for implementing configurators to support their design and specifications processes?

RQ. 2. How successful are manufacturing companies in achieving benefits associated with the initial motivations described prior to the implementation of the configurators?

The research method adopted in this paper is based on survey followed with interviews with 22 companies, which can be categorized as manufacturing companies providing customized or engineered products and use configurators to support the generation of the products´ specifications in the sales and design processes. The survey consisted both of open and closed questions, to capture both the qualitative nature of the main motivations and to quantify to what degree companies agree with achieving the main benefits described in the literature. Based on the answers gathered from the companies the motivations were grouped into seven categorizes. The pre-defined benefits were then grouped according to the identified categorizes of motivations to provide insight weather companies expressing certain motivation were more likely to achieve the related benefits.

2. LITERATURE REVIEW

The literature review focus on the motivations and the benefits described in the literature in relation with configurators.

Aldanondo et al. (2000) describe how configurators can be used in industries providing highly customized products, where there are iterative steps resulting in long cycle time, the risk of wasted time and money if the customer rejects the solution, risk of the proposed solution to be unfeasible, and finally the inaccurate cost estimation. To address these challenges, configurators can be used to limit the numbers of iterations as they support knowledge gathering and error avoidance in the process.

Ardissono et al. (2003) propose a configurators services to support diverse customers in open market environment and to be able to intergrade with suppliers providing configurable sub-products. Standard configurator software is proposed that provides personalized and adaptive user interfaces and communications across the supply chain. The system is capable of automatic exchange of orders, publishing product catalogues, or supporting billing transactions across the supply chain.

Ariano & Dagnino (1996) present a case study based on a manufacturing furniture company. The main objectives of the implementation of the system are described in terms of providing a system that enables the employees to enter an order in quick and accurate manner, provide the mechanism to check the product configuration and finally the generation of BOM and drawings. The main benefits of implementing the system are aligned with objectives for the implementation or organized way to structure the company's product line, more efficient way to enter orders that can be verified for correctness and alignment with the company's product offerings, generation of the dynamic BOM that enables more accurate price estimations, and reduction in duplicated information.

Barker et al. (1989) present a case where the initial purpose of the configurator was to help employees in the manufacturing to validate the technical correctness before production. Since then the system has expanded to address the business needs to a greater extent. The main benefits are described in overall net return of $40 million per year. These savings can be traced to incomplete orders cannot get through the process, optimization of the system performance, more efficient processes when releasing new products, increased manufacturing flexibility, the technical quality of the orders entering the manufacturing has been significantly improved and therefore time-consuming testing process and re-work in the manufacturing can be eliminated.

Fleischanderl et al. (1998) present a case where a configurator is applied in the complex domain of telephone switching systems. The system supports numbers of stages of the products' life cycle that includes sales, engineering, manufacturing, assembly and maintenance. It is claimed that the system has archived positive return on investment in the first year. In addition, benefits are described in terms of the quality of the configuration and elimination of error-prone manual editing of parameters. Furthermore, the implementation of the configurator has enabled training of new employees to be done in a more structured way and help to make the knowledge more accessible to wider range of employees.

Forza & Salvador (2002) present a case study where the introduction of the configurator has positively affected the sales, design, engineering and manufacturing processes at the company. The benefits of using the configurator are described in terms of errors generated in the sales processes are almost eliminated as a result to an automatic validity and completeness check performed by the configurator along with the time for generating a proposal, and consequently, the man-hours are significantly reduced. The technical productivity has also been increased as a result of automation of simpler technical configurations. Finally, in the production, the correctness of the BOM generated by the configurator has made it possible to avoid production stoppages leading to delivery delays. In another study, Forza & Salvador (2002) introduce a case company faced with challenges regarding the performance of correctness check of the products' specifications without increasing the control cost and reducing product variety. To address these challenges, a configurator is implemented where the main benefits are described in terms of reduced man-hours and lead-time (5-6 days to 1 day) and the correctness of product information generated are close to 100%. Furthermore, the ability to deliver on time is also increased as a result of improved correctness and fewer errors identified in the assembly process. Finally, the configurator helps to drive the customer towards a solution within the company's preferred product range. In the third study, Forza et al. (2006) present a company that implemented a configurator and by implemented a different product strategy that involved postponement of product differentiation. The benefits from that are described in term of enabled communications about the product assortment, fast and easy way to explore the company's product solutions, more accurate offers that can be generated within less time as there is no need to consult consistently with the technical offices, and finally the configurator supports accurate production of products code, BOM and production cycle.

Haug et al. (2011) present a study where fourteen companies are analyzed in order to evaluate the impact of implementing a configurator on the lead-time for generating quotes and detailed products' specifications. For the generation of the quotes, the average lead-time reduction is stated to be 83.7% while the average savings in man-hours is 78.4%. In terms of detailed product specifications, the average lead-time reduction is 83.5% as a result of the implementation of the system.

Heatley et al. (1995) present a study where configurator is used to support operational tasks at a company. Initially, the system was implemented to support the ordering process, where errors caused delays, threatened the overall quality, cost and the customers' satisfaction. By implementing the configurator, the correctness and completeness of the orders were significantly improved. Furthermore, the time required for validation and cost of re-work as a result of inaccurate specifications when entering the manufacturing has been eliminated. In addition, the average selection time per unit has been reduced from 2 hours to 6 minutes, the throughput cycle has been reduced from 6 days to 1 day, the orders feasible for manufacturing was increased from 40% to 100%, and finally orders containing pricing errors have been reduced from 80% to 0%. Finally, it is stated that due to increased efficiency a salesperson that on average sold equipment for $2 million can now sell for $4 million.

Heiskala et al. (2005) performed a study to analyze the benefits and challenges of mass customization, configurable products, and configurators with a special focus on services. The main benefits are described in terms of suppliers and customers. In terms of suppliers benefits are described in terms of reducing errors and man-hours, shorter lead-time where irritations can be reduced enabling generation of more quotations without increasing the number of employees, supporting the sales and R&D of more complex products, standardization of specifications, enables less skilled employees or even customers to perform configuration, reduce the need for technical experts in checking consistency, improved ability to make cost and delivery time estimations, improved ability to maintain and manage the configuration knowledge, and finally supporting communication of up-to-date configuration knowledge. In terms of benefits for the customers the ability to explore alternatives solutions and the impact, customers can be provided with access so they can generate the specifications, calculate price and delivery time and finally the configurator can help to explain to the customer why some alternative choices are not compatible.

Hvam et al. (2004) present a case study where a company is faced with a changed market environment and increased pressure to deliver in shorter time, with lower cost and improved overall performance. To respond to those challenges a configurator was implemented to support the overall design and generation of the products' specifications in the sales process. The main benefits were described in terms of reduction in lead-time for generating quotations (15-25 days to 1-2 days), improved quality of the quotations, the ability to optimize plant performance, and finally, reduction in engineering hours for making quotations (5 man-weeks to 1-2 man-days). In another study, Hvam (2006) performed at the same case company, where the company aims to increase efficiency in the sales and engineering processes by implementing configurator. The main benefits are described in terms of 50% reduction of manned activities for generating in the sale process, improved quality and more homogenous budget quotations, by determination of default values a quotation can be generated based on limited input from the customer, different solutions can be simulated, optimization of the plant, improved communication with customer, and increased knowledge sharing. Finally, Hvam et al. (2013) present a study where they describe the observed benefits from applying configurators in four industrial companies. The result presented shows that lead-time has been reduced by 94-99%, on-time delivery is improved to be 95-100% and resources for making the specifications have been reduced by 50-95%. Furthermore, by using configurators companies has achieved increased sales, decrease in the number of products and product variants, improved ability to introduce new products, finally and cost reductions.

Petersen (2007) focus on the benefits in engineering companies from implementing a configurator. The benefits are described in terms of reduction of lead-time and resources for generating quotations, the risk of errors in the sales process is reduced as a result of the knowledge to be embedded in the system and automation in the workflow.

Sviokla (1990) presents the case where, the required demand for flexibility, constant new product development, due to a great number of possible configurations the company was lacking overview, resulting in a number of errors. In order to guarantee the quality of the products a time consuming, the final assembly and test were performed before shipping the product to the customer. To address these challenges, a configurator was implemented where the benefits are described in terms of, elimination of the testing process, which was estimated to result in $15 million savings for the company. Other benefits are described in terms of increased correctness (65-90% to 95-98%), increased order volumes and shorter cycle time in the assembly process (10-13 weeks to 2-3 weeks).

Tiihonen et al. (1996) present a study based on a survey carried out in 10 companies to study the actual problems in the configuration process. In that study, the main motivations for implementing configurators are described in terms of being able to transfer up-to-date information to the sales units and enable them to use it in the right ways, and by increasing atomization by use of configurators the numbers of errors should be reduced leading to improved quality.

Trentin et al. (2012) explore the impact of using configurators on products quality. The results presented are based on the response from 176 manufacturing plants from three industries and six countries. The findings of the survey confirm that use of configurators supports higher product quality. Furthermore, it is stated that use of configurator affects compatibility between product variety and product quality that can be improved by using a configurator.

Finally, Yu & Skovgaard (1998) present a study of a configurator tool where the aim is to guarantee the correctness of the configurations, ensuring consistency, handling constraints, overcome limitations with regards to maintainability and finally to support the use of configuration application in user-friendly manners.

The literature describes the various benefits that can be achieved in industrial settings from implementing a configurator. In few of the research, the initial motivations for the implementation of the configurators are addressed. However, the literature does not provide any evidence of the initial motivations and the realized benefits from implementing configurators based on more than a single case study. This paper aims to capture that research opportunity and explore to a greater extent the main motivations or the drivers' industrial companies providing customized products have when implementing configurators and how successful they are in archiving the benefits associated with those motivations.

3. RESEARCH METHOD

3.1 Population and sampling

The criteria for selecting the company for the research was based on being manufacturing companies providing customized or engineered solution, and finally having experience from using configurators to support their specification processes. In a total of 26 companies were contacted that all fulfilled the selection criteria. The result presented in this article are based on the samples of 22 as those companies were able to provide the required answers. The sample used was aimed to represent manufacturing companies providing customized and engineered solutions. The companies represent small, medium and large-sized companies, where the level of customization and the complexity of the offered products can vary greatly as the companies' offerings include everything from complete plants, equipment and components.

3.2 Design of the questionnaire

Aligned with the focus of the research, the aim is to explore the main motivations manufacturing companies have for implementing configurators and measure how successful companies are in achieving the benefits associated with the motivations. The questionnaire was designed to capture both qualitative explanations and measurements of the degree companies agreed with achieving pre-defined benefits in relation to usages of configurators. The pre-defined motivations were determined based on the literature in the field and experiences from working with configurators, 22 benefits associated with configurators were identified. The respondents were, therefore, asked the following questions for the purpose of this research:

1. What are the main motivations for the implementation of the configurator?
   [Open question]
2. To what extent you agree that the company has obtained the following benefits from using the configurator?
   [On a 5-point scale where 1 represent strongly disagree, 2 disagree, 3 neither agree nor disagree, 4 agree, 5 strongly agree and finally represent 0 that the respondent did not know or to what extent the use of the configurator had on the benefit]

3.3 Data collection and analysis

The data collection phase is divided into two steps, or pre-study and the actual interviewing phase. The pre-study phase was aimed at establishing external validation of the questionnaire and to make sure that the respondents had the right understanding of the questions. For these reasons, three pilot interviews were conducted. Thereafter, the questionnaires were e-mailed to the all the identified companies along with a description of the purpose of the study, the interview procedure, and a follow-up notification. Finally, appointments were made for phone interviews. The interviewing phase was done through structured phone interviews conducted as a walk-through of the questionnaire. The interview process left room for clarification and elaboration of questions to ensure a correct and consistent interpretation of the questions and for the interviewer to gain a holistic understanding of the empirical setting at the companies.

In the analysis phase, interviews were entered into an MS Access database, cross-checked for data entry errors, and the answers were analysed. Based on the answers provided by the companies, they were grouped according to keywords, and the final grouping was discussed among the research team in order to provide consistency in the result presented. Thereafter, the pre-defined benefits were grouped according to categories of the motivations in order to see how successful the companies were in achieving the described motivations. The grouping of the benefits was also discussed by the research team, and keywords from the motivations were used.

4. RESULTS

In this chapter first, each of the identified motivations categories will be explained in more detail based on the answers provided by the companies. Thereafter, the predefined benefits that were grouped according to the motivations categories are presented. The benefits were defined based on the literature and experience. To measure to what degree companies achieved those benefits they were measured on a five-point scale, which represent to what degree companies agree with the individual benefit being realized as a result of implementation and usages of the configurators. First, the percentages of companies' ratings for each of the benefits associated with the motivation are presented. Thereafter, to evaluate whether companies that expressed a motivation in the category were more likely to achieve the benefits the average rating, which is calculated based on all the benefits in the category, are presented.

4.1 General competitiveness

Increased general competitiveness was identified as one of the motivation in 6 out of the 22 companies, or by 27% of the total companies. In terms of general competitiveness, two of the companies described that a use of a configurator was a market condition as they would not be in the market if not they are not able to deliver customized products efficiently. In another company, it was mentioned that the development of the configurator was supposed to enable greater automation of the sales and order process and thereby the company hoped to improve competitiveness. In addition one of the companies aimed that by developing a configurator to get ahead in the market competition. Furthermore, it was described that the configurator was designed to help the companies to reach more customers along with reducing the numbers of orders that do not turn into an actual sale. Finally, it was expressed that by implementing a configurator, it was hoped to minimize the overall cost. In Table 2, the benefits associated with the general competitiveness are presented along with the degree the companies agreed with the benefits to be realized in relation with the configurator.

Table 1. Benefits related to general competitiveness

	Disagree (1-2)		**Neither (3)**	**Agree (4-5)**		**NA (0)**
	Strongly disagree	Disagree	Neither disagree nor agree	Agree	Strongly agree	NA
1. Increased sales revenues for the products included in the configurator	**5%**		**27%**	**64%**		**5%**
	5%	0%	27%	23%	41%	5%
2. Increased gross margin for the products included in the configurator	**0%**		**23%**	**68%**		**9%**
	0%	0%	23%	36%	32%	9%
10. More sales quote result in actual orders	**10%**		**32%**	**32%**		**27%**
	5%	5%	32%	14%	18%	27%
11. More on time delivery result in increased number of orders	**10%**		**41%**	**41%**		**9%**
	5%	5%	41%	14%	27%	9%
20. Larger share of products that meet the quality objectives	**0%**		**32%**	**64%**		**5%**
	0%	0%	32%	32%	32%	5%
3. Increased customers satisfaction when the configurator is used	**5%**		**14%**	**77%**		**5%**
	5%	0%	14%	41%	36%	5%
4. Increased employees satisfaction	**5%**		**18%**	**72%**		**5%**
	5%	0%	18%	45%	27%	5%
The average score for the companies expressing general competitiveness as main motivation (27% of total companies)	**3%**		**14%**	**79%**		**5%**
	0%	3%	14%	31%	48%	5%
The average score for the companies not expressing general competitiveness as main motivation (73% of total companies)	**5%**		**31%**	**53%**		**11%**
	4%	1%	31%	29%	24%	11%

4.2 Knowledge management

Improved knowledge management was identified as one of the motivation in 8 out of the 22 companies, or by 36% of the total companies. In terms of knowledge management, it was mentioned that preserving the knowledge within the companies is vital so they could be less exposed when experienced employees leave. It was also described that by implementing a configurator, it should enable increased learning and knowledge sharing. In this context, it was also described that knowledge held by few experts at the companies should become available to an increased number of employees. Furthermore, it was mentioned that it should help the company to expand as the product knowledge become more accessible and therefore the company is not constraint by a limited number of employees with specific product knowledge. Finally, by storing the knowledge and the product information, it is hoped to enable better knowledge flow and documentation base, which is easier to maintain. In Table 2, the benefits associated with the knowledge management are presented along with the degree the companies agreed with these benefits being realized in relation with the configurator.

Table 2. Benefits related to knowledge management

	Disagree (1-2)		**Neither (3)**	**Agree (4-5)**		**NA (0)**
	Strongly disagree	Disagree	Neither disagree nor agree	Agree	Strongly agree	NA
6. Better documentation and maintenance of knowledge	**0%**		**32%**	**64%**		**5%**
	0%	0%	32%	9%	55%	5%
21. Reduction of redundant information	**0%**		**32%**	**64%**		**5%**
	0%	0%	32%	32%	32%	5%
22. Better accessibility of knowledge about product variants and product specifications	**5%**		**23%**	**73%**		**0%**
	0%	5%	23%	32%	41%	0%
The average score for the companies expressing knowledge management as main motivation (36% of total companies)	**4%**		**21%**	**67%**		**8%**
	0%	4%	21%	21%	46%	8%
The average score for the companies not expressing knowledge management as main motivation (64% of total companies)	**0%**		**33%**	**66%**		**0%**
	0%	0%	33%	26%	40%	0%

4.3 Efficiency in the sales and order processes

Increased efficiency in the sales and order processes was identified as motivation in 10 out of the 22 companies, or by 45% of the total companies. In this relation, it was mention that the salesperson should be able to handle all product configurations even for the complex products through the configurator and at the same time being able to focus on being a good seller. Furthermore, the companies described how they aimed to use the configurators as a tool, which should enable employees to make a configurator and at the same time provide flexibility in options without compromising quality. Another aspect was related to improving the ability to capture all of the customers' requirements in efficient manners and based on that finding the optimal solution. It was also expressed that the configurator should be able to guide the sales process towards selling the right products based on the standard offerings and at the same time finding the optimal fit for the customers. Finally, by automating the sales and the order processes to a greater extent, it is hoped to increase speed and consequently to reduce routine work and the lead-time for the order fulfilment. In Table 3, the benefits associated with the efficiency of the sales and order process are presented along with to what degree the companies agreed with them being a realized benefits in relation with the configurator.

Table 3. Benefits related to efficiency in the sales and order process

	Disagree (1-2)		**Neither (3)**	**Agree (4-5)**		**NA (0)**
	Strongly disagree	Disagree	Neither disagree nor agree	Agree	Strongly agree	NA
5. Reduction of routine work	**5%**		**5%**	**87%**		**5%**
	0%	5%	5%	32%	55%	5%
7. Fewer transfers of responsibility and errors when generating the proposals and specifications	**0%**		**9%**	**87%**		**5%**
	0%	0%	9%	32%	55%	5%
9. Shorter time to generate proposals	**5%**		**5%**	**87%**		**5%**
	0%	5%	5%	14%	73%	5%
12. Reduction of cost when of preparing proposals and specifications	**5%**		**14%**	**77%**		**5%**
	5%	0%	14%	45%	32%	5%

The average score for the companies expressing efficiency in the sales and order processes as main motivation (45% of total companies)	**8%**		**10%**	**78%**		**5%**
	3%	5%	10%	35%	43%	5%
The average score for the companies <u>not</u> expressing efficiency in the sales and order processes as main motivation (55% of total companies)	**0%**		**6%**	**90%**		**4%**
	0%	0%	6%	27%	63%	4%

4.4 Efficiency in the production process

Increased efficiency in the production process was identified as one of the main motivation in 6 out of the 22 companies, or by 27% of the total companies. In this relation, it was mentioned that it was hoped that the configurator would improve the overview of the different products variants and their connections and their effects on the production. Furthermore, in this relation, it is hoped that the configurator can streamline the process of generating BOM, the production specifications, and thereby increase the speed and reduce errors. Finally, it was described that due to the variety of templates and different standards for generating the production specifications, which resulted in errors in the production, it is hoped to make the specifications more homogenous by the implementation of the configurator. In Table 4, the benefits associated with the efficiency of the production process are presented along with to what degree the companies agreed with them being a realized benefit gained in relation with the configurator.

Table 4. Benefits related to efficiency in the production

	Disagree (1-2)		**Neither (3)**	**Agree (4-5)**		**NA (0)**
	Strongly disagree	Disagree	Neither disagree nor agree	Agree	Strongly agree	NA
13. Reduction of cost in relation with construction and production preparation	**5%**		**14%**	**77%**		**5%**
	5%	0%	14%	27%	50%	5%
14. Reduction of cost in relation to production and procurement of materials	**5%**		**45%**	**46%**		**5%**
	0%	5%	45%	32%	14%	5%
The average score for the companies expressing efficiency in the production process as main motivation (27% of total companies)	**0%**		**17%**	**83%**		**0%**
	0%	0%	17%	33%	50%	0%
The average score for the companies <u>not</u> expressing efficiency in the production process as main motivation (73% of total companies)	**6%**		**34%**	**53%**		**6%**
	3%	3%	34%	28%	25%	6%

4.5 Accuracy of the products' specifications

Improved accuracy of the product' specifications and the documentation associated with the product configuration was identified as one of the motivations in 9 out of the 22 companies or 41% of the total. The companies explicitly explained that they aimed to eliminate errors and thereby to improve the quality of the specifications. In this context, one of the companies expressed that they aimed to achieve increased uniformity of the generated quotations, as the salespersons had different routines and preferences that lead to lack of uniformity and errors in the quotations sent out to customers. In another company, it is described that by validating and ensuring that the accurate information is incorporated in the configurator, the number of errors should subsequently be reduced. Furthermore, it was expressed that the implementation of the configurator should enable an improved overview of the different products' parameters, the relationship between the different parameters and why certain combinations are not feasible, to reduce errors. Finally, when errors are discovered it is easier to communicate and correct them, as it only has to be changed in one place or in the configurator, and therefore the same errors should not repeatedly occur. In Table 5 the benefits associated with the accuracy of the products' specifications are presented along with to what degree the companies agreed with them being a benefit gained in relation with the configurator.

Table 5. Benefits related to accuracy of the specifications

	Disagree (1-2)		Neither (3)	Agree (4-5)		NA (0)
	Strongly disagree	Disagree	Neither disagree nor agree	Agree	Strongly agree	NA
8. Improved quality of the response to customer request	**0%**		**9%**	**86%**		**5%**
	0%	0%	9%	36%	50%	5%
15. Reduction in the number of orders where there are deviations between the estimated and the actual cost	**5%**		**18%**	**59%**		**18%**
	5%	0%	18%	23%	36%	18%
16. Less deviation (in percentages) between the estimated and the actual cost	**5%**		**23%**	**54%**		**18%**
	5%	0%	23%	27%	27%	18%
The average score for the companies expressing accuracy of the products' specifications as main motivation (41% of total companies)	**0%**		**4%**	**71%**		**26%**
	0%	0%	4%	30%	41%	26%
The average score for the companies <u>not</u> expressing accuracy of the products' specifications as main motivation (59% of total companies)	**5%**		**26%**	**64%**		**5%**
	5%	0%	26%	28%	36%	5%

4.6 Management of products variants and complexity

Improved management of variants and complexity was identified as one of the motivations in 5 out of the 22 companies, or by 23% of the total companies. In this relation, it was expressed that the configurator should help in the process of managing complex products' portfolio and the associated cost. In the other company, it was expressed that by use of a configurator it is hoped to minimize the number of items and structured BOMs. This should result in reduced variant handling associated with long descriptions with a large number of different SKUs. Furthermore, it was expressed that by use of the configurator it was hoped to standardize the way of offering individualized (customized) products and thereby reducing the overall cost. Finally improved product overview, standardization of the product portfolio, and consistent configurations from time to time were to be achieved by the implementation of configurators. In Table 6, the benefits associated with the management of product variant and complexity are presented along with to what degree the companies agreed with them being a benefit gained in relation with the configurator.

Table 6. Benefits related to management of product variants and complexity

	Disagree (1-2)		Neither (3)	Agree (4-5)		NA (0)
	Strongly disagree	Disagree	Neither disagree nor agree	Agree	Strongly agree	NA
17. Easier to identify and manage product variants	**0%**		**9%**	**91%**		**0%**
	0%	0%	9%	32%	59%	0%
18. Decreased number of product variants	**41%**		**27%**	**32%**		**0%**
	23%	18%	27%	18%	14%	0%
19. Increased use of standard modules / components	**5%**		**14%**	**82%**		**0%**
	5%	0%	14%	32%	50%	0%

The average score for the companies expressing Management of products variants and complexity as main motivation (23% of total companies)	**27%**		**13%**	**50%**		**0%**
	7%	20%	13%	13%	47%	0%
The average score for the companies not expressing Management of products variants and complexity as main motivation (77% of total companies)	**12%**		**18%**	**70%**		**0%**
	10%	2%	18%	31%	39%	0%

4.7 Other motivations

In term, other motivations answer from 5 out of the 21 companies, or 23% of the total companies where grouped in this category. This includes improved visualization, security, innovation and uniformity. In addition one of the companies explained that the ERP system used at the company that included variant management but not financial management, which meant that it was not possible to calculate the production cost, which motivates them to use configurators. In terms of other motivations, no specific benefits could be grouped to the motivations listed in this category as they are to company specific. Therefore, it cannot be determined how successful the companies were achieving them.

5. DISCUSSIONS

Seven main categorize are identified based on the motivations given by the companies, where two of categorizes the are efficiency in the sales and order processes and the accuracy of the products' specifications are the most mentioned motivations, or by 45% and 41% consequently. Knowledge management was mentioned by 36% of the companies as the third most mentioned motivations, and finally, the remaining motivations categorizes were expressed less frequently or by 27-23% companies.

In the first motivation category general competitiveness, seven benefits were grouped, which are (1) increased sales revenues for the products included in the configurator, (2) increased gross margin for the products included in the configurator, (3) more sales quote result in actual orders, (4) more on-time delivery results in increased number of orders, (5) larger share of products that meet the quality objectives, (6) increased customer satisfaction, and finally (7) increased employee satisfaction. Out of these benefits, 77% and 72% of the companies agreed with increased customer and employees' satisfaction consequently being realized benefits from using the configurators, while only 32% of the companies agreed with more sales quotes resulting in actual orders. For the other benefits, 68% - 41% of the companies agreed that those were benefits associated with the configurator. In this category, a significant difference of the companies that expressed a motivation in this category can be seen as 79% on average agreed with those benefits while for companies not expressing a motivation grouped into the category 53% agreed.

The second motivation category knowledge management three benefits were grouped, which are (8) better documentation and maintenance of knowledge, (9) reduction of redundant information, and finally (10) better accessibility of knowledge about product variants and product specifications. Out of these benefits, better accessibility of knowledge about product variants and product specifications was the most recognized benefit or by 73% of the companies, while better documentation and maintenance of knowledge and reduction of redundant information were both recognized by in both cases by 64% of the companies. However, no significant difference can be found between companies expressing a motivation in this category and the ones not expressing a motivation in this category, as the number of the companies agreeing to the benefits on average or 67% and 66% consequently.

The third motivation category efficiency in the sales and order processes four benefits were grouped, which are (11) reduction of routine work, (12) fewer transfers of responsibility and errors when generating the proposals and the specifications, (13) shorter time to generate proposals, and finally (14) reduction of cost when of preparing proposals and specifications. Out of these benefits, 87% of the companies agreed with reduction of routine work, fewer transfers of responsibility and errors when generating the proposals and specifications, and shorter time to generate proposals being a benefit, while 77% agreed with reduction of cost when of preparing proposals and specifications. However, an interesting finding is that on average 90% of the companies, which did not express a motivation in this category agreed with those benefits while 78% of the companies expressing a motivation in the category agreed on average. Therefore, higher percentages of companies not expressing a motivation grouped in the category agreed with achieving the associated benefits.

The fourth motivation category efficiency in the production processes two benefits were grouped, which are (15) reduction of cost in relation to construction and production, and (16) reduction of cost in relation to production and procurement of materials. Out of those two benefits, 77% of the companies agreed to a reduction of cost in relation to construction and production being a benefit while 46% of the companies agreed with reduction of cost in relation to production and procurement of materials. In terms of companies that expressed a motivation grouped into this category, a significant difference was found. On average from the companies expressing a challenge in this category, 83% agreed with this being a realized benefit, while only 53% of companies not expressing a motivation in the category agreed on average with this benefit. The fifth motivation category accuracy of the products' specifications three benefits were grouped, which are (17) improved quality of the response to customer request, (18) Reduction in the number of orders where there are deviations between the estimated and the actual cost, and (19) less deviation (in percentages) between the estimated and the actual cost. Out of those benefits most companies agreed with improved quality of the response to customer request or 86% of the companies, while 59% and 54% agreed with reduction in the number of orders where there are deviations between the estimated and the actual cost, and less deviation (in percentages) between the estimated and the actual cost consequently. In terms of companies that expressed a motivation grouped into this category, a significant difference was found as 71% on average agreed that those three benefits were realized from using the system while 64% of companies not expressing a motivation in the category agreed on average.

The sixth motivation category management of products variants and complexity three benefits were grouped, which are (20) easier to identify and manage product variants, (21) decreased the number of product variants, and (22) increased use of standard modules / components. In relation to the benefit easier to identify and manage product variants 91% of the companies agreed, which makes the benefit that the most companies agree with out of all the benefits. The benefit increased use of standard modules / components also was agreed by the majority of the companies or 82% while only 32% agreed with a decreased number of product variants being benefits associated with using the configurator. An interesting finding is that on average 70% of the companies, which did not express a motivation in this category agreed with those benefits while only 50% of the companies expressing a motivation in the category agreed on average. Therefore, higher percentages of companies not expressing a motivation grouped in the category agreed with achieving the associated benefits.

The implementation of configurators often involves that companies also improve their product designs with special focus and increased standardization and predefined product architectures. The above mention benefits from the application of the configurators also include these aspects, and therefore the benefits are not only gained from implementing the configurators but also as the companies are more in charge of their product designs.

6. CONCLUSIONS

The aim of the study was to provide further insight into the relationship between the initial motivations manufacturing companies have for implementing configurators, and the associate realized benefits. To address this two research questions were developed.

The first research question aims to identify the main motivations for the implementation of the configurators. The main motivations were grouped into seven categories, which are to improve general competitiveness, knowledge management, efficiency in the sales and order processes, efficiency in the production processes, the accuracy of the products' specifications, management of products variants and complexity and finally other motivations.

The second research question aimed to express how successful companies were in achieving the benefits associated with the motivations prior to the implementation. For the motivation categories, general competitiveness, efficiency in the production process and accuracy of the products' specifications, companies that expressed a motivation grouped into these categories agreed to a greater extent with the associated benefits being realized in their companies. That means that companies that have plans from the beginning to achieve those goals are more likely to accomplish them. For the motivation categories efficiency in the sales and order processes and management or product variants, the companies that expressed a motivation grouped into these categories agreed to less extent than the companies not expressing a motivation into the category that this was a realized benefit. Finally, for the motivation category known as knowledge management now, a significant difference could be determined between the companies expressing a motivation in the category and not in terms of the to what degree companies agreed of the associated benefits being realized benefits associated with the usage of the configurator.

The findings presented in this study also raise further questions regarding what is the relation between the planned benefits prior to the implementation of the configurator and the side benefits that are achieved without being planned. Further, studies will, therefore, explore this relationship to a greater extent.

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APPENDIX B

Computers in Industry 88 (2017) 12–18

Contents lists available at ScienceDirect

Computers in Industry

journal homepage: www.elsevier.com/locate/compind

Impact of product configuration systems on product profitability and costing accuracy

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ARTICLE INFO

Article history:
Received 30 May 2016
Received in revised form 4 January 2017
Accepted 9 March 2017
Available online 27 March 2017

Keywords:
Product configuration system
Cost calculation accuracy
Product profitability
Benefits of product configuration systems
Longitudinal case study

ABSTRACT

This article aims at analyzing the impact of implementing a product configuration system (PCS) on the increased accuracy of the cost calculations and the increased profitability of the products. Companies that have implemented PCSs have achieved substantial benefits in terms of being more in control of their product assortment, making the right decisions in the sales phase and increasing sales of optimal products. These benefits should have an impact on the company's ability to make more accurate cost estimations in the sales phase, which can positively affect the products' profitability. However, previous studies have not addressed this relationship to a great extent. For that reason, a configure-to-order (CTO) manufacturing company was analyzed. A longitudinal field study was performed in which the accuracy of the cost calculations and the products' profitability were analyzed before and after a PCS was implemented. The comparison in the case study revealed that increased accuracy of the cost calculations in the sales phase and consequently increased profitability can be achieved by implementing a PCS.

1. Introduction

In today's business environment, companies are forced to offer customized solutions without compromising delivery time, quality and cost [1]. To respond to these challenges, mass customization strategies have received increasing attention over the years, from practitioners and researchers. Mass customization refers to the ability to make customized products and services that fit every customer through flexibility and integrations at cost similar to mass-produced products [2]. Utilizing product configuration systems (PCSs) is one of the key success factors in achieving the benefits of the mass customization approach [2,3].

PCSs are used to support design activities throughout the customization process, where a set of components and their connections are pre-defined and where constraints are used to prevent infeasible configurations [4]. Companies that have implemented PCSs have achieved numerous benefits such as shorter lead times, more on-time deliveries, improved quality, less rework and increased customer satisfaction [1,5–7]. In addition, the supportive function of the PCS enables improved decision making in the early phases of engineering and sales processes [8]. Furthermore, the system can be used as a tool that allows the salesperson to offer custom-tailored products within the boundaries of standard product architectures, thus giving companies the opportunity to be more in control of their product assortment [1]. It can be assumed that these benefits will have an impact on the company's ability to increase the accuracy of the cost calculations in the sales phase, which can positively affect the products' profitability. However, the link between the implementation of a PCS and the effects on the company's ability to increase the accuracy of the cost calculations in the sales phase and consequently increase the products' profitability has not received much attention from researchers [9]. Thus, the focus of this study is assessing the impact of implementing a PCS on a company's ability to make accurate cost calculations in the sales phase and products' profitability. Aiming to investigate these effects, the following propositions were developed:

Proposition 1. *The accuracy of the cost calculations in the sales phase is increased by utilizing a PCS.*

Proposition 2. *Product profitability is increased by utilizing a PCS.*

To test the propositions, a longitudinal field study was performed in a configure-to-order (CTO) company. In 2009, an analysis of product profitability and the accuracy of the cost calculations in the quotations generated in the sales phase was conducted. The results indicated that the performance of the sales processes could be significantly improved by implementing a PCS.

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http://dx.doi.org/10.1016/j.compind.2017.03.001
0166-3615/

That recommendation was adopted by the company; thus, a PCS was developed and implemented in 2011. Although the company has used the PCS since 2011, some salespersons still have not accepted the system and therefore generate quotations outside the PCS. This behavior provides an opportunity to compare quotations generated with the PCS and without the PCS over a 4-year period after the implementation. The results indicate that the quotations generated in the PCS have more accurate cost calculations, and consequently, the profitability of the products sold via the PCS is higher.

2. Literature review of the benefits of utilizing PCSs

In this section, the theoretical background of the present research is reported. To find relevant articles, a literature review was performed in the research area of PCSs. The focus of the literature review was identifying the main benefits and challenges of implementing and utilizing PCSs. Several research groups have conducted extensive studies in this field.

2.1. Benefits

First, the benefits identified by utilizing a PCS are discussed. As the focus of this study was to assess the impact of implementing a PCS, quantitative data were required. The results from the literature study are presented in Table 1. The benefits discussed in the literature are listed, and the articles discussing the benefits are listed in the second column. The last column specifies whether the impact of the utilization of a PCS was measured and shows quantitative data from the benefits identified.

Summarizing the findings from the literature review, the implementation of a PCS provides various benefits to companies, in terms of resource reduction, decreased lead time, better communication with customers and improved product quality (Table 1).

There is a lack of empirical evidence that measured the impact of implementing PCSs on improved profitability and more accurate cost estimates. The present work contributes to the literature by providing a longitudinal field study that compared the economic performance of the products and the accuracy of the cost calculations before and 4 years after a PCS was implemented in an industrial manufacturing company.

2.2. Challenges of implementing a PCS

In this section, the literature focuses on the challenges and practical implications of implementing PCSs. The challenges refer not only to the scope of the PCS but also to the implementation and utilization of the system by employees and its acceptance as part of their daily work routine. The following table summarizes the main challenges identified in the literature (Table 2).

The implementation of PCSs is not free of challenges during the process. This is explained in the difficulties faced by the users and the developers of PCSs related to supporting customers' needs in the configuration process, product modeling and data acquisition, errors in the configuration process, documentation and maintenance and challenges regarding change management and acceptance of the system as part of the work procedures.

3. Research method

This research was conducted as a longitudinal field study, where the impact of implementing PCSs was analyzed, focusing on the accuracy of the cost calculations and profitability. The research was conducted as a collaboration between the Technical University of Denmark (DTU) and the case company over the 2009–2014 period and included multiple observations of the change process. The research team monitored the implementation and the impact of the PCS from the beginning until the PCS was fully integrated into the company's business processes. The company was selected as it is highly representative of medium-sized CTO companies that provide highly customized products and operate globally.

A longitudinal field study was selected as the research method for this work as this design allows the team to make real-time and in-depth observations of the change process and development in organizations [29,30] and specifically in this case, the process of implementing and utilizing a PCS over a 4-year period. Longitudinal field studies are a special type of case study in which the phenomenon is studied in its natural setting over time using

Table 1
Benefits obtained from implementing PCSs.

Benefit	Authors	Measurement
Reduction in lead time for making specifications	[1,5,7,10–16]	From 5–6 days to 1 day [10] The real working time for preparing offers and production instructions is near zero [11] 75–99.9 % reduction in the quotation lead time [7] 15–25 days to 1–2 days [12]
Reduction in lead time for delivering the product	[11,14–18]	Delivery time reduced from 11 to 41 days to 1 day [11]
Saved work-hours	[1,10,12,15–19]	The engineering hours for creating quotations were reduced from 5 work-weeks to 1 to 2 work-days [12] Throughput cycle was reduced from 6 days to 1 day [19]
Increased quality of product information/ specifications	[1,6,10,12–16,18–23]	Reduction to almost zero of errors in configurations released by the sales office [1] Increased level of correctness of product information to almost 100% [10] Specifications quality improved from 60% to 100% manufacturable [19]
Improved product quality	[21,24]	N/A
Improved on-time delivery	[1,10,25]	N/A
Increased employee productivity	[1,14,22]	N/A
Lower production costs	[11,21]	Fixed production costs were reduced by 50% and variable costs by 30% [11] Reduction from 30% to less than 2% in the number of assembly errors [11]
Improved efficiency in aftersales	[11]	Time for replacement was reduced from 5 to 6 h to 20–30 min [11]
Improved knowledge management	[1,6,11,22,26]	N/A
Improved control of product variants	[1,10,20,25]	N/A
Reduced product lifecycle cost	[27]	PCS supporting the complete configuration process may reduce the configuration cost up to 60% over the product lifecycle [27]
Increased customer satisfaction	[21]	N/A
Improved customer relationships/ communications	[1,10,13,20,22,26]	N/A

Table 2
Challenges associated with utilizing PCSs.

Challenges	Authors
Supporting customers' needs in the configuration process	[27,28]
Product modeling and data acquisition	[1,6,10,27]
Errors in the configuration process	[6]
Documentation and maintenance configuration model	[6,10]
Change management	[1]

multiple observations where the change process is observed as it unfolds in real time [31]. This type of study is most suitable when the aim is to explore new ground as the study design allows the researcher to be close enough to the studied phenomenon to discover the causal links among events and constructs [31].

Based on the nature and requirements of longitudinal field studies, this study was designed to investigate and analyze the existing problem of the lack of accuracy in cost calculations and product profitability. The unit of observation [32] was the different projects sold during the 2009–2014 period. The data required for the analysis included the estimated costs for each project sold and the actual cost. Data was collected about the salespersons and the quotations they generated at the company by using Excel spreadsheets and PCS. All data sets refer to 2009, before the PCS was implemented, and then to the 2011–2014 period when a PCS was used at the company. The data set for the analysis was extracted from the company's internal database and verified with specialists at the company.

4. Case study

4.1. Background of the case company

The case company analyzed in this study is a Scandinavian company in the building industry, which manufactures pre-made structural elements for buildings and provides installation services. The company is highly representative as a medium-sized company, which includes manufacturing, installation and maintenance in its business processes. In 2014, the company had around 100 employees and yearly turnover of approximately €17 million. In that year, the company sold 168 projects, and the average turnover per project was therefore €106,158. The company's product portfolio consists of six product families, of which five are standard products and one special.

In 2009, the process of generating quotations in the sales phase and the accuracy of the cost calculations were analyzed. The analysis revealed that the company's methods for accurately calculating costs were inadequate and affected the products' profitability. The results also indicated that the company's current procedure of using Excel spreadsheets to calculate the costs led to numerous errors, which were traced back to human mistakes. Based on this initial analysis, the company decided to invest €150,000 in order to develop a PCS to improve the process of generating quotations in the sales phase. The PCS used at the company was commercial configuration software, which builds on constraint propagation.

The PCS was developed from 2009 to 2010, and by the beginning of 2011, the company had developed a PCS able to handle most of the quotations in the sales phase. Only special products, which are categorized as non-standard solutions or engineered solutions, were not included in the system. Although the company developed and implemented a PCS to support the sales process, organizational resistance to using the system and changing current work procedures resulted in some salespersons still using the Excel spreadsheets to calculate costs for the quotations in the sales phase.

In this study, the impact of utilizing the PCS on the company's ability to make accurate price estimates for the quotations and product profitability was assessed. First, the company's overall performance is analyzed before the system was implemented in 2009 and 4 years after the implementation during the 2011–2014 period. Then the accuracy of the cost calculations and products' profitability in the quotations generated by using the Excel spreadsheets and the PCS were compared.

4.2. Analysis of the company's performance before and after implementation of the PCS

To compare the overall performance before the PCS was implemented (2009) and after the implementation (2011–2014), the contribution ratio (CR) is calculated for each project that was carried out at the company within the timeframe of this research. The CR is calculated as the ratio of the sales price and the contribution margin (CM), where the CM is the difference between the sales and the cost price. The cost prices of the projects are calculated as the sum of expenses, including construction site, subcontractors, materials and salaries. The formulas for the calculations of the CR and the CM are as follows [33]:

$$CR = CM/Sales\ Price \tag{1}$$

$$CM = Sales\ Price - Cost\ Price \tag{2}$$

The deviation in the CR is calculated as the actual CR (calculated after the project was completed when all expenses are known) minus the estimated CR (calculated in the sales phase when the cost is estimated). The formula for calculating the deviation of the CR as follows:

$$DEV_{CR} = CR_{actual} - CR_{estimated} \tag{3}$$

If the real cost of the project is higher than the estimated cost, it results in negative deviation of the CR. Respectively, if the real cost of the project is less than the estimated, it results in positive deviation in the CR. Any deviation in the CR is something companies must be aware of. If the cost is overestimated, the company might lose the customer, and if the cost is underestimated, then revenue is lost.

The projects used for the comparison are from 2009, when only Excel spreadsheets were used to calculate the cost, until 2014. For the 2011–2014 period, the cost calculations were either performed in the PCS or by using Excel spreadsheets. Due to organizational resistance, not all salespersons used the PCS. In Table 3, the company's overall performance for 2009 and the 201–2014 period is shown in terms of number of projects sold, the deviation in the CR and the average profitability.

The analysis showed that the average CR steadily increased from 25.0% in 2009 to 29.0% in 2014. The implementation of the PCS was aimed to improve the company's CR by increasing the accuracy of the cost calculations in the quotations and thus the

Table 3
Overall analysis of the company's performance before the PCS was implemented (2009) and after (2011–2014).

Year	No. of projects	Average DEV_{CR}	Average CR per project
2009	55	−1.5%	25.0%
2011	117	−3.5%	27.2%
2012	90	−1.1%	28.5%
2013	116	−1.0%	28.2%
2014	168	−0.8%	29.0%

profitability of the projects. Furthermore, an additional functionality was included in the PCS that allowed the salespersons to set the desired CR for the project under question from an early stage of the sales process in order to make it easier to reach the goal.

Deviations in the CR also show positive improvements over the period as the average deviation was improved from −1.5% in 2009 to −0.8% in 2014. However, in 2011, the first year the PCS was utilized, the deviations in the CR increased considerably. This increase in deviations can be traced to the fact that the system had not been fully tested before the implementation and the users of the system lacked training. However, as the users became more experienced in using the system and errors were fixed, the PCS started providing valuable results.

This analysis indicates that the calculations are now more precise than before the implementation of the PCS and the company is moving closer to the targeted CR, and, consequently, the products' profitability is increasing. The results also highlight the importance of properly testing the system and training employees before the system is launched and fully functioning to avoid costly mistakes and to avoid resistance to using the system due to a lack of confidence.

4.3. Comparison of cost estimations and profitability between Excel and PCS

In this section, the yearly turnover, the CR of the projects and the deviations of the CR are analyzed and compared in terms of whether the initial quotation created during the sales phase was generated by the Excel spreadsheets or by the PCS. For this analysis the same data is used as explained in Section 4.1 and 4.2. The data acquired from the company's database is used to calculate the turnover and the CR of the projects sold both for the quotations generated through the PCS and Excel. This comparison is possible because the PCS has not been accepted by all salespersons due to organizational resistance. Some still use Excel spreadsheets to generate quotations. The main reason is the lack of change management initiatives and the system being launched before it was fully tested, which resulted in some employees sticking to their old work habits [1].

4.3.1. The contribution to yearly turnover

To increase the understanding of to what extent the PCS is used at the company, the yearly turnover for the projects was compared based on whether the quotation was generated with the PCS or the Excel spreadsheets.

In 2011, the first year the PCS was utilized in the company, the turnover for the products' quotations generated with the PCS was higher than the ones created with Excel spreadsheets. However, in 2012 the turnover for the products' quotations generated by using Excel spreadsheets was higher. In the first year the system was running, the lack of training and errors in the system affected its functionality. However, in 2013, the quotations generated with the PCS contributed more to the yearly turnover, and in 2014, this difference increased even more, indicating that the salespersons were using the system to a greater extent. Fig. 1 shows the yearly turnover for the quotations created in Excel and by using the PCS.

However, no clear trend was identified in the comparison. As can be seen in Fig. 1, in 2012, the projects handled by the salespersons with Excel spreadsheets contributed more to the company's turnover although the PCS had already been implemented. Some salespersons were reluctant to use the PCS in their working processes, as they still used Excel spreadsheets for calculating costs and generating quotations. Second, lack of training and errors in the system in 2011 might have given some salespersons the wrong impression of the usability of the system, which resulted in them not using the PCS in the following year. In

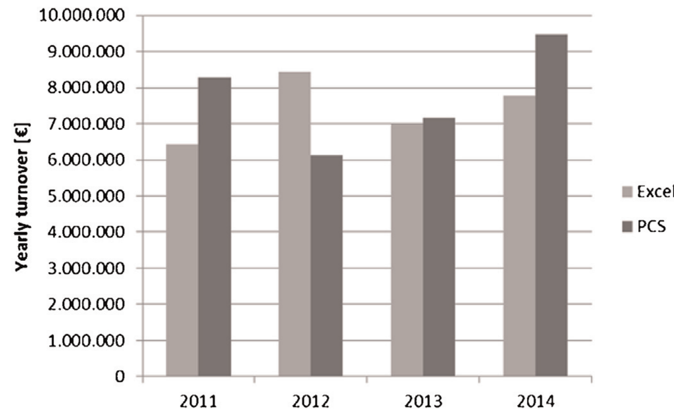

Fig. 1. Comparison of turnover generated for quotations created in Excel and PCS.

detail, in 2011, 52% of the projects were handled with Excel spreadsheets to generate quotations, which corresponds to 47 out of 90 projects. The 2011–2012 period was the initial introduction of the PCS at the company, and the PCS did not include all products at that point; therefore, utilization was by definition limited. During the trial period, the turnover contributed by the projects handled in Excel was higher than the turnover from the projects handled in the PCS, but this changed significantly in the following 2 years. Thus, in the 2013–2014 period, when the company took greater advantage of the PCS, and its utilization was strongly established, the turnover of the projects worked out by using the PCS outnumbered the ones generated with Excel spreadsheets.

Overall, by comparing the yearly turnover of the projects handled through Excel spreadsheets and the PCS, no clear conclusion was reached. Thus, the next step of the analysis focused on identifying and comparing the CR for products sold via Excel and PCS.

4.3.2. Comparison of project profitability

To compare the profitability of the projects, the CR was used as it represents the ratio between sales prices and the CM, and a good indicator of project profitability. As previously explained, the company's goal for all projects is a CR of 30%, as a result of a strategic decision made in 2009 to increase the CR from 25% to 30%. The implementation of the PCS was aimed to reach the targeted CR of 30% for the projects. The analysis of the overall company's performance (Table 3) showed how the CR has increased since 2009. However, to confirm that this can be traced to the implementation of the PCS, a comparison of the CR of the quotations made by using the PCS and Excel spreadsheets was performed. In Fig. 2, the actual CR (calculated based on the actual cost of the projects) is illustrated for the quotations created with the PCS and Excel.

Salespersons who used the PCS contributed a higher CR than those who used Excel spreadsheets. Furthermore, the gap in the CR increased between the salespersons who used the Excel spreadsheets and those who used the PCS. In 2014, the average CR was 29.0%; salespersons who used the PCS had an average CR of 32.1% while salespersons who used Excel spreadsheets had 23.8%. In other words, the salespersons who used the PCS achieved a goal of 30%. The increasing gap between the CR for the quotations generated in the two systems can also be explained as a result of the increased utilization of the PCS and the company's effort to update prices in the PCS instead of the Excel spreadsheets. Finally, special products were not included in the PCS; therefore, to calculate the costs, Excel spreadsheets were always used. Although

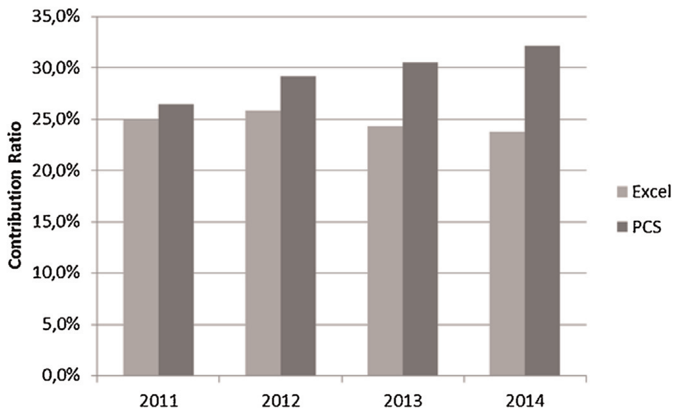

Fig. 2. Comparison of CR for salespersons using Excel and PCS.

those products were not included in the calculations for the quotations made in Excel presented in Fig. 2, they did not contribute significantly to the average CR. For example, for 2014 they affected the CR for the quotations created in Excel by only 0.2%. Therefore, the lower CR cannot be traced to special orders. This result confirms the second proposition formulated in this study: Product profitability increased when the projects are handled through a PCS.

4.3.3. Comparison of the accuracy of the cost calculations

To compare the accuracy of the cost calculations generated in the PCS and Excel spreadsheets, the DEV_{CR} is calculated. The results are shown in Fig. 3.

The CR showed less deviation for the products for which salespersons used the PCS than the CR for the products for which salespersons used Excel spreadsheets, with the exception of 2011. The deviation in the CR for the PCS in 2011 can be explained as a result of insufficient testing and a lack of training, which affected the performance in the first year after the implementation. In the following year, 2012, there was a significant reduction in deviations for quotations created via Excel spreadsheets and,

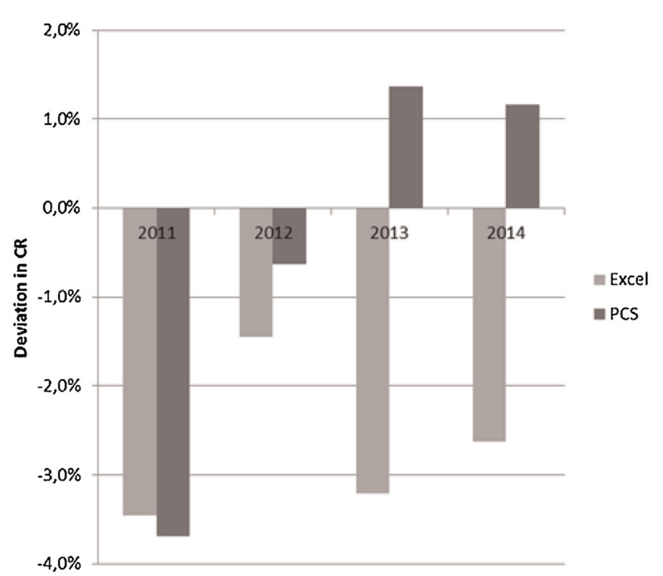

Fig. 3. Comparison of deviations in CR for salespersons who used Excel and PCS.

mainly, for the ones created through the PCS. Moreover, in 2013 and 2014, the deviations in the quotations created by the PCS were positive (1.4% and 1.2%, respectively), while the deviations for the cost calculations generated with the Excel spreadsheets were negative and still quite high (–3.2% and −2.6%). Another possible explanation for the increasing gap between the CRs is the more complete cost calculations via the PCS than Excel spreadsheets. All parts required for every product were included in the PCS, while when the cost estimate was created in Excel spreadsheets, the salesperson might forget to include all of them. As a result, the estimated cost did not include all required parts and was lower than the actual cost, which led to the negative deviation in the CR. The analysis of the performance of the salespersons who used Excel and the PCS therefore indicates that the PCS affected the accuracy of the cost estimates and the CR positively, which supports Proposition 1.

5. Discussion

This work focused on measuring the benefits of implementing a PCS in a CTO manufacturing company. To measure the benefits, the CRs of the products handled in Excel and the PCS were calculated and compared. The comparison revealed that the CR of the products handled via the PCS was higher than the ones in Excel. Taking into account the increase in the CR from 25% to 29%, which is equivalent to €654,000 per year, and the cost of the development of the PCS was €150,000, the annual return on investment (ROI) was 336%. In addition, the accuracy of the quotations generated by the PCS was higher than those generated in Excel.

Regarding the salespersons who were still using the Excel spreadsheets while the PCS was implemented, reasons similar to those identified in the literature review were reported [1,6,10,27]. In detail, the most experienced salespeople in the company were those who were still using Excel in 2014 to generate quotations. They stated that the PCS did not add value to their daily routine as long as it was not updated for the user interface and functionalities and included all relevant products. Therefore, the PCS had to be upgraded with all functionalities in order to be fully accepted and adopted by all employees and enable the company to seize the full benefits of the PCS.

To improve the company's general performance, several factors were identified, which could help the company reduce even further the deviations in the CR and increase the overall profitability of the products. For instance, the company intends to implement a checklist at the end of each configuration in order to ensure that all required information is gathered during the sales phase and is up-to-date. Implementing the checklist will reduce the number of errors made during the sales process. Furthermore, the company plans to increase standardization in their product range, by moving further to modular-based product designs. Regarding the further development of the PCS, the company has decided to invest €140,000 to include more products. Finally, to implement an organizational change [1] and boost utilization of the PCS, all new employees are trained to use only the PCS; thus, the Excel spreadsheets will become obsolete.

6. Conclusions

The aim of this case study was to measure the impact of utilizing a PCS on product profitability and the accuracy of cost estimates. The study resulted in significant improvements in the CR of products sold through the PCS due to the accuracy of the cost calculations. The results from the longitudinal case study confirmed the propositions. In detail, the improved accuracy of the cost calculations and the increased profitability of the products sold via the PCS were demonstrated. The quotations generated by the PCS and Excel for the 2011–2014 period were compared, when the PCS had been implemented and was used to its full potential. The analysis led to the conclusion that the contribution of the PCS is noteworthy, as the performance of the products included in the PCS improved in terms of more accurate cost estimates and improved profitability (Propositions 1 and 2). This could be explained by the fact that the data used in the PCS is updated and all possible solutions are validated before making an offer, the generated quotations include fewer errors and more accurate price estimates than the quotations for products not included in the PCS. However, this study also highlights the importance of fully testing a PCS before making it operational. To this end, as can be seen from the results, the implementation had a negative impact in the first year due to insufficient testing. In addition, the challenges of scoping and utilizing a PCS are discussed in the literature and the empirical evidence here.

This research is the first step in exploring the impact of a configurator on product profitability. Thus, more cases need to be examined, to compare the profitability between projects going through the PCS and outside it and salespersons' performance before and after the implementation of a PCS. By examining more cases, a deeper understanding can be gained, and a more detailed explanation of the correlation between the configuration tools and product profitability can be provided. In this paper, empirical evidence was provided by only one case company. However, the impact registered in this company indicates that there could be significant impacts from implementing a PCS, which have not been previously discussed in the literature. The increase in the CR of the products is important, and the PCS brought significant value to the company. Therefore, this requires further research and additional cases to confirm the underlying correlation between a PCS and an increase in profitability. Future research should include investigation of other benefits of utilizing a PCS, such as its impact on an increase on sales.

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APPENDIX C

Economic Value Creation from Using Product Configuration Systems – A Case Study

K. Kristjansdottir, S. Shafiee, L. Hvam, M. Bonev, A. Myrodia

Abstract. Product configuration systems (PCS) are being increasingly used in industrial companies to enable the efficient design of customized products. The literature describes substantial benefits that companies have achieved from using PCS, such as reduced resource consumption, reduced lead-time, improved quality and increased sales, which should lead to economic value creation in these companies. However, the process leading to this economic value creation has not been addressed much in the literature. Hence, this study quantifies (1) the cost savings from using this system in terms of reduced man-hours and (2) the cost factors in terms of the development, implementation, and maintenance of this system. In addition, the benefits of using PCS are analyzed in terms of outcomes such as increased sales and improved quality of product specifications. This research verifies the benefits of using PCS, which are described in the literature. Further, it contributes to the field by introducing a method to quantify the economic value creation and illustrate how PCS can be used in companies having product portfolios consisting of standard to engineered products.

Keywords: *Information systems, mass customization, product configuration system (PCS), economic value creation, case study*

1. Introduction

In today's business environment, customers are increasingly demanding customized products that can be delivered within a quick turnaround time and at competitive prices [1]. In response to the emerging challenges, mass customization strategies have received increased attention from both industrial practitioners and researchers over the last decades. Mass customization refers to the ability to provide customized products and services with flexibility and at a cost similar to that of mass-produced products [2]. To enable the successful implementation of mass customization, companies need to develop a solution space that can enable robust process design and navigational choice, over the existing systems [3]. One way of achieving mass customisation is by designing more modular products for which a product configuration system (PCS) is used in the customisation process [2]. PCS is used to support design activities throughout the customisation process, during which a set of components and their connections are pre-defined, and constraints are developed to prevent infeasible configurations [4].

The literature describes numerous benefits of implementing PCS to support the specification processes. The specification process can be defined as one that is concerned with generating different product specifications (e.g., quotes, sales prices, bill of materials, CAD models), which normally involves employees from different departments [1]. Companies utilizing PCS demonstrate a better capability in terms of offering a variety of products, improving product quality, simplifying the customer-ordering process, and reducing the complexity of both process and products, in addition to increased product profitability [5–9]. Further, PCS facilitates knowledge sharing, uses fewer resources, optimizes product designs, performs less routine work, ensures timely delivery, reduces the time required to train new employees, and increases customer satisfaction [1,10–15]. The literature confirms that companies can achieve economic value from using PCS [16–19]. However, while the literature explains both the benefits and economic value gained from using PCS, further research is needed to understand the process leading to this value creation and to perform a comparison of the cost savings (e.g., reduced man-hours) and the cost factors (e.g., the development, implementation, and maintenance) of the PCS. To measure the economic value creation, return on investment is used, which is defined as the ratio of cost to benefit and it is a performance measure used to evaluate the efficiency of a number of different investments [20].

The aim of this article is to provide more understanding of the economic value creation from implementing and utilizing PCS. More specifically, the objective of the article is to analyze the cost savings (benefits) and the cost factors so the return on investment can be calculated. Additionally, the processes changes and the product coverage of the PCS are elaborated based on a case company, which is classified as global manufacturing company having product portfolio consisting of standard to engineered products. To address these issues, the following research question is developed:

What is the long-term economic value creation for implementing and utilising PCS in terms of realised cost and cost savings factors?

To answer the research questions, we first determined whether prior research quantifies the economic value creation from implementing and utilizing PCS based on quantification of cost and cost savings (benefits) factors. Additionally, the literature is reviewed in order to define different production strategies in companies making both standard and engineered products and how PCS support these activities. Next, a case study is conducted at a case company, which is a global company producing industrial pumps and utilizes PCS to support their sales and specification processes.

The remainder of this paper is organized as follows. Section 2 presents a literature review, and Section 3 describes the research method. Section 4 contains the main results of the case study analysis. Finally, Section 5 discusses these results, generates the conclusions, and provides the direction for future research.

2. Literature review

In this section, the literature background for the study is presented. First, in terms of PCS, product structure and classification of order fulfilment strategies. Second, the economic value of implementing and utilizing PCS is elaborated. Finally, based on the relevant literature, we establish our research focus.

2.1 PCS and product structure

The configuration task can be described in terms of a pre-defined set of components, which are described by a set of properties (attributes) and their values, connections of the components (ports) and constraints to prevent infeasible configurations [4,21]. PCS can be applied both to support the end-user of the product and/or as an internal tool to increase efficiency by improving the dialogue with the customer and automating the generation of product specifications, e.g., [1,10,12,22].

Aligned with the configuration task companies need to define parts/modules and constraints that ensure only allowed combinations can be selected. Product architecture can be defined as (1) the arrangement of functional elements; (2) the mapping from functional elements to physical components; (3) the specification of the interfaces among interacting physical components. [23]. The highest degree of modularity can be defined when each functional requirement can be directly connected to one module and where there are few interactions between the modules, making it possible to change specific modules without affecting other parts of the design [24].

The customer-order-decoupling point (CODP), distinguishes between the work carried out before and after the customer places the order and is commonly defined to classify companies' order fulfilment strategies [1]. Thus, the CODP can also be defined in terms of the separation of decisions made under uncertainty from decisions are made based on customers demand, where the position of the CODP determines the optimal balance between the productivity and flexibility of companies [25]. Order fulfilment strategies can be classified in terms of make-to-stock (MTS), assemble-to-order (ATO), make-to-order (MTO) and engineer-to-order (ETO) (Figure 1) [26].

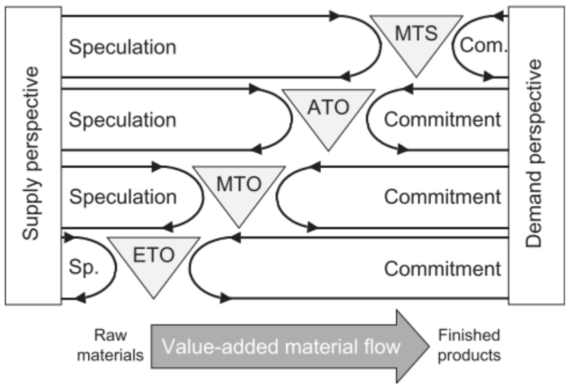

Figure 1. Customer order decoupling point (COPD) and classification of production strategies [26]

Aligned with the definition of different order fulfilment strategies used in companies the application of PCS will be affected. Where in companies that can be classified in terms as MTO and ATO there is a defined solution space where modules and components are combined according to pre-defined constraints. Solution space can be defined in terms of all the product attributes a company offers to cover diverse customers' needs [3]. However, in ETO companies the solution space is not as defined where a number of possible configurations can be close to infinite [27]. Thus, in ETO companies, PCS are usually gradually implemented where they support a specific part of the specification process (e.g. sales or engineering) or a subset of the product families. That is since it requires significant work to acquire and structure the product knowledge needed to be modelled into the PCS due to the complexity of products and the specification processes. Therefore, it may not be profitable to formalize the complete product knowledge, especially if the sales volumes are low [5,28].

2.2 Economic value creation from implementing and utilizing PCS

The literature on PCS describes several benefits achieved from using these systems; in particular, three benefits are widely discussed and are considered to be directly linked to cost savings: (1) the reduction in resource consumption (man-hours) and lead time, (2) improved quality of product specifications, and (3) increased sales. Second, previous works have addressed the cost factors in relation to PCS, which are defined based on the cost of developing, implementing, and maintaining the systems. Third, the literature has addressed and economic value creation where the return on investment is quantified.

2.1.1 Cost savings related to the benefits of implementing PCS

Previous works have shown that using a PCS results in *reduced man-hours and lead time for generating product specifications* [5,12,16,18,19,29–42]. Even though this benefit is the most commonly mentioned and quantified in previous studies, the literature does not explain the extent to which reduced man-hours and lead time result in direct cost savings. Table 1 summarizes the studies that quantify the reduction in man-hours and lead time due to the utilization of PCS.

Table 1. Works that quantified a reduction in man-hours and lead time due to the utilization of PCS

Research Work	**Method**	**Contribution**
Forza and Salvador [19]	Case study of one company	- The PCS reduced the amount of time required for manned activities in the tendering process from 5–6 days to 1 day.
Forza, Trentin and Salvador [32]	Case study of one company	- The average time needed to make an offer reduced from 1–2 days to a few hours, and for technical specifications, from 2.5 days to a few minutes.
Haug, Hvam and Mortensen [33]	Survey	- On average, the lead-time required to generate proposals are be reduced by 83.7%. - The man-hours in the configuration process are be reduced by up to 78.4%.
Heiskala, Paloheimo and Tiihonen [34]	Case study of two companies	- The average selection time reduced from 2 hours to 6 minutes. - The throughput cycle reduced from 6 days to 1 day.
Hvam et al. [37]	Case study of one company	- The lead-time required to generate tenders reduced from 15–25 days to 1–2 days. - The amount of time required for engineering in the quotation process reduced from 5 weeks to 1–2 days.
Hvam [38]	Case study of one company	- The real working time for preparing offers and production instructions was close to 0. - The delivery time reduced from 11–41 days to 1 day.
Hvam [39]	Case study of one company	- The resources required to generate the quotations reduced by 50%.
Hvam et al. [40]	Case study of four companies	- The lead-time required to generate an offer reduced by 94–99%. -The resources needed to create product specifications reduced by 50–95%.

Improved quality due to more accurate product specifications is another benefit of PCS that is frequently described in the literature [5,7,12,16–19,29–43]. The improvement in quality can be attributed to the reduced number of errors in product specifications. Table 2 summarizes the research that quantifies improvements in quality as a result of utilizing PCS.

Table 2. Literature that quantifies improvements in data quality due to the use of a PCS

Research Work	Method	Contribution
Forza and Salvador [5]	Case study of one company	- Errors in configurations declined to almost 0.
Forza and Salvador [19]	Case study of one company	- The correctness of product information increased to almost 100%.
Heiskala, Paloheimo, and Tiihonen. [34]	Case study of two companies	- Quality of specifications improved from 60% to 100%, and specifications were always ready for manufacture (without errors). - The pricing accuracy improved from 80% to 100%.
Hvam [38]	Case study of one company	- The number of assembly errors reduced from 30% to less than 2%.
Sviokla [18]	Case study of one company	- The accuracy of product specifications improved from 65–90% to 95–98%.
Yu and Skovgaard [43]	Case study of one company	- The configuration accuracy reached 100%.

Previous research also describes how *increased sales* can be achieved as salespersons are able to respond to all customers due to the increased throughput enabled by PCS [35,36,39,40]. Even though increased sales are mentioned as a benefit of utilizing PCS, the impact remains largely unaddressed. The literature has also not quantified the relation between PCS and increased sales.

2 2.2 Cost factors in relation to PCS

Few researchers have addressed the cost factors in relation to PCS. Forza and Salvador [5] mention that a high investment in terms of man-hours might be needed to introduce a PCS into a company. According to Hvam [39], the cost of developing and implementing a PCS is approximately USD 1 million with operating costs of USD 100,000 per year. These costs are compared with the usage of the system, which is estimated to generate a budget and detailed quotations, where the total sales price is USD 500 million. However, Hvam [39] does not link the direct cost savings achieved by utilizing PCS to the actual cost; the cost is compared to the sum of the total sales price in the quotations generated by the PCS. Table 3 summarizes the previous research that quantified the cost factors in relation to PCS.

Table 3. Literature that quantifies cost factors in relation to a PCS

Research Work	Method	Contribution
Hvam [39]	Case study based on one company	The overall cost of developing and implementing a PCS is approximately USD 1 million, and the operating cost is around USD 100,000 per year.

2.2.3 Return on investment from using PCS

Few researchers have elaborated on return on investment in relation to PCS. Barker et al. [16] discuss not the return on investment but the net return of the system, which is estimated to be in excess of USD 40 million. In another study, Fleischanderl et al. [17] report that the PCS in their case company achieved a complete return on investment within its first year of operation. Finally, Forza and Salvador [19] describe how small enterprises can benefit from implementing PCS, where not only a rapid return on investment but also a competitive advantage can be anticipated. Table 4 summarizes the research that quantifies the savings accrued from using a PCS.

Table 4. Literature that quantifies the return on investment from a PCS

Research Work	Method	Contribution
Barker et al. [16]	Case study based on one company	- Overall net return of the PCS is over USD 40 million.
Fleischanderl et al. [17]	Case study based on one company	- Using the PCS to support the complete configuration process was shown to reduce products' lifecycle cost by up to 60%. - The PCS had a positive return on investment within its first year of operation.
Sviokla [18]	Case study based on one company.	- Savings were estimated at USD 15 million, plus other savings from previous years given that an expensive testing phase is not required.

2.1.3 Summary

Thus, a number of works in the literature have quantified the benefits of PCS in terms of the reduced man-hours, lead-time, and quality of product specifications. However, the research does not link those benefits to the actual costs accrued in these companies. Only Hvam [39] mentions and quantifies the cost of development and implementation of a PCS. Further, in terms of economic value creation, only Barker et al. [16] quantifies the net return, and Sviokla [18] the savings; however, they do not break down the net return into cost savings and cost factors. Thus, the quantification of cost savings and cost factors related to PCS and the return on investment, referred to here as economic value creation, remains unaddressed in the literature. To understand the circumstances under which companies can achieve this economic value creation, this article also elaborates on the process changes undertaken and the product coverage of the system in the case company.

3. Research Method

To examine the economic value creation this study presents a case company, which operates worldwide and has a mixed product portfolio varying from standard and engineered pumps where the PCS is used to support the sales process. The company has used PCS since 2001 that, which allows analysis of the economic value creation of using PCS. Further, both access to the company and data allows this analysis to be done within industrial settings. For the analysis presented in this article two product families are selected. The analyses are scoped to include data both covering cost and cost savings factors. The cost is divided into development, implementation and maintenance. The development took place over a two-year period, and the implementation is considered as a one-time pay-off when the system is launched. Further data for the maintenance and the cost savings factors are gathered for a five-year period. The data gathering was carried out by the project team over a period of five months.

The main strength of case research is defined in terms of the phenomenon can be studied in its natural settings, allowing the question of "why", "what", and "how" [44,45]. This motivates the case research to answer the presented research question in this study of "what". Further, a case study is defined as "a study that investigates a contemporary phenomenon (the 'case') in depth and in its real-world context, especially when the boundaries between phenomenon and context may not be clearly evident” [46]. The phenomenon investigated in this study is the economic value creation of PCS where the context is global manufacturing companies producing a standard to engineered products. Further, case studies enable a deeper understanding of the relationships among the different variables and phenomena that are not fully examined or understood [45].

Single cases allow the phenomenon to be studied in more details where the main disadvantages are described in terms of generalizability [44]. By using multiple cases, the limitation of generalizability can be overcome but may not allow as in-depth study of the phenomenon as more resources are required [44]. As by using multiple cases studies, it shows whether the findings are simply distinctive to a single case or consistently replicated over several cases [47]. Thus, as this is defined as an explorative study, a more focus is set towards getting an in-depth understanding of the case company and the utilization of the PCS, where multiple data sources are used in this research to triangulate the data and overcome the limitation of using only one data collection method [48]. Further, the literature reflects on the benefits and their quantification, which allows comparison to other previous studies in order to validate the results presented.

To gather data for these analyses meetings were set up with the main stakeholders from the relevant departments at the company. This includes employees from the local sales offices (LSO), customer support units (CSU), production, distribution, development & engineering, and product & program management. The number of employees interviewed varied from 2-6 within each of the departments, and wherein total 20 employees are interviewed, which included both managers, engineers, and specialists. Additionally, two workshops were held for the main stakeholders from the departments previously mentioned. The first workshop aimed to introduce the purpose of the study and get input how the data gathering should be scoped and organized. In the second workshop, the findings were presented, discussed, and verified by representatives from each of the departments. Finally, data was retrieved from internal systems at the company. Table 5 summarizes the sources of data used in the analysis.

Table 5. Data sources used in the research

Required data	**Data source**
Process flow description (Before and after implementing the PCS)	Interviews
Time required to generate specifications (Before and after implementing the PCS)	Interviews Project reports
Quantity of sales	ERP system
Extent of reduction in errors regarding generated specifications	Interviews Study of the quality of the specifications
Increase in sales	Interviews
Cost of the PCS (development, implementation, and maintenance)	Interviews Project reports

3.1 Data analysis

Based on interviews the processes flow before and after the implementation of the PCS are drawn up in order to provide a more fundamental understanding of the process changes when implementing a PCS and to set the presented analysis into context.
The sales number are extracted from the companies ERP system for each of the year analyzed for both product families. The presented sales numbers only include CTO and light ETO products as they are supported by the PCS. Thus, sales numbers of standard and heavy ETO products are not included as the sales process for these products is not affected by the PCS. Further, the classification of CTO (configured either by LSO or CSU) and light ETO products are only available for one of the year. Thus the same ratio between the years is thus used for all of the analyzed years. This can be done as the ratio is rather constant between years even though the sales number differs.

To determine the lead-time and the man-hours, with respect to time saved in the sales process, project reports and interviews are used. The activities within each of the departments (LSO, CSU, production, distribution and development & engineering) are first identified and then minimum and the maximum time is assigned. This is done to take into the calculations that different factors can influence the time consumption, e.g., the experience of the salesperson and complexity of the orders. To calculate the cost and the cost savings factors two assumptions are made, which are related to the hourly rate of 50 € and a workweek of 37 hours. The hourly rate is based on the internal rate used at the company and where the workweek of 37 hours is the standard in Denmark where the company's headquarters are located. These numbers might not be generalizable outside of Denmark, and if to repeat this analysis in companies located in other countries these assumptions should be adjusted.

The quality of the specifications is measured only for CSU at the company's headquarters and where analysis was only available for one year. Thus a comparison before and after the implementation of the PCS could not be conducted. The analysis include returns of the production lines, which are dived into seven categories, which include test data, basis data, error reported, name plate data, bill of materials, other errors and operations. Each time an error is noticed it is registered whether the entry is created manually or by the PCS. Additionally, interviews are used both to validate if the PCS supports improved data quality and increased sales.

4. Results

4.1 Background

The case company introduced in the study has a world-leading position in pump manufacturing. The company's headquarters are located in Denmark, where over 16,000 employees' are employed worldwide and with annual production of more than 16 million pumps on a yearly basis. The company offers high-quality solutions that can be fitted to different industries. The company first introduced PCS in 2001, where SAP is used as a platform to build the configurators. Since then around 20 new PCS have been introduced at the company. The market environment is highly competitive, and thus, delivery time and cost are critical. The main motivation for implementing the PCS was to reduce the time required to respond to customer inquiries and thereby increase the company's overall competitiveness.

The PCS is used internally at the company where both the local sales offices (LSO) and the customer support unit (CSU) at the company's headquarters use the system. The LSO operate globally and are responsible for all interactions with customers during the sales process. In total, 43% of the LSO have access to the PCS, which allows them to configure products to a greater extent without having to contact CSU at the company's headquarters. In cases where the LSO do not have access to the PCS, CSU performs the configuration while the LSO interfaces with the customer.

Prior to the implementation of the PCS, the company improved standardization of the product families analyzed in the study, and thus they were good candidates to be supported by the PCS. Both of the product families have predefined configurations, referred to as CTO products that are fully supported by the PCS. In cases where the customer's requirements exceed the coverage of the PCS, the CSU department creates the product specifications manually. Depending on the degree of customization, products are manually created either partially or fully. In the case of partial manual creation, CSU uses data from similar configured products in the PCS, and only a few attributes are created manually. The result is termed as a Light ETO products. Fully manual creation applies when the customer's requirements are very specialized and cannot be supported by the PCS. These are termed as Heavy ETO products. Finally, the company also offers standard products, which are classified as a predefined range of configured products that can be selected from.

4.2 Changes in the product specification process

This section elaborates on the product specification process before and after PCS implementation.

4.2.1 The product specification process before PCS implementation

Before the PCS was implemented, the generation of product specifications involved two different scenarios, which are defined based on standard and ETO products. The first scenario relates to standard products (Figure 2). In this case, a customer orders products that are available on the company's homepage and in different product catalogues through one of the LSO. If the customer is unable to find the product they need, the sales office makes recommendations. For standard products, all product specifications are available.

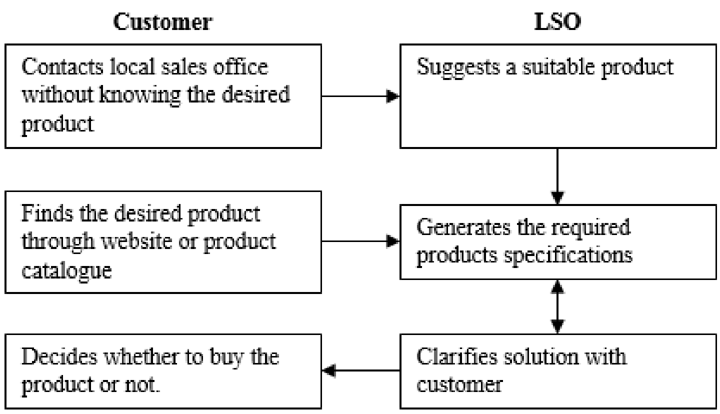

Figure 2. The product specification process for standard products

In the second scenario, customers order non-standard products, including light and heavy ETO products (Figure 3). This requires the involvement of CSU in the sales process, which can result in time-consuming interactions between the customer, the LSO, CSU and the customer. In these cases, the product specifications are generated manually, where the engineering department and the production department are also involved.

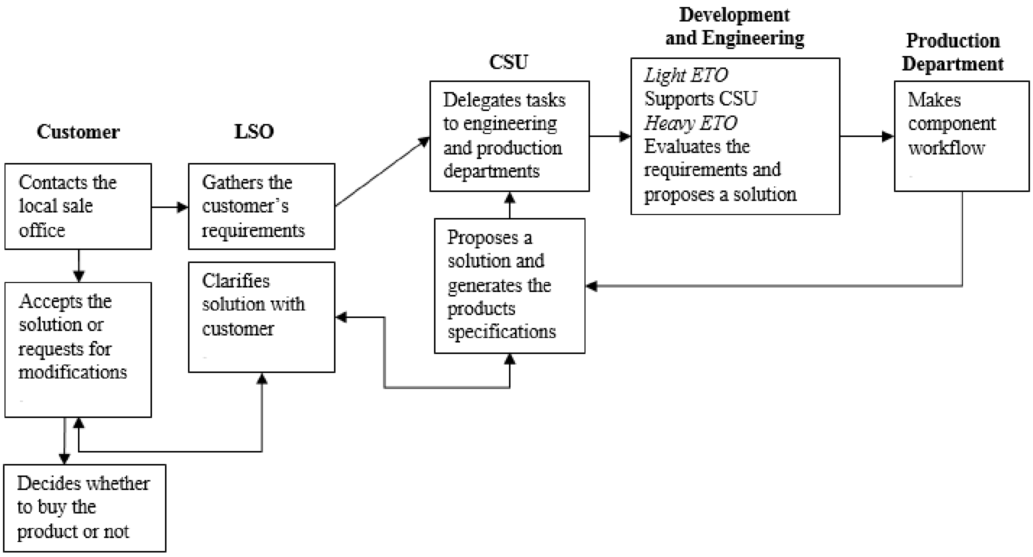

Figure 3. The product specification process for non-standard (light and heavy ETO) products before PCS implementation

The time taken to respond to the customer is one of the main criteria based on which customers decide whether to order a product. A large number of orders processed by the CSU department at the company's headquarters was causing a severe bottleneck in the product specification process, due to which customers had to wait up to weeks to receive a response. To address these challenges, the company decided to introduce a PCS to support the product specification process for light ETO products. As the PCS did not affect the product specification process for standardized and heavy ETO products, this study will not further discuss these product types.

4.2.2 The product specification process after PCS implementation

The PCS supports the configuration process for light ETO products, which are further divided into light ETO and CTO products. The CTO products were introduced as a part of the standardization project of the product families, which was done prior to the implementation of the PCS. This section presents two scenarios, namely, the configuration process for CTO products and that for light ETO products.

CTO products are configured either by the LSO or by CSU. For the LSO that have access to the PCS, they can independently configure the products, generate product specifications, and send them to the customer. However, in cases where the LSO do not have access, the customer's requirements are sent to the CSU, which configures the product via the PCS. The CSU then sends the product specifications back to the LSO, which forwards them to the customer. Figure 4 illustrates the product specification process for CTO products when supported by the PCS.

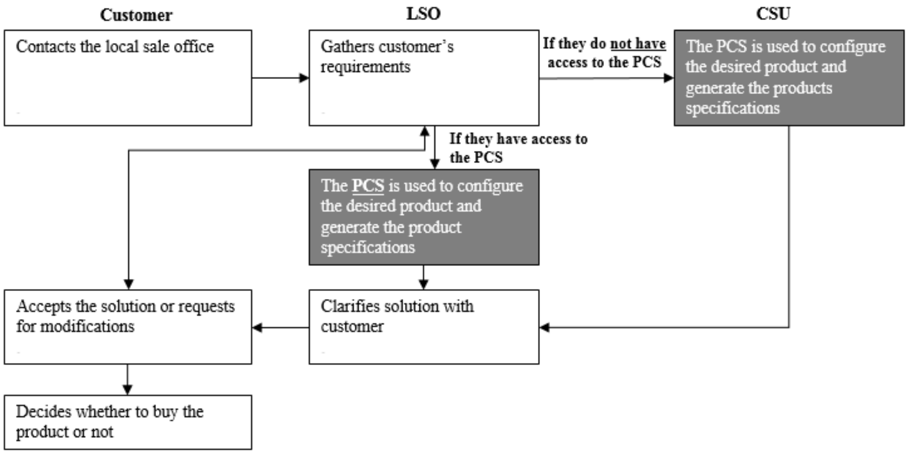

Figure 4. The product specification process for CTO products after PCS implementation

In the case of light ETO products, the customer requirements exceed the solution space of the PCS. In such cases, the LSO require the assistance of the CSU. The CSU can accordingly delegate the necessary tasks to other departments. The product specifications are created partly manually and partly automatically with the support of the PCS. Figure 5 describes the product specification process for light ETO products supported by the PCS.

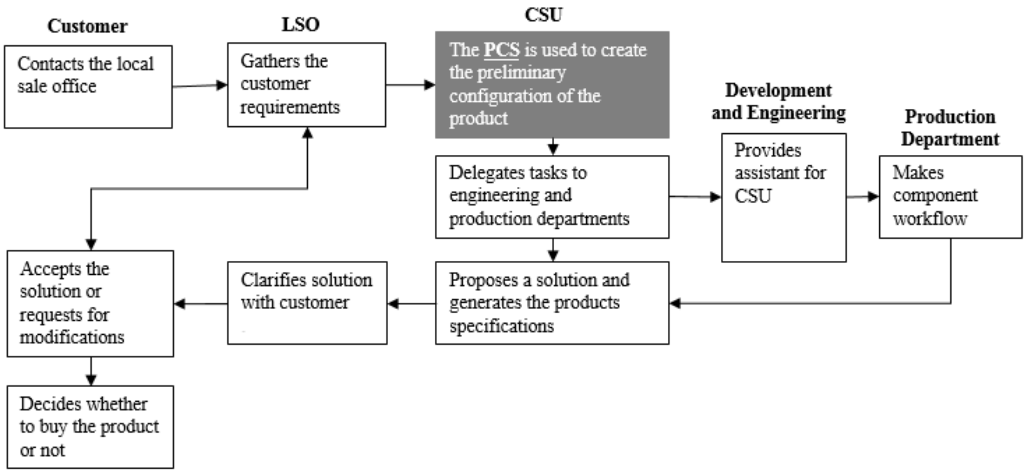

Figure 5. The product specification process for light ETO products after PCS implementation

4.3 Economic value creation from using the PCS

This section will quantify the cost savings factors and the cost factors in order to identify the economic value creation from using the PCS over a five-year period.

4.3.1 The main cost savings factors from using the PCS

This article quantifies the cost savings factors pertaining to resource consumption and lead-time, improved quality of product specifications, and increased sales. The following sections elaborate on the quantification of the above cost savings factors based on data that includes a five-year period.

The impact of applying the PCS on resource consumption and lead time

To estimate the impact of PCS implementation, the quantity of product sold over a five-year period is compared to the amount that would have been sold if the PCS were not implemented. To quantify the cost savings, resource consumption is evaluated both when the process was and was not supported by PCS. The time spent configuring different products can vary due to a variety of factors, such as employee's experience and product complexity. Therefore, the minimum and maximum times required to generate the product specifications are considered in the calculations presented in this section (Appendix 1). Table 6 presents the time required to create the configuration and generate specifications for different products.

Table 6. Time required to respond to customer orders for CTO and light ETO products

Product types	**CTO**	**CTO**	**Light ETO**
Responsible for the configuration	**LSO**	**CSU**	**CSU**
Sales offices *(hours)*	0.39	0.19	0.19
CSU *(hours)*	-	0.27	1.10
Development and Engineering *(hours)*	-	-	0.54
Production *(hours)*	-	-	0.38
Distribution *(hours)*	-	-	0.07
Total man-hours *(hours)*	**0.39**	**0.46**	**2.28**
Quotation lead time *(days)*	**2**	**5**	**9.5**

The cost savings are calculated by comparing the time consumption of different products before and after PCS implementation. Since all CTO products were treated as light ETO products prior to implementing the PCS, the time required to generate specifications for these products is used to calculate how much time the product configuration would have taken if not supported by the PCS. To make the calculations more conservative, the analysis assumes that no savings are gained in the case of light ETO products as they are only partially supported by the PCS. Table 7 shows the total average resource consumption (man-hours) when the configuration process was and was not supported by PCS.

Table 7. Man-hours required to respond to customer orders before and after PCS implementation

	With PCS			**Without PCS**
Product types	**CTO**	**CTO**	**Light ETO**	**Light ETO**
Responsible for the configuration	LSO	CSU	CSU	CSU
Average time per order (hours)	0.39	0.46	2.28	2.28
Total quantity sold over a five-year period (pieces)	175,699	66,553	23,960	266,212
Total time spent on orders over a five-year period (hours)	68,815	30,503	54,669	607,407
Weighted average of the total man-hours spent on orders over a five-year period (hours)	**153,988**			**607,407**

As Table 7 shows, the resource consumption for generating quotations reduced significantly; 453,419 man-hours (75%) were saved due to the implementation of the PCS over a five-year period. Thus, the company saved 22,670,971 € in direct salary costs in the customer order process over the five-year period. PCS implementation also impacted the lead-time for generating quotations, as shown in Table 8.

Table 8. The quotation lead-time (days) before and after PCS implementation

	With PCS			**Without PCS**
Product types	CTO	CTO –	Light ETO	Light ETO
Responsible for the configuration	LSO	CSU	CSU	CSU
Average lead-time (days)	**2**	**5**	**9.5**	**9.5**
Total quantity sold over a five-year period (pieces)	175,699	66,553	23,960	266,212
Weighted average of the quotation lead-time per order (days)	**3.4**			**9.5**

As shown in Table 8, the average lead-time for generating quotations reduced from 9.5 days to 3.4 days, which means that 6.1 days (64%), on average, were saved per quotation generated when the PCS was used.

Improved quality of product specifications

To measure whether the quality of the product specifications improved after PCS implementation, the number of errors were measured based on returns of the production lines, which are dived into seven categories, which include test data, basis data, error reported, name plate data, bill of materials, other errors and operations. The errors were then divided based on whether they were caused automatically by the PCS or manually by the employees. This analysis covers all the product specifications generated by CSU at the company's headquarters. This department is responsible for generating quotations both fully automatically (CTO), partially automatically (light ETO), and fully manually (Heavy ETO). Manual work is required when the requirements exceed the solution space of the system (light ETO = partially manual and heavy ETO = fully manual). Figure 6 presents the results of the analysis for a one-year period.

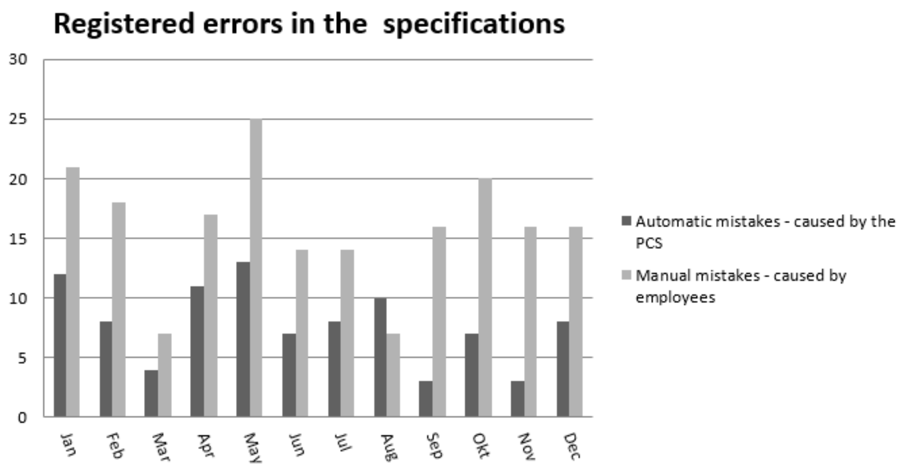

Figure 6. The number of errors reported over a year that was caused by manual mistakes and the PCS

In most cases (except in August), the specifications generated by the PCS have fewer errors per month than those that were generated manually outside the PCS. When the requirements exceed the solution space in the PCS, the specifications need to be generated manually. This comparison, therefore, has limitations, as the complexity of the products is higher when the specifications are generated manually. Specialists (employees from sales and production) from the company confirmed, through interviews, that the PCS leads to higher data quality due to a standardized and guided structure. Moreover, the specialists explained that the errors in the specifications generated by the PCS were not caused by the system itself but, in most cases, by the incorrect input. Therefore, it can be assumed that if the PCS did not support generating specifications, the number of errors would be even higher.

Increased sales due to faster response time

Time and cost are critical factors based on which customers decide whether to purchase from a given company. Thus, it is assumed that increased responsiveness in the customer order process can lead to increased sales. Increased responsiveness is measured by the productivity of employees and the lead-time in responding to a customer's order.

The findings show that responding to the same number of orders over a five-year period (266,212 pieces) would require 153,988 man-hours with the PCS and 607,407 man-hours without the PCS. Thus, the PCS helps achieve a productivity increase by a factor of 3.94. Consequently, it can be assumed that 3.94 more resources became available to handle additional customer orders. As previously explained, before the implementation of the PCS, the CSU became a bottleneck in the sales process due to the high number of orders being processed by the department. However, after the PCS was implemented, the number of orders that reached CSU reduced significantly, resulting in increased productivity. Further, the time taken to respond to customer orders reduced significantly (from 9.5 days to 3.4 days, or by 64%). This should, in turn, lower the threat of losing customers to a competitor due to insufficient response time. Even though there is no solid evidence that the use of the PCS led to increased sales, this assumption is supported by the study findings. These findings—that the implementation of the PCS stimulated additional sales due to increased responsiveness—were verified by specialists at the case company.

4.3.2 The main cost factors of the PCS

This section elaborates on the different cost factors associated with the development, implementation and maintenance of the PCS. A number of different stakeholders are involved in development and implementation; after developing the PCS model, it needs to be tested, training sessions need to be held, and licenses must be bought in advance. Finally, both the system itself and the product data needs to be maintained to ensure that they are up to date and aligned with the companies offerings.

To render the calculations comparable with those previously described for cost savings, the maintenance cost was calculated over a five-year period. In addition to the maintenance cost, the development cost, which is spread over a two-year period and the cost of implementation, was considered. Table 9 presents the individual cost factors, which are discussed in detail later in this section.

Table 9. Cost factors associated with developing (two-year period), implementing, and maintaining the PCS (five-year period)

Cost elements associated with the PCS		Amount	Unit
Development			
Weekly workload		88.80	Man-hours
Duration of development (over a two-year period prior to PCS implementation)		104	Weeks
	Total	9,235	Man-hours
	Total	461,760	€
Implementation (Training and Software)			
Estimated total		300,000	€
Maintenance of the PCS			
Weekly workload		92.50	Man-hours
Duration of maintenance		2	Years
	Total	24,050	Man-hours
	Total	1,202,500	€
Maintenance of product data			
Weekly workload		34.00	Man-hours
Duration of maintenance		5	Years
	Total	8,840	Man-hours
	Total	442,000	€
Total cost of development, implementation, and maintenance		**2,406,260**	**€**

Cost of development and implementation

There are several roles and responsibilities associated with the development and implementation of the PCS. However, most of the workload was handled by two product configuration engineers, who spent 80% of their time on development, and a product data engineer supervisor, who spent 20% of his time. Other responsibilities required less than 10% of the employees' weekly workload, but when considered together, one person was required to spend 60% of his or her time on the project. Therefore, in total, about 88.8 man-hours per week were spent in developing the PCS model. The development took two years, requiring a total of 9,235 man-hours.

PCS implementation also requires that the necessary training is conducted at different LSO. One person was responsible for conducting training on both the PCS and the ERP system at the company. The cost of implementation and software, including licenses, maintenance and upgrades, was estimated to be around 300,000 €.

Cost of maintenance

Besides the work required for development and implementation, another factor that should be considered is the data maintenance of PCS models, which includes both the PCS model and the product data.

Two full-time persons and one person that spent 50% of his/her time were allocated the task of maintaining the PCS models. The weekly workload was therefore estimated to be 92.5 hours; over a five-year period, an estimated 24,050 man-hours were spent on software maintenance.

Data maintenance mainly covers product-specific data at three different levels: the sales offices, production sites, and distribution centres. At each level, there is at least one product data engineer working in close collaboration with the configuration engineers, as product-specific data is constantly updated. The amount of work required to maintain the PCS at the sales offices and distribution centres was relatively low, estimated at 0.5% of the total workload for each location. In this case, the production facilities had to allocate additional resources toward data maintenance. An estimated 34 man-hours per week were required to maintain product-specific data. In total, around 8,840 man-hours would be required over the five-year period.

5. Discussion and conclusion

The study findings describe the economic value creation from using a PCS in a case company. By comparing the direct cost savings from the reduced man-hours to the direct cost of developing, implementing, and maintaining the PCS, the PCS was concluded to be highly beneficial for the case company across the five-year period analyzed. Furthermore, this study provides insight of how PCS can be used in companies both producing standardized and highly engineered products. The analyses revealed that the case company saved 453,419 man-hours over a five-year period by utilizing the PCS, which corresponds to 75% reduction of man-hours used in the sales process. This is aligned with other research, which has also reported significant time reduction of maned activates, [e.g., 19,33,37,40]. Further, the lead-time for answering the customer is also reduced on average from 9.5 to 3.4 days, or by 64%. Other researchers have also quantified this, where a significant reduction of lead-time is reported, [e.g., 32,33,40]. Additionally, evidence of improved quality of the specifications when supported by PCS and increased sale is identified as a result of utilizing the PCS.

The direct cost factors were divided into three groups: the cost of development, implementation and maintenance. Development of the PCS was performed over two years and cost 461,760 €, and implementation costs totalled 300,000 €. The maintenance is divided into the maintenance of the PCS and of the product data. Over a five-year period, the cost of maintenance was estimated to be 1,202,500 € for the PCS and 442,000 € for the product data. Thus, in total the cost of the PCS for the two product families considered in the study is 2,406,260 €. The cost factors related to PCS are discussed by a few researchers [5,39]. Hvam [39] calculates the cost of development and implementation of a PCS to be $ 1 million and operating costs to be about $ 100,000. However, in that study, the development cost is higher while the maintenance cost is lower compared to the analysis presented in this study. There, can be several factors to explain this, e.g., ongoing development in the maintenance phase, the complexity of the data that needs to be managed, changes in the product design. As in Hvam [39], the cost factors are not broken down it makes it difficult to find the underlying difference.

Based on the findings presented in this study it can be concluded that the PCS is highly beneficial for the company. Where over a five-year period, the company saved 20,264,711€, with an 842% return on investment for the PCS over the five years analyzed. Further, if the previously described benefits of using PCS were interdependent, even greater value creation would be possible. There are several examples of how these benefits can interact: First, fewer errors in the product specification would lead to additional savings in resource consumption and reduced lead time, as the errors do not have to be corrected. Second, using a PCS can enable employees to engage in a better dialogue with customers, which would also reduce resource consumption and lead-time. In this case, fewer resources would be required to work on the product specification, creating additional time that can be used to undertake specialized orders and improve the product platform Third, reduced lead-time could also result in increased sales because it reduces the risk of the customer going elsewhere since time is a competitive factor. In this manner, higher value creation can be identified by the use of PCS; in other words, the economic benefits from the actual value created by PCS might be even higher.

The findings of this research provide a more fundamental understanding of the economic value creation and offer a method to evaluate the value creation; as such, the findings are significant not only of interest to the research community but also for practitioners. Companies with a product portfolio-comprising standard to engineered products can therefore potentially enjoy significant economic value creation by using PCS, in addition to improving the standardization of their product range by supporting the product specification processes for CTO and light version of ETO products. The study illustrates how PCS can be used to support the product portfolio partially. This is also aligned with the literature, where it is described that it might not be economically feasible to have the PCS supporting the most complex products especially if the sales volume are low [5,28].

This research constitutes the first step toward analyzing the actual economic value creation from using PCS. The authors recognize the limitation of the study findings as they are based on case study of one company, which may lead to findings that are too narrow in their application [49]. Thus, it is not argued that the findings of the cost and the cost savings factors are generalizable. However, the approach to the PCS setup and commercial configuration platform (SAP in this case) should be applicable to others manufacturing companies making both standard and engineered solutions. Further, the article presented in detailed manners how the economic value creation from implementing and utilizing PCS can be calculated, which can be used in other companies. In order to find a benchmark for the economic value creation by using the return on investment from implementing and utilizing PCS further studies are needed in addition to criteria under, which circumstances the benchmarking is valid. This would be beneficial not only to the research community but also to practitioners and suppliers of PCS software.

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Appendix 1

	CTO		**CTO**		**Light ETO**	
Responsible for the configuration	LSO		CSU		CSU	
	Min	*Max*	*Min*	*Max*	*Min*	*Max*
Distribution	50%	50%	50%	50%	-	-
Sales offices *(hours)*	0.20	0.58	0.13	0.25	0.13*	0.25*
CSU *(hours)*	-	-	0.20	0.33	1.00**	1.50**
Development and Engineering *(hours)*	-	-	-	-	0.08*	1.00*
Production *(hours)*	-	-	-	-	0.03***	7.00***
Distribution *(hours)*	-	-	-	-	0.05*	0.08*
Total man-hours weighted average *(hours)*	**0.39**		**0.46**		**2.28**	

* Distribution min 50% max 50%
** Distribution min 80% max 20%
*** Distribution min 95% max 5%

	CTO		**CTO**		**Light ETO**	
Responsible for the configuration	LSO		CSU		CSU	
	Min	*Max*	*Min*	*Max*	*Min*	*Max*
Distribution	50%	50%	50%	50%	50%	50%
Quotation lead time *(days)*	1	3	3	7	7	12
Quotation lead time weighted average *(days)*	**2**		**5**		**9.5**	

APPENDIX D

The main challenges for manufacturing companies in implementing and utilizing configurators

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Abstract. Companies providing customized products increasingly apply configurators in supporting sales and design activities, thus improving lead-times, quality, cost, benefits perceived by customers, and customer satisfaction. While configurator advantages are substantially investigated, the challenges of implementing and utilizing configurators are less often considered. By reviewing relevant literature, the present study first categorizes the main challenges faced by manufacturing companies when implementing and utilizing configurators. Six main categories of challenges are identified: (1) IT-related, (2) product modeling, (3) organizational, (4) resource constraints, (5) product-related, and (6) knowledge acquisition. Second, through a survey the importance of those categories of challenges is assessed and the specific challenges within each of those categories are highlighted. The results of the survey, which studies manufacturing companies that use configurators in providing customized products, offer new insights into the importance of these categories of challenges. The findings contribute to the research on manufacturing companies' utilization of configurators and raise awareness of the main challenges associated with their implementation and use.

Keywords: *information technology, configurators, mass customization, challenges, explorative survey*

1. Introduction

In today's business environment, customers increasingly demand customized products with short delivery times, adequate quality, and competitive prices [1,2]. As one means of responding to those demands, mass customization strategies have attracted increased interest from both practitioners and researchers. Mass customization refers to an organization's ability to provide customized products and services that fulfil each customer's idiosyncratic needs without considerable trade-offs in cost, delivery time, and quality [3–5]. An important support in reaching this ability are configurators, which are information systems that support the specifications of the product configuration as well as creation and management of configuration knowledge [6]. Configurators can support the interaction with customers directly or through a salesperson, thus presenting the product offer, collecting the customer requests, and producing tenders (i.e., quotations) [2,7]. Configurators can also support the translation of commercial product specifications into product documentation needed for producing the required product variant (e.g., bill of material and production sequence) [2,7]. Some configurators support both commercial and technical processes, while others support one or the other [2].

The benefits of configurators in supporting commercial and technical processes have been deepened by academic literature [2,7–24]. The use of configurators notably: reduces lead-times [8–10,19], improves quality of product specifications [7,10–12] and products [13,14], improves costing accuracy and product profitability [20], preserves product knowledge [7,16], reduces routine work [2], improves the certainty of delivery [7,10,17,19], augments the product related and experience related benefits perceived by customers [21–24], and increases customer satisfaction [7,10,18]. On the contrary, the challenges companies face in implementing and using configurators have not been addressed to the same extent as the benefits derived from the use of configurators, given the tendency in the literature to highlight successful uses [25]. A number of projects involving the adoption of configurators do fail [2,25], therefore, diminishing benefits derived from company resources and innovation efforts. Further, even companies that managed to implement and utilize configurators have faced, and are still facing, various challenges. The empirical studies of these challenges are mainly based on case studies [6,7,10,14,20,26–29] and only to a limited extent are based on surveys [30–32]. Even though some limited indications of the importance of the described challenges are given in some studies [10,20,25,26,30–32], a direct comparison of the importance of different challenges has not yet been provided.

The limited understanding of challenges and, more importantly, the importance of the challenges in implementing and utilizing configurators restricts the help that managers can find based on research results to reduce the difficulties their companies encounter in exploiting configurators. To move further in this direction, it is necessary to continue to explore for unknown challenges and—even more important, given the status of the knowledge on this issue—to explore the relative importance of known and unknown challenges. The knowledge that can be gained through this kind of investigation will provide precious insights for the future development of theories on the mechanisms that prevent or mitigate the negative effects of the challenges under consideration. The present study aims to bridge this research gap by addressing the following research questions.

> **RQ 1:** What are *the main categories of challenges* faced by manufacturing companies when implementing and utilizing configurators?

RQ 2: What is the *level of importance of each category* of challenges faced by manufacturing companies when implementing and utilizing configurators?

RQ 3: Which *specific challenges within each category* do manufacturing companies face when implementing and utilizing configurators?

We address these research questions by means of an exploratory survey, designed based on what is already known in the relevant literature. To comply with the exploratory nature of the research, we have used open questions answered through phone interviews. To comply with the necessity to compare the relative importance of the challenges already known, we used closed questions sent by email. More specifically, in relation to RQs 1 and 3, open questions searched for both additional categories of challenges not described in the existing literature and specific challenges within each of those categories. For RQ 2, we asked closed questions to compare the importance of the different categories of challenges. To answer RQ2, however, the present study also compares the answers obtained through both closed and open questions to determine the importance of the challenges, thus increasing the reliability of data and reducing the dependency on data collection method.

The remainder of the paper is structured as follows. Section 2 presents the relevant literature base. Section 3 explains the research method, and Section 4 presents the results of the research. Finally, Section 5 discusses those results in relation to the RQs and the existing literature and presents the conclusions of the study.

2. Literature review

As this paper considers the challenges of implementing and utilizing configurators, rather than the algorithms or technologies used to make those configurators more powerful, the literature review reported hereafter focuses on managerial rather than technological challenges. The considered publications are presented by combining chronological order and the groups of researchers involved; in this way, the reader can get a rough description of the evolution of the discussion on the challenges under consideration.

When reporting the configurator case of Digital Equipment Corporation in 1989, Barker et al. [14] described strategic/business challenges, technical challenges, and human resource/organizational challenges. *Strategic/business challenges* relate to cross-functional business needs that are traced to the implementation of configurators for enhancement of business processes, requiring support from top management. The identified *technical challenges* include underdeveloped commercial configuration software with limited functionality (i.e., since 1989, the functionality of commercial configuration software has evolved significantly); application challenges in aligning the system with frequent product updates and launches of new products; scope expansion of the system (i.e., in response to increased user requirements and increased number of users); and size and complexity of the configurators. The managerial issues implied by these technical challenges include the development of an explicit understanding of the software architecture; the time-consuming training of new configuration experts, and prioritization of configurator maintenance without limiting the development of supporting tools for the configurators. Finally, *resource/organizational* challenges concern the awareness of key players and roles requiring organizational changes.

Tiihonen et al. [30], in 1996, published a study based on a survey of 10 Finnish industrial companies (answer rate 5.6%) to assess the state-of-the-practice in product configuration (The National Product Configuration Survey, 1995). The studied companies had not yet implemented configurators, but almost all of them were planning to do so. They identified the following five problems areas in the product configuration: economic importance of product configuration, product configuration task, product configuration processes, long-term management of product knowledge and configurations, and interfaces to other systems and processes. The identified problem areas of the product configuration and the long-term management of products and relevant information are tightly interconnected and visible in the 10 companies that the study analyzes. The challenges of configurators, when supporting the product configuration process, include: configuration knowledge (that is often not systematically documented), configurators' ability to support parametric components, geometry, and product configuration (e.g., to generate 2D and 3D drawings of parametric instances), customer requirements at different levels of abstraction, level of automatic operations (where it is not always desirable to automate the complete process), long-term management of configurators' models, semi-configurable products, and finally market areas that the configurator should support.

In another paper published in 1998, Tiihonen et al. [31] went deeper into the main challenges of long-term configurator projects by using the same 10 Finnish industrial companies analyzed in the previous study [30]. They underscored that long-term management of product knowledge is a challenge: difficulties in maintaining the configuration models have been the cause of configurator project failure. After a successful introduction of a configurator, it is meaningful to encourage its use by the entire sales force (i.e., those who sell configured products) and integrate it into retailers' IT systems. This wide adoption improves the front-end processes of a company system-wide. If retailers, however, are unwilling to acquire or use a configurator, integrating automatic and manual configuration processes is a challenge.

Ariano and Dagnino's [26] study in 1996 related to a furniture manufacturing company where a primary challenge was that too few employees understood the structure of the configurator; this caused difficulties when the only employee who fully understood the structure left the company. Additionally, when the main sponsor of the projects left, the company failed to further develop the system because of lack of support and resistance to changing established work practices. The company lacked the expert knowledge needed to expand the system and was unwilling to allocate the required resources despite the known benefits. An overall lack of commitment from the company was, therefore, the main challenge in relation to the implementation of the configurator.

In 2000, Felfernig et al. [33] found that the complexity of configurator software development requires highly technical expert knowledge and that the knowledge base must be adapted continuously because of changing components and configuration constraints. Additionally, the development and maintenance time for configurators is strictly limited as the configurators need to be aligned with product developments and companies' offerings.

Also in 2000, Aldanondo et al. [34] described two kinds of expertise needed to develop a configurator: industrial expertise and configuration expertise. They reported, however, that it was too time-consuming to train people to become experts in both areas. People with industrial knowledge do not usually develop the configurators, and industry knowledge is often distributed among various employees, making it difficult to develop a comprehensive understanding of both areas (i.e., both configuration and product expertise). Furthermore, other challenges include representing the underlying structure of the configurators' models and finding a logical way to ask the customers questions in the configuration process.

Forza and Salvador [10], in 2002, identified product modeling as the main challenge of configurators' implementation and use in a small manufacturing company that made mold-bases for plastics molding and punching-bases for metal sheet punching. High product variety resulted in a complex product model, especially when there was heavy interdependency among product characteristics. Difficulties in constructing the product model can cause project delays, and challenges in documenting the product model can arise after the configurator has been implemented. Delays were also caused by not relieving people responsible for the setting up of the configurator from their daily activities at the company and committing them full-time to the implementation of the product model.

In another study in 2002, Forza and Salvador [7] described the main challenges of implementing a configurator in a small manufacturing company that designs, produces, and sells small- and medium-power voltage transformers as: personal role changes, inter-function collaboration, workload, and software personalization. Personal role changes occur as the system takes over routine tasks, a takeover that some employees considered a threat to their positions, and difficulties in inter-function collaboration within the company made it more difficult to build the product model. Because of the considerable time required to build the product model and the consequent increase in workloads, the company did not implement the most complex products into the configurator. Software personalization was considered challenging because the commercial configurator was unable to meet the company's specific needs.

In 2006, Forza et al. [27] studied a machinery company that produces small, medium, and large electric motors and alternators. Based on their findings, they explained that for highly complex products involving a very large solution space that is difficult to pre-define, it might not be economically feasible to implement a configurator—not only because the cost of implementation was greater than the benefits, but also because the amount of time and effort involved increased the burdens to be overcome.

Forza and Salvador [2], in a 2007 analytical study, combined the results of anecdotal cases, case studies, and exploratory surveys, and identified the following project killers for configurators: changes in employees roles and responsibilities, reduced freedom of actions, conflicts between the front and back offices regarding the requirements of the configurator, excessive workload, unreasonable architecture of the product families, and excessive software customization.

In 2003, Ardissono et al. [35] identified the main challenges experienced with configurators as increased complexity of products and services offered, which resulted in increased complexity of the systems, making it difficult for the end-user to utilize the system due to a lack of technical knowledge. They also mentioned the dependency on retrieving information from the suppliers of the customized products because knowledge representations were not shared across companies.

Heiskala et al. [28], in 2005, investigated challenges related to configurators in service companies. Heiskala et al. first identified from literature the following main challenges (for configurators in manufacturing companies): rapid update and maintenance requirements, knowledge acquisition, knowledge testing, maintenance requiring configuration and product experts, high dependency on configuration experts, and specification errors arising from misunderstandings. Subsequently, they studied two service companies, and found out that the identified challenges affected service companies too.

In 2007, Heiskala et al. [6] described challenges related to configurators by reviewing the literature on how configurators affected the operations and business of companies pursuing mass customization with configurable products. Their discussion is divided into customer and supplier viewpoints. The supplier viewpoint is further divided into issues concerning the business (e.g., major changes might be required that can be difficult to achieve; the introduction of the configurator can be both costly and time-consuming), organization (e.g., employees' role changes can cause resistance; required cooperation within the companies), specification processes (e.g., understanding the customer needs, fixed interaction with customers, difficult to modify created configurations), long-term management of configuration knowledge (e.g., fast updating, growing configuration models and complexity, different expertise required), and development and initial introduction of the configurators (e.g., knowledge acquisition, knowledge systemization and formalization, integration to other IT systems, user-interface).

In 2006, Hvam et al. [29] described challenges related to knowledge acquisition and product modeling in configuration projects for complex products, as well as communication difficulties between domain and configuration experts. They also reported the challenges of implementing a configurator in an investigated engineering company, including resistance to using the configurator because of previous unsuccessful implementations of other IT systems.

Petersen [36] found in 2007 that the main challenges in implementing configurators in engineering companies concern product characteristics, customer requirements, and lengthy project time spans. In relation to product characteristics, where the complexity of products offered by engineering companies is high, product families may not be clearly defined. As customer requirements can be both diverse and highly specific, the configurator must be able to support products that have not previously been defined in the system. Finally, this study [36] mentions that it might not always be cost-effective to include all customers' requirements in the configurator.

To explain why configuration projects dealing with complex products and multiple users do not deliver the expected results or are even abandoned, in 2012, Haug et al. [25] noted two major difficulties. First, if the configurator project is more expensive than anticipated, companies may abandon the implementation to prevent further losses before a prototype is fully developed. Second, the company may refuse to accept the configurator because of its insufficient capability to support sales and engineering processes. Finally, Haug et al. [25] mentioned the need for sufficient accuracy and allocation of maintenance resources to preserve alignment with the company's offerings.

In 2017, Shafiee et al. [37] described the main challenges for a configurator project based on a large international company providing catalysts and process plant technology in terms of documentation and communication with domain experts. The significant time and effort needed to maintain the documentation of the configurator model results in both insufficient time spent on documentation and a lack of validation by domain experts that can, in turn, lead to errors in the configurator.

In a 2017 study analyzing the impact of a configurator on the accuracy of cost calculations and, consequently, on product profitability, Myrodia et al. [20] identified three challenges faced by a small-sized company which manufactures pre-made structural elements for buildings and provides installation services. Those challenges were: lack of proper testing before launching the configurator, failure to support the entire product portfolio, and employee resistance to changes in their work routines.

In 2016, Zhang and Helo [32] conducted a survey to analyze changes in companies' business activities and also to identify difficulties and potential barriers to designing, developing, and using configurators. The survey analyzed 61 companies (answer rate 20%) in computer, telecommunication systems, and industrial machinery industries. The respondents were mainly IT managers or managers with sales IT responsibilities. The survey was conducted in collaboration with the EMpanel Online consulting company. Their findings showed that continuous product evolution is the challenge mentioned by most respondents. Other challenges frequently mentioned included a lack of IT designers, unclear customer requirements, and employees' concern about losing their work.

The challenges indicated in the reviewed studies fall into six main categories: IT-related, product modeling, organizational, resource constraints, product-related, and knowledge acquisition. While the literature also describes other challenges, this categorization encompasses the most commonly reported challenges, as reported in Table 1.

Table 1**.** Categories of challenges related to implementation and utilization of configurators

The main categories of challenges	*Nature of challenges within the category*	*Main contributions*
1. IT-related	All technical challenges related to IT systems (e.g., software personalization, design of a user interface, scope expansion, interaction with software suppliers, functionalities)	[2,6,7,14,26,30,31,33–35]
2. Product modeling	Challenges related to formalizing the product knowledge and model to be embedded in the configurator	[6,7,10,25,28–31,33,34,36–38]
4. Organizational	Lack of support from management, resistance to change, allocation of resources	[2,6,7,14,20,25,26,29,31,32]
3. Resource constraints	Lack of personnel to model the configurator, to gather and provide information, and dependency on resources	[2,14,25,26,28,32,34]
5. Product-related	Challenges in the product range, commonly described as complexity of product structure and continuous change in products	[2,6,7,10,14,27–33,35,36]
6. Knowledge acquisition	Difficulties in knowledge-gathering and availability of information in the development and maintenance phases	[6,28–35]

While previous studies [2,6,7,10,14,25–38] have identified several challenges for configurators' implementation and use, their relative importance remains largely unknown. This knowledge limitation relates not only to the categories of challenges reported in Table 1, but also—and to a greater extent—the specific challenges included in each category. Furthermore, the specific challenges in several publications are simply mentioned and not clearly defined, exemplified, and contextualized. For both practitioners and academics, it would be useful to know which challenges have greater impact and whether this impact varies across contexts. This would help to focus managerial attention and research efforts on the more important challenges, supporting strategic prioritization of investment to address these challenges.

The fact that empirical studies on challenges are based mainly on case studies [6,7,10,14,20,26–29,37,38] and, to a limited extent, on surveys [30–32] and that our knowledge of the relative importance of challenges is very limited [10,20,25,26,30–32] suggests that we still need exploratory research into the relative importance of the main categories of challenges. Even if exploratory, this research should specify clearly the contexts in which the various challenges appear and should also detail the description of the challenges to prepare for well-grounded extensive studies.

3. Research method

Commensurate with the research questions of the present study and the current knowledge of challenges companies face when implementing and utilizing configurators, exploratory survey research design is selected to help us become more familiar with the studied phenomenon and to provide the foundation for future descriptive or explanatory survey research [39,40]. To get a deeper understanding of the challenges and the context in which they take place, we administered the survey using a combination of e-mailed questionnaires and telephone interviews. The sample used in this study included 22 manufacturing companies that were producing and selling customized products and utilizing configurators to support their commercial or technical processes. This sample allows us to explore the main challenges from implementing and utilizing configurators that experienced adopters have faced. Accordingly, with the exploratory nature of the study, more effort is devoted to ensuring the depth of the data, and less effort is devoted to enlarging sample size. Small sample sizes are justifiable for exploratory research [41,42]. The following sections provide further details on sampling, questionnaire design, data collection, and data analysis.

3.1 Sample

The Danish Association for Product Modeling was used to identify companies that fulfilled the selection criteria for the study; eligible companies were required to manufacture customized products and to have established experience using configurators, to allow for analysis of the challenges of both implementing and utilizing configurators. Brainstorming sessions (e.g., with consultancies, vendors of configurators, and other collaborators) were conducted to identify additional companies of relevance. During the interviews, respondents of sampled companies were also asked to list other companies that might fulfil the selection criteria, thus identifying another couple of companies. In total, 26 companies were contacted; of those, 22 answered (response rate of 85%). Further attempts at telephone contact with the remaining four companies have not been successful. These four companies have sizes of 500, 2,000, 13,000 and 21,000 employees. Two of them make customized plants and system solutions, while the other two produce customized machines and components.

The resulting sample is made of 22 manufacturing companies of various sizes. The sampled companies range from small companies (i.e., 20 employees) to very large companies (i.e., 15,000 employees), with more of the larger companies (i.e., 81.81% of the companies in the sample have 450 or more employees, and 90.91% of companies have more than 100 employees).

All companies in the resulting sample produce and sell physical products characterized by different levels of complexity. The main product categories offered by these companies are plants (very high complexity), system solutions (high complexity), machines (high/medium complexity), and components (medium/low complexity). Each company in the sample has at least one of these five categories as its main product category. Thirteen companies (59.09%) offer products in more than one of these product categories. Two companies (9.09%) generate the most significant part of their revenues from plants, and in total four companies (22.73%) get some part of their revenues from selling plants. The plant category includes solutions (e.g., processing material for food and heating supplies). A *plant* consists of several machines, their interfaces, and surrounding constructions. Six companies (27.27%) get the most significant part of their revenues from systems solutions, and in total, 10 companies (45.45%) get some part of their revenues from systems solutions. The *systems solutions* category includes complete solutions for the building industry, electronic systems, ventilation systems, and climate control systems, among others. Five companies (22.73%) get the most significant part of their revenues from machines and in total 7 companies (31.82%) get some part of the revenues from machines. A *machine* is a product that includes a number of components and their interfaces (e.g., supporting agricultural, printing, building, and shipping industries). Nine companies (40.91%) get a significant part of their revenues from components, and a total 17 companies (77.27%) get some part of their revenues from components. The components in this category include mechanical, hydraulic, control boards, buildings, and heating systems components, among others. None of the sample companies gets their largest share of revenues from products outside the five main product categories. Four companies (18.18%), however, get a significant part of their revenues from spare parts and services that are listed under the other categories.

In adherence with the sample selection criteria, all sampled companies offer customized products. More specifically, 59.09% of the companies get over 60% of their sales revenues from customized products. This high incidence of customized products is not surprising, given the type of products offered and the fact that all the sampled companies operate in the business-to-business (B2B) markets.

The use of configurators in each company of the sample is significant, even though it varies considerably across companies. Eleven companies (50.00%) get over 60% of their revenues from products supported by the configurators, while seven companies (31.82%) receive less than 20% of their revenues from such products. The reasons for not supporting the complete product range with configurators include excessive product complexity, inadequate sales volumes, newly introduced products not yet added to the configurator, and product families without customization.

All companies in the sample have considerable experience in using configurators and can, therefore, inform researchers of the challenges of both implementing and utilizing configurators. The companies' experience using configurators ranges from a minimum of 3 years to a maximum of 25 years, where 77.27% of the companies have 7 years' or longer experience from configurators.

The sampled companies differ considerably also in the number of configurators they use, up to a maximum of 20. The sample companies have at least one configurator in operation, whereas 54.55% of the companies have two or more configurators in use, and 27.27% of companies have five or more configurators in use. In counting configurators in use, we consider a configurator as having a separate knowledge base, irrespective of the software (SW) platform used. Two different knowledge bases (e.g., where each knowledge base includes knowledge about a single product family) built on the same SW platform counts as two configurators. A product family supported with both commercial and technical configurators can be counted as either one or two. If the commercial and the technical configurators are built on the same knowledge bases (i.e., the knowledge of the technical configurator is added to the commercial configurator), it counts as one configurator. When the commercial and the technical configurators are built up in separate knowledge bases (i.e., the commercial and the technical configurators can be defined as a separated standalone system), however, they count as two configurators.

3.2 Respondents

One person from each company was responsible for answering the survey, based on their familiarity with the configurators and irrespective of the respondent's formal role at the company; top-level management might not possess the required in-depth knowledge of configurators. It is notable that those responsible for managing configurators occupy different positions within the organizational structure of participating companies. The respondents' positions at their respective companies are the following (the number of companies are indicated in parentheses): business process manager (1), consultant (1), design support manager (1), group manager (1), information officer manager (1), manager of customization and specialized equipment (1), manager of the drawing department (1), mechanical engineer (1), customer support and master planner (1), product data manager (2), product manager (1), production technician (1), project manager (2), sales technician (1), sales manager (1), strategic development (1), system developer (1), system manager (1), and technical director (2).

3.3 Questionnaire

A first version of the questionnaire was developed based on the literature review, using a brainstorming approach to specify the main constructs. The study was designed to explore—both qualitatively and quantitatively—the importance and the characterization of the main challenges. For the purposes of this research, respondents were asked the following questions:[1]

1. What are the three greatest challenges your company has faced or is facing when implementing and utilizing the configurator?

2. On a 5-point scale, ranging from 1 (*not important*) to 5 (*very important*), please rate the importance of the following types of challenges your company has faced or is facing when implementing and utilizing configurators:
    - IT-related challenges

[1] Additional questions have been asked to characterize the company context. The answers to these additional questions are used in section 3.1 to describe the sample studied for the present work.

- Product modeling
- Organizational challenges
- Resource constraints
- Product-related challenges
- Knowledge acquisition.

The first question was designed to capture the nature of the challenges and to encourage respondents to describe in their own words the main challenges their companies had encountered in relation to implementing and utilizing configurators. The aims were (1) to identify additional categories of challenges that had not been described in the literature, and (2) to gain further insights into the main categories of challenges already addressed in the literature (i.e., RQs 1 and 3). The second question was designed to quantify the importance of the main categories of challenges described in the literature to allow for direct comparison (i.e., RQ 2).

To validate the questionnaire, three pilot interviews in differing industrial configuration settings were conducted. The pilot interviews focused on (1) testing the relevance of questions and instruments to ensure that questions made sense, formulations were accurate, and assumptions were explicit; and (2) discussing companies' configuration practices to identify additional topics of relevance for the questionnaire. Following the pilot interviews, small amendments were made to the questionnaire, which included changes in wordings for improved clarity.

3.4 Data collection

To begin, the questionnaires were e-mailed to respondents, along with a description of the study's purpose, interview procedure, and follow-up notification. Appointments were made for telephone interviews, which were conducted as a walkthrough of the questionnaire. During the interview, the researcher made notes of the respondent's answers. Each interview lasted 40–90 minutes, depending on the complexity of the configuration setting and the respondent's particular situation. This time allowed the interviewer to also build some positive rapport with the interviewees, hopefully leading to more specific—and we think also more reliable—information. Immediately after the interviews, the completed questionnaires were e-mailed to respondents for verification while the interviews were fresh in their minds, and a few respondents used the opportunity to modify their answers.

The interview process enabled clarification and elaboration of responses to ensure correct and consistent interpretation of the questions and to ensure that the interviewer gained a complete understanding of the companies' settings. Most respondents listed three or four challenges; five companies mentioned only one challenge as their primary difficulty, and one company listed five challenges. When needed, respondents were asked to elaborate on the challenges to provide us a deeper understanding of the difficulties in question, and we made notes of their answers.

3.5 Data cleaning and analysis

Once data had been collected, responses to the questionnaire and interviews were entered into a database. Subsequently, the responses have been cross-checked for data entry errors and analyzed.

Answers to the open questions were coded and grouped into the main categories identified based on the literature; to prevent any bias, the interview data were coded and analyzed by a person other than the interviewer. Grouping of responses was discussed among the authors to check consistency, and the data were cleaned to ensure their reliability. In one case, an inconsistency was found between the qualitative data (i.e., gathered through the open questions) and quantitative data (i.e., gathered through closed questions); the discrepancy was corrected after further investigation. In one other case, where the company reported only one challenge, the reported challenge was assigned to different categories because the content of the answer touched on more than one category. In a few cases, an individual answer was broken down into two separate challenges, since it was addressing multiple challenges. In other cases, individual answers have been collapsed into the same challenge, because the respondent was describing different aspects of the same challenge. At the end of this process, from the open questions, we had three challenges for 15 (68.18%) companies, two challenges for three (13.64%) companies and one challenge for four (18.18%) companies.

Subsequently, overall consistency across qualitative and quantitative data was checked to ensure that the challenges mentioned or omitted in the qualitative part (i.e., where we asked for the three greatest challenges) were assigned a coherent importance in the quantitative part (i.e., where we asked for the level of importance of each category of challenges). Appendix 1 reports some of the details from this analysis. The consistency checks confirmed that:

- In the quantitative part, companies assigned higher importance to a challenge category for which they identified a corresponding challenge in the qualitative part than did companies that did not identify such a challenge.
- None of the companies that expressed a challenge in the qualitative part rated the category that included such a challenge as unimportant in the quantitative part.
- Companies that made no mention (in the qualitative part) of any challenge belonging to a certain category also did not assign very high importance to that category.

In one exception, a company rated resource constraint challenges as highly important without mentioning any challenge related to this category in the qualitative part. Specifically, this company rated IT-related, product-related, and knowledge acquisition challenges as highly important; product modeling as very important; and organizational challenges as important. By further analyzing the data retrieved from the specific company, resource constraint emerged as the underlying challenge. The lack of resources intensified IT-related, product-related, and organizational challenges.

Finally, descriptive statistics are used to present the findings of the study. All the reported percentages in the results section refer to the same number of companies (N = 22), with no missing data in the dataset. The fact that in the open question, some companies provided less than three challenges, does not generate missing data since our intention is to find the most important challenges; for that purpose, even absence of important challenges is an admissible answer. If a company, when answering the open question, points out one or two challenges only, it means that, for this company, there are only one or two important challenges. Our objective is not to provide an exhaustive list of challenges; rather, we aim to point out the unimportant ones.

4. Results

This section presents the results of the performed analyses. Section 4.1 reports the results of the analysis of the qualitative data, while Section 4.2 presents the results of the analysis of the quantitative data.

4.1 Identified challenges in implementing and using configurators

The results presented in this section aim to assess the main challenges that manufacturing companies encounter when implementing and utilizing configurators, thus (1) indicating whether the categories derived from literature are considered among the main categories, and whether additional categories are identified (RQ 1), and (2) highlighting and describing specific challenges within each of the derived categories (RQ 3). Table 2 details the percentages of companies that referred to the different main categories of challenges identified based on the literature.

Table 2. Number of companies reporting challenge belonging to the main categories of challenges

The main categories of challenges	*Number of companies*	*Percentage of companies*
IT-related	8	36.36%
Product modeling	9	40.91%
Organizational	15	68.18%
Resource constraints	5	22.73%
Product-related	5	22.73%
Knowledge acquisition	13	59.09%

Based on the answers from the company respondents, we concluded that no additional categories were required. The following sections describe the individual categories of challenges, based on the respondents' answers, in more detail.

4.1.1 IT-related challenges

The reported IT challenges are grouped into two subcategories related to (1) software development and (2) system design to achieve user-friendliness.

With regard to *software development*, two of the respondents explained that the technical aspects of developing and implementing a Web-based configurator had presented a major difficulty; two other respondents reported difficulties in integrating the configurators with other IT systems at their companies. One respondent also referred to challenges in exchanging information across different configurators. Operating the database and developing customized functionalities had also caused problems for some respondents.

Designing *user-friendly* configurators was also considered challenging. One respondent reported that salespersons' desire to use the configurator was proportional to its user-friendliness. The same respondent added that the sales configurator was launched and tested to achieve user-friendliness and was later expanded to include the technical configurator. Another respondent reported that the complexity of technical requirements and the product range had made it difficult to incorporate all the right product combinations in the configurator and, thus, compromised the configurator's user-friendliness.

4.1.2 Product modeling

The reported product modeling challenges can be grouped into three subcategories: (1) complexity due to lack of overview of product range, (2) correctness of specifications generated by the configurator according to product model, and (3) lack of knowledge related to product modeling.

Regarding *complexity due to lack of overview*, respondents highlighted problems caused for users by the complexity of the configurator. Two respondents noted that lack of a product overview made it difficult to formalize in a logical way the questions asked in the configuration processes; another respondent referred to difficulties in maintaining an overview, and another said that it was difficult to ensure the configurator's ease of use with increasing complexity. These answers confirm the need for modeling techniques to establish an overview of companies' product ranges and to reduce the complexity of linkages between offered solutions and customer needs. Product models also need to be regularly updated to provide an overview and to reflect the product knowledge incorporated in the configurator.

The *correctness of specifications* generated by configurators depends on the underlying product model. One respondent reported a constant need to test whether parts were properly configured, owing to a lack of product modeling and validation. Another respondent stated that in addition to ensuring that the configurator could generate bills-of-materials (BOMs) in the configuration process, it was also important to verify that the individual parts or components fit together and that instructions were provided for setting up the individual parts or components. This highlights the importance of a product model that accurately represents the different relationships in the product structure to ensure the correctness of configurations and outputs.

Regarding *unfamiliarity with product modeling*, one respondent reported challenges in establishing knowledge and acquiring information about how configurators work and how to build the underlying product model.

4.1.3 *Organizational challenges*

Organizational challenges refer to (1) a lack of support from management, (2) resistance to using the configurator, and (3) disagreements about the scope of the configurator.

Two respondents reported a *lack of support from management* and lack of backup to address change management challenges. As implementation of a configurator is usually cross-functional and affects multiple stakeholders, increased support from management promotes project success. This support can ensure that key activities are prioritized and that resources are assigned to the project. As one respondent explained, key people at the company have the necessary knowledge to develop and validate the system; to secure access to this professional knowledge, management must prioritize configurator projects. One respondent said that the configuration team found it difficult to keep current with product development because the team was usually the last to know about new products. Failing to involve the configuration team in the early stages of product development can cause delays in releasing new products because those products are not included in the configurator and are, therefore, not available to sales personnel. Finally, one respondent referred to lack of documentation, and another one to lack of ongoing training and documentation, as organizational challenges when resources and central activities are not prioritized by management.

One respondent mentioned the challenge posed by *resistance to using the system*, emphasizing the difficulty of changing employees' habits so they could adapt to use of the configurator as part of a new work procedure. Another respondent stated that this resistance might stem from employees' reluctance to abandon the comfort of the old system (e.g., employees who were used to working alone experienced difficulties in adjusting to a system that required them to work on the same things in client mode). Increased standardization of products and processes was also mentioned as a source of organizational resistance. One respondent explained that the configurator marked a move toward a more standardized and structured sales process, limiting individual freedom and shifting the focus from prices to customer value creation. In addition, one respondent explained that sales representatives used the configurator only in special cases while continuing to use the old system in other cases, indicating that sales representatives were not committed to the new procedure, even in cases that could be handled by the configurator. As well as this internal resistance, four respondents reported difficulties in convincing their sales agents or customers to use the configurator despite offers of training and discounts for using the systems in the sales process.

Disagreement about configurator scope was also reported as a major organizational challenge. Not all products are supported by the configurator, which means that employees may lack experience in using it. One respondent mentioned that all products need to be supported by the configurator if salespersons were to recognize the system's usefulness. To ensure successful implementation and acceptance, then, it is essential that the system meets all requirements while avoiding increased complexity. Finally, two respondents noted a challenge in agreeing on the configurator's content and boundaries. According to the companies, not all products were included in the configurator because that would result in great complexity. It follows that, in supporting configuration for a greater variety of products, the system can compromise user-friendliness.

4.1.4 Resource constraints

The main challenges related to resource constraints were described in terms of (1) lack of resources, (2) vulnerability if key personnel leave.

With regard to challenges related to *lack of resources* in configuration projects, two respondents highlighted the lack of resources for the configuration team and the release of resources from the business (e.g., product experts). Another respondent explained this in terms of capacity planning difficulties; yet another said that a lack of resources meant that not all products were included in the configurator, thus increasing resistance to using the system (as explained in section 4.1.3).

In terms of *vulnerability if key personnel leave*, one respondent also indicated that a lack of resources made it difficult for anyone other than key personnel to gain an overview of the configurator and the knowledge embedded in the system. Confining access to all of the valuable knowledge to a small number of employees puts the company at risk if these key personnel leave; it can be difficult for another person to become familiar with the system because this requires knowledge about both the companies' products and the configuration software.

4.1.5 Product-related challenges

The main challenges related to the products were described in terms of (1) complexity of product structures and (2) continuous change in product offerings.

One respondent explained that as *complex products* entail more options, rules, and dependencies, that require improved decision-making and more complex configurators; in this sense, managing complexity is a challenge. Another respondent emphasized that proceeding with the configurator requires a high level of standardization of the product range. This corresponds to how configurators require components or modules to be defined with constraints that determine how different parts and components can be combined. Another respondent explained these challenges in relation to the generation of BOMs enabling individual parts and components to fit together and generating setup instructions.

With respect to challenges related to product range and continuous changes in product offerings, one respondent pointed out that configurators must be capable of rapid updating to align with product offerings. Another respondent expressed the view that configurators must stay updated to ensure that they are aligned with the company's product offerings. The configuration team, therefore, needs to be at the forefront of new product development.

4.1.6 Knowledge acquisition

The main challenges relating to knowledge acquisition were characterized as (1) difficulties in acquiring the correct knowledge, (2) a lack of knowledge needed to meet users' and customers' needs, and (3) failure to communicate knowledge in the maintenance phase.

The process of *acquiring correct product knowledge* was considered critical in ensuring configurator quality. One of the interviewees explained this in terms of the need to transfer specifications to the configurator without misinterpreting or losing knowledge. Other problems arose regarding the requirement specifications should be as accurate as possible, so all users have the same starting point. Another respondent explained that incomplete product definition made it difficult to keep track of products and their variants. A respondent from a company specializing in engineered solutions for individual customers referred to challenges resulting from an inadequate product program structure, which made it difficult to capture the required knowledge and expand the configurator. Similarly, another respondent noted challenges in relation to parameters of each variant requested by the customer and another described lack of knowledge of how different parts can be combined as a key challenge. In this way, knowledge acquisition challenges can be related to the product types offered—that is, companies providing more engineered solutions (i.e., with a high level of customization) may have less product knowledge because each product is engineered for a specific customer. For that reason, these companies may encounter more knowledge acquisition difficulties. Finally, it was also observed that organizations had different approaches to validate the correctness of the configurator and the generated product specifications. While some organizations started out with the product model, others went through an extensive testing phase to eliminate errors, and others relied on feedback from installation and error correction as an input for correcting the configurator. As knowledge acquisition challenges can lead to configurators generating inaccurate specifications, the focus should be on ensuring that the correct information is retrieved the first time, which may be difficult if only a few people are in possession of the required knowledge.

Another challenge related to knowledge acquisition was expressed in terms of *understanding customers' and users' needs* to ensure that these can be fulfilled in the configuration process. As configurators are commonly used to guide sales processes, it is critical to gather sufficient information to capture users' and customers' needs. As in the case of organizational challenges, if the system lacks the necessary scope to address users' needs, resistance to the use of the system is likely to increase. This was also expressed as a problem of knowledge acquisition; one respondent noted that the configurator could not meet all salespersons' needs and all product variants because of a lack of knowledge. Another challenge was expressed by respondents in two companies in terms of acquiring knowledge of the customers' needs to be reflected in the configurator setup.

Issues related to *knowledge acquisition in the maintenance phase* were also considered a challenge. This relates to lack of troubleshooting knowledge, which is why certain configurations are unfeasible and why error messages are generated. Two other respondents stated that new options were not being updated in the configurator because product knowledge was not being communicated in the maintenance phase. Finally, it was also seen as challenging that new products had to be approved each time because of a lack of validation and information from product experts.

4.1.7 Summary of the main challenges identified within each category of challenges

In Table 3, the specific challenges within each of the main categories of challenges are synthesized based on the previous description of the specific answers given by the companies' respondents. For each of the categories, two or three challenges are highlighted, providing an answer to RQ 3.

Table 3. Specific challenges per main category – derived through open questions on three main challenges per company.

Main categories of challenges	*Specific challenges within each category of challenges*	*Companies (%)*	*Companies (%)*
IT-related	Software development	27.27%	36.36%
	Systems design for user-friendliness	9.09%	
Product modeling	Complexity due to lack of overview of product range	22.73%	40.91%
	Correctness of specifications generated by the configurator according to product model	13.64%	
	Lack of knowledge related to product modeling	4.55%	
Organizational	Lack of support from top management	27.27%	68.18%
	Resistance to using the configurator	36.36%	
	Disagreements about the scope of the configurator	13.64%	
Resource constraints	Lack of resources	18.18%	22.73%
	Vulnerability if key personnel leave	4.55%	
Product-related	Complexity of product structures	13.64%	22.73%
	Continuous change in product offerings	9.09%	
Knowledge acquisition	Difficulties in acquiring the correct knowledge	27.27%	59.09%
	Lack of the requisite knowledge to meet users' and customers' needs	13.64%	
	Failure to communicate knowledge in the maintenance phase	18.18%	

4.2 Importance of the main reported categories of challenges

The second part of the research focuses on assessing the importance of the categories of challenges encountered when implementing and managing configurators (RQ 2). Table 4 sets out the main categories of challenges in terms of their importance as measured on a 5-point scale, ranging from 1 (*not important*) to 5 (*very high importance*). In Table 4, levels 4 and 5 are aggregated to signal the *primary importance*, and levels 2 and 3 are aggregated to signal the *secondary importance*. Furthermore, Table 4 recalls the percentage of companies related to a given category in the qualitative part of the study (see also Tables 2 and 3) when informants were asked to list the three most important challenges faced by their company in implementing and using configurators.

T**able 4.** The importance of the main categories of challenges – pulling together qualitative and qualitative analyses

Categories of challenges	**Qualitative results**	**Quantitative results**					**Overall importance**
	Percentage of companies referring to the category	**Not important**	**Secondary Importance**		**Primary Importance**		
			Very Low Importance	*Low Importance*	*High Importance*	*Very High Importance*	
Organizational	68.18%	**13.64%**	**36.36%**		**50.00%**		**Very high**
			13.64%	22.73%	36.36%	13.64%	
Knowledge acquisition	59.09%	**18.18%**	**31.82%**		**50.00%**		**High**
			18.18%	13.64%	36.36%	13.64%	
Product modeling	40.91%	**9.09%**	**40.91%**		**50.00%**		**Medium high**
			22.73%	18.18%	36.36%	13.64%	
Resource constraints	22.73%	**18.18%**	**36.36%**		**45.45%**		**Medium Low**
			13.64%	22.73%	31.82%	13.64%	
IT-related	36.36%	**9.09%**	**54.55%**		**36.36%**		**Low**
			31.82%	22.73%	18.18%	18.18%	
Product-related	22.73%	**22.73%**	**50.00%**		**27.27%**		**Very low**
			31.82%	18.18%	18.18%	9.09%	

Each category of challenges was recognized as important in the closed questions by at least 77.27% of the companies. The levels of importance, however, differ across categories. To provide an overall assessment of the importance of each category of challenges hereafter, we complement the information gathered by the closed questions with the information gathered by the open question.

Three categories have been recognized of primary importance by 50% of companies: organizational, knowledge acquisition, and product modeling. Surprisingly, the percentage of companies that rate them as very high importance is the same (13.64%) as well as those that rate them as highly important (36.36%). *Organizational challenges* were not only the highest in the quantitative part but also by far the highest in the qualitative part (i.e., 68.18% of companies mention a challenge that falls into that category among the three main challenges); these results are of very high overall importance. Knowledge acquisition results are slightly higher than those of product modeling in the quantitative part but much lower in the qualitative part. Thus, we ranked knowledge acquisition as being of high overall importance and product modeling being of medium overall importance. Notably, these two categories address related issues.

The other three categories (i.e., resource constraints, IT-related, product-related) are of secondary importance. The product-related challenges category results are by far the lowest among these three categories in both the qualitative and quantitative parts. Resource constraints and IT-related are close in results, but almost half of the companies rated this category of primary importance, while the IT-related category has been rated of primary importance by only one-third of companies. The overall rating of the resource constraint category, therefore, is medium-low, while the overall rating of the IT-related category is of low importance.

Notably, there are two categories (i.e., resource constraints and product modeling) with bimodal distributions. In addition, the importance of the various categories is quite dispersed among all values of the provided scale. These two facts suggest that the importance of each category varies considerably across companies.

5. Discussion and conclusion

The present study explores the hidden side of product configurators—namely, the challenges companies face in implementing and utilizing them. While the benefits from using the configurators have received considerable attention from the research community over prior decades [e.g., 7,10–18], the issue of challenges has received much more limited attention [25]. The findings of the present article complement existing studies that mention the challenges of implementing and utilizing configurators [2,6,7,10,14,25–38] by strengthening and detailing our knowledge about what these challenges are and by providing the first insights into a comparison of importance across the main categories of challenges.

5.1. The main categories of challenges: identification

The first research question presented in this study sought to identify the main categories of challenges faced by companies when implementing and utilizing configurators based on a literature review. The following six main categories of challenges were identified: (1) IT-related, (2) product modeling (3) organizational, (4) resource constraints, (5) product-related, and (6) knowledge acquisition. The qualitative part of the study confirmed that these six categories all remain relevant and that no additional categories are required (see Tables 2 and 3). Furthermore, the quantitative part of the study showed that each category was important in at least 77.27% of companies, thus further supporting the relevance of these categories (see Table 4).

The proposed categorization of the main challenges of implementing and utilizing configurators shows the ability, to some extent, to parsimoniously address the categories of the main challenges. The fact that (as shown also in Appendix 1) the challenges expressed by managers openly without verbal constraints correspond (once grouped accordingly to the proposed categories) with data that emerges when asking them the importance of each one of these categories means that these categories do have some potentials to synthetically gather data on the main challenges of implementing and utilizing configurators. The fact that respondents did not have difficulties in interpreting the meaning of the various categories and that they differentiated the importance between the various categories provides evidence that this categorization may be useful to communicate with practitioners. So, this categorization constitutes a new ad hoc proposal that moves a step further the work initiated by Barker and O'Connor [14], Tiihonen et al. [30], and Heiskala et al. [6], which presented the various challenges from specific perspectives.

5.2 The main categories of challenges: level of importance

The second research question presented in this study considered the importance of the categories representing the main challenges when implementing and utilizing configurators. In Section 4.2, we presented the quantitative results and complemented them with qualitative results to provide an overall indication of the importance of each category of challenges (see Table 4).

Table 5. The importance of the main categories of challenges – comparison of results with related studies

Main categories of challenges	*Overall importance*	*Number of articles [and articles] mentioning a challenge in the category*	*Number of articles [and articles] that consider as important a challenge in the category*
1. Organizational	Very high	10 [2,6,7,14,20,25,26,29,31,32]	4 [20,25,26,32]
2. Knowledge acquisition	High	9 [6,28–35]	3 [30–32]
3. Product modeling	Medium high	13 [6,7,10,25,28–31,33,34,36–38]	2 [10]
4. Resource constraints	Medium low	7 [2,14,25,26,28,32,34]	2 [10,32]
5. IT-related	Low	10 [2,6,7,14,26,30,31,33–35]	1 [32]
6. Product-related	Very low	14 [2,6,7,10,14,27–33,35,36]	0 None

Our results show that all categories are important, although at different levels. While organizational, knowledge acquisition, and product modeling are challenging categories of primary importance, resource constraints, IT-related, and product-related are of secondary importance, and the product-related category is of very low importance. If, however, this is the global view, a more detailed view highlights that some categories have a bimodal distribution of their importance, and almost all are characterized by a high dispersion of their importance. Each category, therefore, could be of limited importance in some contexts and of high importance in other contexts.

Previous research has identified many challenges in relation to implementing and utilizing configurators. The attention paid to the various categories from the research community in some cases, however, does not correspond to the categories' relative importance as have emerged from the present study. The most frequently mentioned category in the literature (i.e., product-related challenges) is of secondary importance, while the organizational and knowledge acquisition—rated with primary importance—are not as often addressed in the literature. Since all these categories of challenges are important, we can simply conclude that future research should devote more attention to organizational and knowledge acquisition challenges. Furthermore, future research should consider more carefully resource constraints (the least-frequently mentioned challenge in the literature) since challenges in that category can be factors that influence or interact with other challenges, and thus are not immediately detectable.

Very limited insight has been provided by previous research on the level of importance of the various challenges. Notwithstanding this fact, we can use the number of articles considering as important at least one challenge of a given category as a rough proxy of the importance recognized by previous studies of that category of challenges. Interestingly, the order of importance of the various categories resulting from this rough proxy coincides with the order identified by our study. Our results show some differences, however, from those reported in the only other study [29] that provides some quantitative data. Even though the results are not fully comparable (i.e., the questions asked in [29] are different from the ones in this study), it seems that for Zhang and Helo [29], resource constraints, IT-related, and product-related results are more important than they were in our study. In particular, Zhang and Helo report that most companies (75%) agreed that continuous evolution of products is a challenge to continuously applying the product configurator. The different roles of respondents may also have had an effect on the differences assigned to IT-related and resource constraints challenges. It could be that the inclusion in their sample of computer and telecommunication systems companies make the product-related challenges more relevant compared to the companies analyzed in this study. This possible explanation once again suggests that difference in contexts likely impacts the importance of the various challenge categories.

5.3 Structuring challenges: the importance of categories and sub-categories of challenges

Finally, the third research question presented in this study sought more in-depth knowledge about the specific challenges within each of the categories faced by manufacturing companies when implementing and utilizing configurators. This study details each of the main categories by identifying sub-categories and provides a description of each subcategory (Section 4.1).

Previous studies [6,7,14,30,32] list the main challenges, and some of them [6,14,30] also articulate some sub-challenges. In particular, Heiskala et al. [6] provide a multilevel description of challenges, but their description is organized to pursue the wider objective of reviewing the literature on how configurators affect the operations and business of companies pursuing mass customization with configurable products. The present paper moves further towards a categorization and subcategorization focused on important challenges. The sub-categorization proposed here is grounded on the empirical data gathered through the explorative survey. Each of the main categories of challenges is described in more details by two or three sub-categories. Table 6 shows this categorization and also reports the level of importance of categories of challenges (as evident from both our quantitative and qualitative analyses) and the level of importance of sub-categories of challenges (as evident from our qualitative analysis). Table 6 also reports the articles in which the specific challenges have been considered and studies that have indicated the importance of the different challenges.

Table 6. The sub-categories of the main challenges and their importance – comparison with related studies

Main categories of challenges	*Overall importance*	*Specific (sub-category) challenge within each category of challenges*	*Importance (% of companies reporting the challenge)*	*Number of articles [and articles] mentioning the challenge*	*Number of articles [and articles] considering the challenge important*
Organizational	Very high	Resistance to using the configurator	Highest (36.36%)	8 [2,6,7,20,25,29,31,32]	3 [20,25,32]
		Lack of support from top management	Among highest (27.27%)	3 [6,14,26]	2 [25,32]
		Disagreements about the scope of the configurator	Low (13.64%)	2 [2,7]	0 None
Knowledge acquisition	High	Difficulties in acquiring the correct knowledge	Among highest (27.27%)	8 [6,28–30,32–35]	3 [30–32]
		Failure to communicate knowledge in the maintenance phase	Medium (18.18%)	4 [6,28,30,31]	0 None
		Lack of requisite knowledge to meet users' and customers' needs	Low (13.64%)	4 [6,30,32,34]	1 [32]
Product modeling	Medium	Complexity due to lack of overview of product range	High (22.73%)	12 [2,6,7,10,29–31,33,34,36–38]	2 [7]
		Correctness of specifications generated by the configurator according to product model	Low (13.64%)	4 [6,25,28,37]	0 None
		Lack of knowledge related to product modeling	Low (4.55%)	0 [Found no reference]	0 None
IT-related	Medium	Software development	Among highest (27.27%)	9 [2,6,7,14,26,28,30,31,33]	1 [32]
		Systems design for user-friendliness	Low (9.09%)	4 [6,14,34,35]	1 [32]
Resource constraints	Low	Lack of resources	Medium (18.18%)	9 [2,10,25,26,32]	2 [10,32]
		Vulnerability if key personnel leave	Low (4.55%)	4 [6,14,26,28]	0 None
Product-related	Low	Product complexity	Low (13.64%)	8 [2,6,7,10,27,29,35,36]	0 None
		Continuous change in products offerings	Low (9.09%)	7 [6,14,28,30–33]	1 [32]

The results reported in Table 6 give preliminary indications of the importance of the subcategories based on numbers of companies reporting the specific challenges, as illustrated in the fourth column. Obviously, stronger results need a quantitative analysis as done for the categories of the main challenges and as explained in Section 4.2. The numbers of companies reporting the specific challenges range from 4.55% (1 company out of 22) to 36.36% (8 companies out of 22).

As expected, most of the sub-categories of challenges that were most frequently mentioned by the respondents (i.e., in answers to the question about the three most important challenges) belong to challenge categories of primary importance. Resistance to use of the configurator (36.36%) and lack of support from top management (27.27%) belong to the organizational category. Difficulties in acquiring the correct knowledge (27.27%) belongs to the knowledge acquisition category. Complexity due to lack of overview of the product range (22.73%) belongs to the product modeling category. One of the most frequently mentioned sub-categories, however, is software development (27.27%), which belongs to the IT-related category—of secondary importance.

Further, by considering articles mentioning the different sub-challenges, we see that the challenges which are most frequently mentioned in literature are not necessarily those most often mentioned by the company's respondents among the three most important. More specifically, three publications mention lack of support from top management as a challenge while 27.27% of the companies report this specific challenge as one of the three main challenges. This is quite surprising, given the recognized relevance of top management support in implementing and using information systems [e.g., 43–45]. Additionally, while product complexity is mentioned by eight publications, only 13.64% of the companies recognize it among their three top challenges. We have a very similar situation for continuous change in products offerings and, to a lesser extent, for vulnerability if key personnel leave. The companies in our sample (skewed towards big companies operating with complex products in B2B markets) are less affected than others by these challenges due to their size and their long experience in managing the evolution of complex products.

Interestingly, the challenge sub-categories which are most frequently mentioned in literature as important are also the most-often mentioned by the company's respondents as among the three most important ones. Even though this correspondence is evident, we should be cautious in trusting this finding because the results available in literature regarding the importance of challenges are very limited, and our sample size is small. In any case, the emerging picture is coherent and tells researchers that in analyzing challenges, there is a degree of importance that should be considered. It is not the same to ask whether, or to state that, a challenge exists, is important, or is of primary importance. Our results, derived from a joint investigation of the importance of categories and sub-categories, move the research a step further toward the understanding of the structure of challenges affecting the implementation and use of configurators.

5.4 Research limitation and further studies

The present exploratory study devoted more efforts to gathering in-depth information from the companies than to having a large sample size. It used a combination of an emailed questionnaire (with closed questions) and phone interviews (with open questions) to assure high-quality data and a good understanding of the context of the 22 analyzed manufacturing companies. The size of our sample, nevertheless, limits the possibility of generalizing our results. Future research moving forward from the exploratory phase should seek larger samples or at least provide the information that facilitates meta-analysis [35].

This is the first quantitative study that specifically asks informants to quantify the importance of different challenges concerning implementation and utilization of configurators. Even though some clear indications emerged, there are multiple signals (i.e., multimodal distributions, dispersion of answers, differences with other studies) that suggest caution in generalizing the results due to a potential presence of significant contingency factors. Very likely, different contexts lead to differing importance of the various challenges. For example, the size of the companies, the experience of using configurators, the previous presence of configuration supporting tools (e.g. those implemented in Excel), and the product complexity may influence the importance of the various challenges. Future research should be designed to specifically investigate the influence of these and other potential contingency factors, both to detect these factors and to explain how and why they play a contingency role. Given the importance of the organizational challenges, future research could take advantage of recent results in mass customization studies, which recognized that external environmental factors (e.g., demand dynamism) play a fundamental role in the strategic decisions (e.g., degree of product customization) a company intends to make, which in turn influence the organizational design choices (e.g., training and development of people for mass customization) [46–48].

This study focuses on the challenges of implementing and utilizing configurators by studying companies that are using configurators. Companies that abandoned their configurators (either in development or after launching the system) are not specifically addressed. Studying challenges that have led to abandonment of configurators' projects is surely interesting and valuable for both the research community and practitioners.

Finally, we focused our attention on identifying challenges and their importance. Challenges, once identified, need to be dealt with. More research should, therefore, be devoted to eliminating or reducing the impact of the important challenges. This includes more formalized procedures and methods to address the individual challenges (e.g., in terms of change management, knowledge acquisition and product modeling) specifically aimed at configuration projects.

5.5 Implications for researchers and practitioners

This study provides novel insights for researchers and practitioners by analyzing the main challenges manufacturing customizers face when implementing and utilizing configurators. This new insight has implications for both research and practice.

Having structured challenges in categories and subcategories allows the design of research on a high level (categories) and on a detailed level (sub-categories) of analysis. The results obtained at different levels can be compared, thus facilitating the building on the results of other studies. This facilitation is important, given the need to investigate different settings to assess generalizability and to explore possible contingency factors. Knowing the relative importance of the various categories and subcategories of challenges in specific kinds of companies not only sets a clear reference point for future studies, but also indicates more valuable directions on which to start to develop tools, support, and approaches to face the considered challenges successfully.

The results of the study provide practitioners a short list of main categories of challenges which are further structured in subcategories, each of which is described in various short examples. This structured and exemplified list of challenges may help managers to identify potential challenges. Furthermore, the information concerning the relative importance of these challenges in a sample accurately described allows them to understand whether their contexts are similar or not to that of one of the companies in the sample. In the end, practitioners can derive some indications on the most important challenges and strategically focus their attention to address them.

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Appendix 1: Consistency of the data

We check the overall consistency of the data gathered through open and closed questions. To perform this check, we used the figures shown in Table 1. For each category, columns 2-6 show the percentage of companies that (in the closed question) assigned a given level of importance to that category and that indicated (in the open question) a challenge belonging to that category. Columns 7-11 show the percentage of companies that (in the closed question) assigned a given level of importance to that category and that not indicated (in the open question) a challenge belonging to that category.

Table 1. Consistency check of the data sets – overall comparison between the data acquired through the closed and the open questions

	Companies indicating a challenge					**Companies not indicating a challenge**				
	None	**Low**		**High**		**None**	**Low**		**High**	
	None	*Very Low*	*Low*	*High*	*Very High*	*None*	*Very Low*	*Low*	*High*	*Very High*
IT challenges	**0%**	**13.64%**		**22.73%**		**9.09%**	**40.91%**		**13.64%**	
	0.00%	0.00%	13.64%	4.55%	18.18%	9.09%	31.82%	9.09%	13.64%	0.00%
Product modeling	**0.00%**	**9.09%**		**31.82%**		**9.09%**	**31.82%**		**18.18%**	
	0.00%	9.09%	0.00%	18.18%	13.64%	9.09%	13.64%	18.18%	18.18%	0.00%
Organizational challenges	**0.00%**	**22.73%**		**45.45%**		**13.64%**	**13.64%**		**4.55%**	
	0.00%	9.09%	13.64%	31.82%	13.64%	13.64%	4.55%	9.09%	4.55%	0.00%
Resource constraints	**0.00%**	**0.00%**		**22.73%**		**18.18%**	**36.36%**		**22.73%**	
	0.00%	0.00%	0.00%	13.64%	9.09%	18.18%	13.64%	22.73%	18.18%	4.55%
Product-related challenges	**0.00%**	**4.55%**		**18.18%**		**22.73%**	**45.45%**		**9.09%**	
	0.00%	0.00%	4.55%	9.09%	9.09%	23.73%	31.82%	13.64%	9.09%	0.00%
Knowledge acquisition challenges	**0.00%**	**18.18%**		**40.91%**		**18.18%**	**13.64%**		**9.09%**	
	0.00%	9.09%	9.09%	27.27%	13.64%	18.18%	9.09%	4.55%	9.09%	0.00%

APPENDIX E

International Journal of Industrial Engineering and Management (IJIEM), Vol. 8 No 3, 2017, pp. 157-165
Available online at www.iim.ftn.uns.ac.rs/ijiem_journal.php
ISSN 2217-2661

UDK 658.5:005

How to Identify Possible Applications of Product Configuration Systems in Engineer-to-Order Companies

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Received (07.03.2017.); Revised (09.05.2017.); Accepted (11.07.2017.)

Abstract *Product configuration systems (PCS) play an essential role when providing customised and engineered products efficiently. Literature in the field describes numerous strategies to develop PCS but neglects to identify different application areas. This topic is particularly important for engineer-to-order (ETO) companies that support gradual implementation of PCS due to large product variety and, several times, higher complexity of products and processes. The overall PCS process can thereby be broken down, and the risk minimised. This paper provides a three-step framework to identify different applications of PCS including the following steps: (1) identifying potential PCS, (2) aligning IT development, and (3) establishing an overview of PCS application. The study is supplemented by results from a case study in which the proposed framework was tested. The results from the testing confirm that the framework is applicable, as it leads to strategic and smart decisions regarding the implementation of PCS.*

Keywords: product configuration systems (PCS), *engineering-to-order (ETO) companies, applications*

1. INTRODUCTION

In response to increased global competition, companies are pressured to improve the capabilities of their products without compromising on price and time of delivery [1]. To cope with these challenges, companies are applying mass customisation strategies to greater extent.

Mass customisation strategies are applied both to mass producers that aim to increase variety and to engineering-to-order (ETO) companies that aim to increase the standardisation of their product offerings without limiting their customers. Product configuration systems (PCS) are a key element for achieving the benefits of mass customisation strategies [2] and represent some of the most successful applications of artificial intelligence [3]. PCS support in the product configuration process, which consists of activities that involve gathering information from customers and generating the required product specifications [4,5].

The literature describes numerous benefits that can be gained from implementing PCS, including preservation of knowledge, use of fewer resources, less routine work, reduced lead time, improved quality, and improved certainty of delivery [1,5–7]. However, there are also several challenges, such as applying PCS to complex products that become more expensive than anticipated and suffer from lack of acceptance due to insufficient scope [8]. For highly complex products with a large solution space, it can be infeasible to include all the requirements, as they can be very customer specific [9,10]. Other challenges include lack of documentation [11], updates and maintenance, knowledge acquisition, testing of knowledge, high dependency on configuration experts, and specification errors [12].

The implementation process for PCS is highly dependent on companies' manufacturing strategies and the degree of customisation. The degree of customisation offered by companies can be determined based on the customer order decoupling point, or the time when the customer becomes involved in the customisation process [1]. External factors such as dynamism in market and customer demands can also push these companies towards higher degrees of product customisation [13].

Traditional order fulfilment strategies, a highly characterizing component of the manufacturing strategies, are ETO, make-to-order (MTO), assemble-to-order (ATO), and make-to-stock (MTS) [14]. As there is no product customisation in MTS companies, this paper does not address them further. In MTO and ATO companies, there is a defined solution space where modules and components are combined according to pre-defined constraints. Solution space includes all the product attributes a company offers to cover diverse customers' needs [15]. The solution space is undefined in ETO companies and thus the number of possible configurations can be close to infinite [3]. PCS in ETO companies are, therefore, created with a high level of abstraction, as it can be too time consuming to define the solution space in a more detailed way [16]. Furthermore, due to the undefined solution space and the complexity of processes and products, multiple PCS are often implemented [17] to support specific parts of the sales and engineering processes. This raises challenges in identifying and prioritising different projects when implementing PCS in ETO companies.

The current literature describes different strategies for the development of PCS [1,5,8,18,19] but neglects to identify different applications for PCS. This is the step before the development process where potential PCS are identified, and it is especially important in ETO because of the vast product variety and process complexity that result in numbers of PCS. Thus, identifying the possible applications of PCS in a structured way is important to align the stakeholders and prioritise PCS projects. This paper aims to contribute to the literature and help practitioners by providing a framework that ETO companies can use to identify different applications of PCS. More specifically, this paper aims to answer the following research question (RQ):

> *How can ETO companies identify possible applications of PCS?*

A framework based on the experience of the research team and the literature in the field of PCS is proposed to answer the RQ. The study then validates this framework in a case study within an ETO company.

The remainder of the paper is organised as follows: Section 2 discusses the relevant literature, and Section 3 explains the research method. Section 4 proposes the framework. Section 5 presents the results from the case study. Section 6 discusses the results, presents the conclusions, and provides a direction for future research.

2. LITERATURE REVIEW

The literature is divided into three sections. Section 2.1 elaborates on the structure of PCS and interactions with other IT systems. Section 2.2 discusses the application of PCS. Section 2.3 describes development strategies for PCS and highlights the research gap.

2.1 Structure of PCS and integrations

The underlying IT structure of a PCS consists of configuration knowledge representation and reasoning, conflict detection and diagnosis, and, finally, a user interface [20]. The knowledge base, which represents the actual product data and the configuration logic, is the most fundamental technical component of PCS [3]. The configuration processes for complex products can be overwhelming in terms of the number of solutions that can be selected, and this can result in optimal solutions being ignored [21]. Therefore, a recommendation system is suggested in the IT architecture [21]. These recommendation technologies can be integrated into the PCS to support the end-user in the configuration process [22].

PCS can be applied as standalone software and as data-integrative and application-integrative systems [3]. Data-integrative PCS can be used to avoid data redundancies, as application-integrative PCS allow communication across different applications (e.g., CAD drawings can be generated from the output of the PCS) [3]. In terms of data integration for PCS, common sources for master data can be found in Enterprise resource planning (ERP) systems that often define a production-relevant view of the material. This is required for the assembly process and for product data management (PDM) and product lifecycle management (PLM) systems. It is also used for maintaining production-relevant data and for product information management (PIM) systems used to maintain sales-relevant data [19].

Different PCS can be integrated to increase the level of automation in the overall process (commercial and technical PCS, for example) [5]. Finally, PCS can be integrated into suppliers' systems to retrieve the required data from the configuration processes [23,24]. Numerous have explored the hypothesis that "the higher the degree of integration across the supply chain, the better a company performs" [25–28]. Having PCS integrated across supply chains (e.g., retrieving the information directly from suppliers in the configuration process) increases the accuracy of the specifications of highly customised products [17].

2.2 Application of PCS

The product configuration process can be defined as "all the activities from the collection of information about customer needs to the release of the product documentation necessary to produce the requested variant" [5]. The overall product configuration process can then be divided into sales and technical configuration processes [29]. The sales configuration process identifies products that fulfil customers' needs and determines the main characteristics of the products [29]. The technical configuration process generates documentation for the product based on the input gathered during the sales phase [29]. Customers may use PCS as a system that allows them to configure a product (e.g., on the Internet) and visualise the changes and impacts of specific selections. Alternatively, the system can be used as an internal tool to support the company's employees during the product configuration process [3].

The configuration process is more complex in ETO companies than in MTO and ATO companies due to the defined solution space [3]. PCS in ETO companies are normally used for design on a high level of abstraction, as defining the solution space on a more detailed level can be extremely time consuming [16]. This is in contrast to the solution space in MTO and ATO companies, which is better defined for different product configurations and enables detailed designs to be generated in the sales phase [1]. PCS can generate quotes for more detailed designs in MTO and ATO companies than it can for ETO companies [30]. The main output types generated by the PCS can divide the process of generating the products' specifications into three phases: (1) initial specification, (2) further product specification, and (3) quote creation [16]. Figure 1 illustrates how the level of detail for the PCS can be determined based on the output generated.

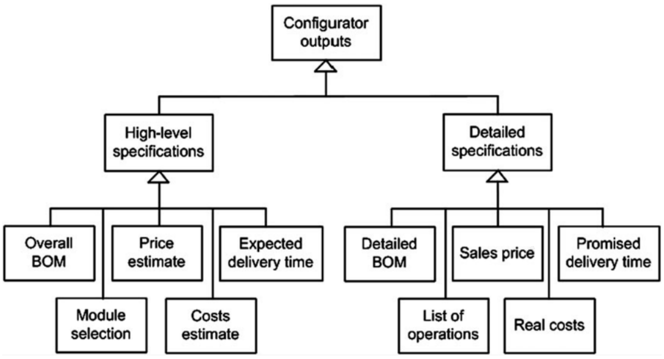

Figure 1. The main output from the PCS and level of detail required [16]

2.3 **Development strategies for PCS projects**

Studies in the field of PCS have proposed frameworks to guide the development of PCS projects [1,5,8,18,19]:
Shafiee et al. [18] propose a framework for scoping PCS projects in ETO companies. The framework helps companies to identify the users, IT architecture, prioritisation of products and product features, and project plan.
Haug et al. [8] have defined strategies for PCS in ETO companies by focusing on the involvement of different experts (product, knowledge representation, and configuration software) in the development and implementation processes of PCS.
Felfernig et al. [19] propose a development strategy based on the standard Unified Modelling Language (UML) design language to develop and cope with increasing complexity of the knowledge base. The three main components of the configuration environment are defined as knowledge acquisition, configuration, and reconfiguration. The authors propose a diagnosis at each stage [19].
Hvam et al. [1] provide a seven-phase framework that includes analysis and redesign of business processes, modelling of the product range, selection of PCS software, and modelling, implementation and maintenance of the plan.
Forza and Salvador [5] provide guidelines for the implementation of PCS, including benefit and cost analyses, planning of the implementation processes, and aligning the execution of the implementation with best practices.
These frameworks aim to increase efficiency of PCS projects, but none provides guidelines on how to identify different applications for PCS. In addition, only two of the frameworks mentioned above [8,18] are specifically aimed at ETO companies. Authors of a few studies [1,5,19] propose comprehensive frameworks that describe different processes involved in PCS projects. However, the literature does not provide instructions on how to identify different applications for PCS. As mentioned previously, this is especially important in ETO companies due to vast product variety and complexity. Thus, there is a need to create a structured framework to identify different applications for PCS in ETO companies.

3. RESEARCH METHOD

The research method in this paper is structured in two phases. The first phase explains the development of the framework that aims to provide a structured approach to identify different applications for PCS in ETO companies (Section 3.1). The second phase explains the validation of the framework that was achieved with a case study of an ETO company (Section 3.2).

3.1 **Framework development**

The framework is based on the literature in the field of PCS and the experience of the research team. More specifically, the literature enabled a better understanding of (1) PCS and their interaction with other IT systems, (2) application of PCS with a special focus on ETO companies, and (3) development strategies for PCS. The literature provides an input for the individual steps of the framework. The framework was developed in an iterative process and was improved based on feedback from the case company and discussions within the research team.

3.2 **Validation of the framework**

To validate the framework, a case study was conducted in an ETO company. A case study was selected for this purpose to allow this phenomenon to be studied in its natural setting [31]. Case studies also provide researchers with a deeper understanding of the relationships between variables and phenomena that are not fully examined or understood [32]. Further, they can be used to understand IT-related innovations and organisational contexts [33].
The company selected for the case study has worked with PCS since 2012, and the PCS projects have been selected mainly based on stakeholders' interests. There are numerous possible applications of PCS in the company, but an overview and a clear framework for implementing PCS were lacking. The company was selected based on its alignment with the focus of this study: to identify different applications of PCS in ETO companies.
To validate the framework, a project team was formed that included both researchers and the manager of the configuration team at the case company. The research team organised five workshops over a five-month period, each of which lasted an average of 1.5 hours. The first two workshops aimed to apply the proposed framework to the company's settings to identify different applications of PCS. These two workshops resulted in a report that drew on the proposed framework steps to

demonstrate different PCS applications for the company.

These results were presented to the managers of the IT department in the third workshop. Feedback received at this stage was used to improve the generated report.

In the fourth workshop, the revised results were presented to managers of the different business units (BUs) at the company. Approval to further involve employees, which was needed to verify the proposed applications of the PCS, was received in this workshop.

In the fifth workshop, managers at different levels from one of the BUs identified possible application areas for PCS. A valuable discussion arose among the managers. The first draft of the overall configuration process was aligned according to feedback received from these discussions. The final version of the report was then sent to all workshop participants for approval.

Section 5 provides examples of the results from the individual steps of the framework. Following the case study, we revised the framework—including a realignment of the proposed steps—to increase its clarity.

4. FRAMEWORK

This research proposes a three-step framework to guide the implementation process of PCS in ETO companies. The framework builds on related research fields and attempts to include the main aspects that must be considered when identifying possible applications of PCS in ETO companies. The steps of the proposed framework are: (1) identifying potential configurators, (2) aligning IT development, and (3) establishing an overview of PCS applications. Figure 2 shows the steps of the framework. The following sections provide further details of the individual steps.

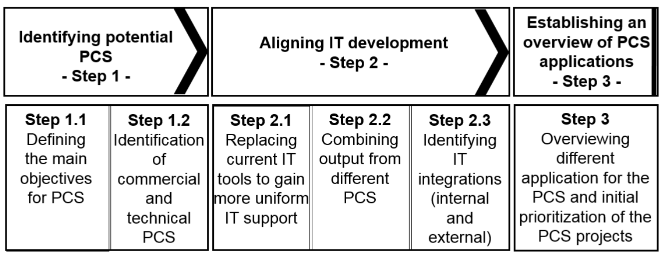

Figure 2. The proposed framework to identify applications of PCS

4.1 **Step 1: Identifying potential PCS**

Step 1 aims to identify potential PCS. This step is divided into two sub-steps: step 1.1 defines the main objectives for PCS, while step 1.2 identifies potential PCS (commercial and technical).

4.1.1 *Step 1.1: Defining the main objectives for PCS*

The literature describes numerous benefits achieved from using PCS, including reduction of man-hours and lead time when making product specifications [4,9,12,16], improved quality of product specifications [4,12,34,35], more on-time delivery [4,34,36], improved control of product variants [1,4,29,34,36], increased sales [30,37], improved knowledge management [4,30,38], improved accuracy of cost calculations, and, thus, increased profitability [39]. It is important that the objectives or benefits to be achieved are clear from the start, as they influence decision-making when evaluating commercial and technical PCS separately (Section 4.1.2) and when evaluating the complete overview of different PCS applications (Section 4.3.1).

4.1.2 *Step 1.2: Identifying commercial and technical PCS*

In this step potential PCS to support both the sales and engineering processes, or commercial and technical PCS [29] are identified. The objectives determined in step 1.1 serve as guidelines in this process. The following questions can be used as guidelines but can change depending on the objectives defined.

- Where are a considerable number of man-hours used when making product specifications?
- Are there quality issues related to specific product specifications?
- Where are the long lead times or bottlenecks? (For example, long waiting times can result from lack of work on product specifications, redesign loops, and lack of information).
- When are critical decisions made to avoid unnecessary complexity and increased cost?
- When are there delays (e.g., late delivery)?
- Where are there deviations between estimated and realised costs?

4.2 **Step 2: Aligning IT development**

Step 2 aims to provide an understanding of current IT systems used to generate product specifications, interactions across PCS, and other IT system interactions with PCS. This step is divided into the following three steps: 2.1 replacing current IT tools to gain more uniform IT support, 2.2 combining output from different PCS, and 2.3 identifying IT Integrations (internal and external).

4.2.1 *Step 2.1: Replacing current IT tools to gain more uniform IT support*

This implies a more standardised way of applying the IT systems needed to generate proposals and different product specifications. Actions can include replacing current tools or IT systems (e.g., Excel sheets) to create more uniform IT support for generating product specifications. This, in turn, allows for interactions across PCS used in different departments, as explained in Section 4.2.2. More uniform IT support can also be valuable in terms of: maintenance, user acceptance, and quality [39].

4.2.2 *Step 2.2: Combining output from different PCS*

Combining different PCS [1,5] means that different PCS within a company can interact. This helps to avoid data redundancy, as the same information does not have to be included in multiple PCS. Combining different PCS also streamlines the communications across different departments, where the PCS are used as platforms to exchange data and to give input (e.g., sales to engineering, and vice versa). This also implies that the outputs from one PCS are used as inputs for the other PCS (e.g., sequential process such as pre-sales, sales and engineering).

4.2.3 *Step 2.3: Identifying IT integrations (internal and external)*

The configuration process is highly dependent on retrieving information from both internal and external IT systems. Redundancy can be avoided by having integrations with other IT systems [3]. This step is thus concerned with identifying required IT integrations, both internal and external, in the configuration processes. Internal integrations include IT systems used within the company. These can include CAD, ERP, PDM, and PLM [1,3]. External IT systems integrations can retrieve information (prices, sizing parameters, etc.) needed during the configuration process from a supplier's database or even a PCS [17,23,24].

4.3 **Step 3: Establishing an overview of PCS applications**

Step 3 draws on analysis of the previous steps to establish an overview of different applications for PCS and create an initial prioritisation of the identified PCS.
This step takes into account the analysis performed in the previous two steps. The company's complete specification process is mapped based on the analysis performed in steps 1 and 2. This should provide a clear overview of how the specification process can be supported with PCS. After the overview is established, the overall specification process is evaluated based on the objectives defined in step 1.1. This provides initial input for the prioritisation of the identified PCS.

5. CASE STUDY

The case company is a world leader in catalysts and surface science. It offers a variety of catalysts and a complete range of proprietary equipment, spare parts, and consumables. The first PCS in the company was launched in 2013; since then, five new PCS have been introduced. The PCS cover some of the main product categories offered, such as catalysts, equipment, and processing plants. The approach of expanding the application of PCS has focused primarily on implementing new PCS, with little consideration for creating an optimised workflow based on overall objectives and aligning the different stakeholders. This approach served its purpose by quickly establishing the application of PCS and demonstrating the benefits the company can achieve. As the company recognised its expansion of PCS applications, an overview of the specification process was required where the potential PCS were identified. The results of implementing the individual steps of the framework at the case company are presented in the following sections.

5.1 **Step 1: Identifying potential PCS**

5.1.1 *Step 1.1: Defining the main objectives for PCS*

This step provides an understanding of the main objectives to be achieved from using PCS. The objectives are based on discussions with different stakeholders in the company and their experiences using PCS.
The case company has a high-level focus on increased digitalisation and automation of the sales and engineering processes. The following are the main objectives the company aims to achieve from increased use of PCS:

- Reducing routine work in the sales and engineering processes
- Decreasing the lead time to generate proposals and other specifications
- Increasing the hit rate as a result of shorter lead time to respond to customers' requests
- Improving the quality of the product specifications by reducing errors and increasing accuracy
- Empowering the global sales offices to generate product specifications

The importance of these individual objectives differs from project to project. For instance, a processing plant with a very low sales rate would invest in PCS to empower sales offices around the world and extract implicit knowledge from employees to make the information more explicit. The objectives are determined at the company level. However, since the following analysis was conducted on the BU level (as explained in Section 3.2), the following examples from the case study are based on one of the BUs.

5.1.2 *Step 1.2: Identifying commercial and technical PCS*

In this step, the sales and engineering processes were analysed based on the objectives in step 1.1 to identify processes where PCS can add value.
The BU already uses one commercial PCS that supports the sales process. The analysis revealed three potential new PCS: one commercial PCS and two technical PCS. Using both commercial and technical PCS enables the engineers to base their work on the output from the commercial PCS and to further work with the data inside the technical configurator.
This optimisation of workflow means that the relevant data for configuration is stored in a single system: a setup that allows both sales persons and engineers to work in a more optimal way. Figure 3 summarises the setup of the users, output documents, and interactions between the commercial and technical PCS identified. The interactions between the PCS are further discussed in step 2.2.

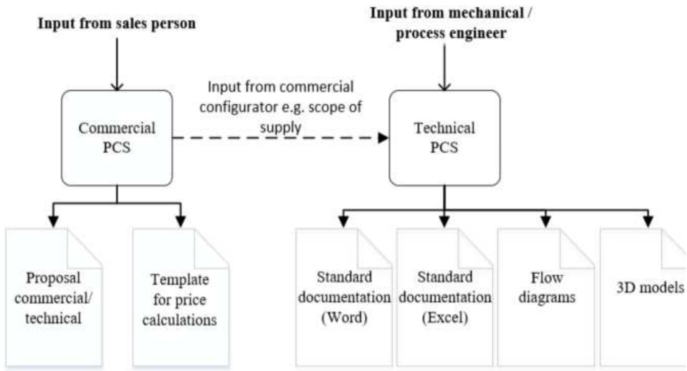

Figure 3. Setup for the identified commercial and technical PCS

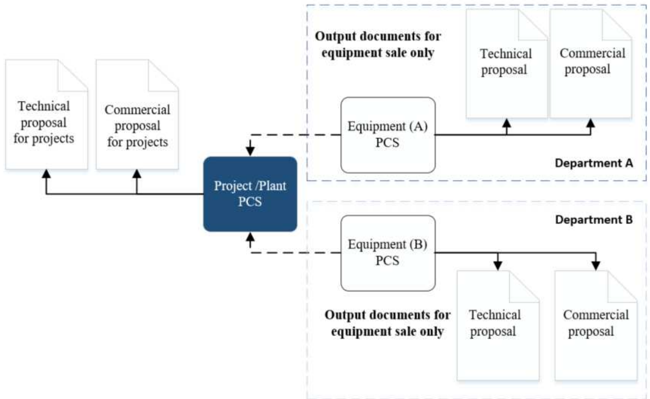

Figure 4. Generating output documents using information from PCS across departments

5.2 **Step 2: Aligning IT development**

5.2.1 *Step 2.1: Replacing current IT tools to gain more uniform IT support*

This step establishes an overview of different IT systems used to create product specifications with the aim of gaining more uniform IT solutions to support the sales and engineering processes.

The analysis revealed three Excel-based tools used in the sales process to generate quotations. These tools number more than 30 in the engineering processes. The reason for so many Excel-based tools is that specification processes are designed on a component level. In almost all cases, the Excel-based tools used by the engineers have interfaces to interact with other IT systems (e.g., calculation and simulation tools, CAD). They require expert users and are very department specific. This means that cross-department input requires an expert user in that department to operate the Excel-based tool.

The identified PCS (Section 5.1.2) can replace some of the Excel-based tools used to generate product specifications. The commercial PCS can replace the three Excel-based tools used in the sales process. The two technical PCS are not able to replace all Excel-based tools, but they can reduce them by about 80%. The reason for incomplete replacement is that the requirements in about 20% of the cases are too complex to include in the PCS.

5.2.2 *Step 2.2: Combining output from different PCS*

This step focuses on listing dependencies across departments, data sharing, and identifying how PCS support that process.

The analysis revealed great dependency across the different departments. When a project/plant is sold, input data for different equipment are required from the relevant sales departments.

This requires stakeholders to attend time-consuming meetings; often, the input data is received late. In response, a project/plant commercial PCS that can retrieve information from the other departments was identified. Figure 4 shows the interactions between the identified project/plant PCS and the other commercial PCS used for equipment configurations.

5.2.3 *Step 2.3: Identifying required IT integrations (internal and external)*

This step lists the different IT systems used in the BU and includes descriptions of how those IT systems are used.

The company has already established some essential integrations for the commercial PCS already in use. These include integrations to databases storing information related to previously sold equipment and software performing both complex calculations and simulations. Other minor integrations are also established (e.g., to retrieve an updated currency rate). The analysis in this step reveals the following IT system requirements for interacting with the PCS:

- Integrating the commercial PCS to an ERP system to retrieve information related to customers and cost
- Integrating the technical PCS to a CAD system to generate 3D models
- Integrating the commercial PCS in the company with the *suppliers' systems* to ensure that information is up-to-date and to eliminate the need for manual adjustments

5.3 **Establishing an overview of PCS applications**

The overview was generated in a workshop where the results of the previous steps were presented to the managers of the BU. The results provided a guideline to draw up a figure that the managers could agree on. Figure 5 shows a simplified version of the overview. Additionally, based on how the PCS contributed to the overall objectives, the BU managers could make the initial prioritisation of the different PCS.

By involving BU managers in the process of creating this overview, a common understanding and ownership were established regarding the application of PCS. Having managers within the BUs on board is defined as a key success factor in achieving the objectives of the PCS.

The results of applying our framework to the company and establishing an overview of different PCS applications led to additional work to support expansion of the PCS. This included defining how testing, maintenance, and user support should be designed. Furthermore, recourse was considered for the configuration team to ensure they would have the capacity to implement the potential PCS identified. A governance structure and a commitment of business resources were also defined. Finally, collaborations with external actors were discussed to share knowledge across ETO companies and to stay up-to-date on the newest developments in the area.

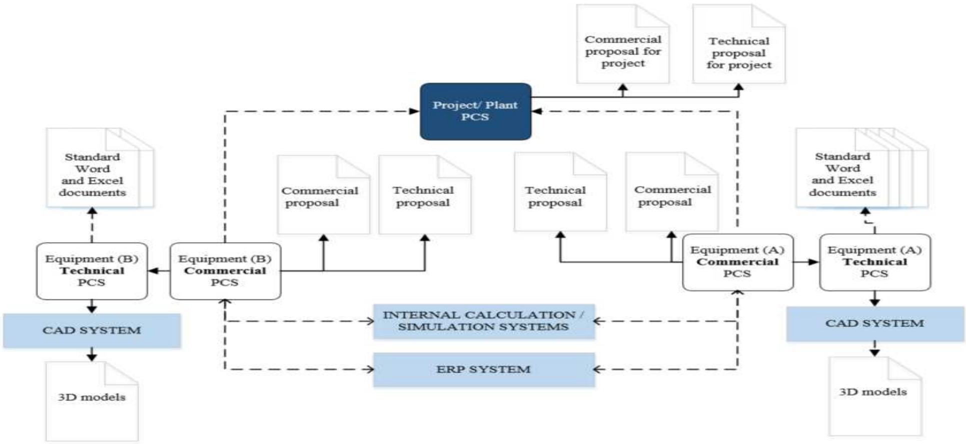

Figure 5. Simplified overview of how the sales and engineering processes can be supported by PCS and other IT systems

6. DISCUSSION AND CONCLUSION

In many cases, ETO companies are characterised by high product and process complexity. PCS used in ETO companies are often designed with a high level of abstraction due to a large solution space [16]. The configuration process can be divided into sales and technical processes, and corresponding commercial and technical PCS can be used to support those processes.

While the literature describes different development strategies [1,5,8,18,19], these frameworks do not provide guidelines for identifying different applications of PCS. This type of framework is especially important in ETO companies because projects with high complexity require gradual implementation of PCS [10]. The complexity in ETO companies results in multiple PCS. This paper contributes to the literature of PCS and managerial practice by proposing a framework to identify different applications of PCS in ETO companies to guide the implementation process.

Following a structured method of identifying different applications of PCS in ETO companies helps companies with strategic planning when justifying their investments in PCS projects, as they can demonstrate different PCS applications. This helps to align the main stakeholders, as they have a common understanding of different possibilities of using PCS.

Furthermore, this method provides an overview of the complete product specification process that can be supported with multiple PCS and the required integrations with other IT systems. With a complete overview of the configuration process, optimised workflow can be established and different PCS projects can be prioritised.

The proposed framework to identify different applications of PCS is based on both literature and experience of the research team. The framework consists of three main steps: (1) identifying potential PCS, (2) aligning IT development, and (3) establishing an overview of PCS applications.

The framework is validated through a case study in an ETO company. The case company had already introduced commercial PCS with the aim of supporting the sales process. However, the company recognised that they needed an overview to further expand the application of PCS. The results of the case study show that the framework provided a structured approach for this purpose. The framework also gave the main stakeholders a common understanding of the overall objectives of PCS in terms of implementation and the initial prioritisation of projects. The process of creating this overview proved beneficial, as the stakeholders were able to express their opinions and take ownership of the projects. The involvement of relevant people thus led to strategic and smart decisions.

Even though the proposed framework is successfully validated in an ETO company, the authors of the paper recognise the limitations of having only one case study. Further studies should therefore include testing the proposed framework in other ETO companies. This should also include companies that have not introduced PCS. We decided to focus on ETO companies because they cover both process and product complexity. Future studies will also validate if the proposed framework can be used in companies with different manufacturing strategies and degrees of customisation.

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Kako identifikovati moguću primenu sistema konfiguracije proizvoda u kompanijama koje projektuju po narudžbini

Katrin Kristjansdottir, Sara Shafiee, Lars Hvam

Primljen (07.03.2017.); Recenziran (09.05.2017.); Prihvaćen (11.07.2017.)

Apstrakt *Sistemi konfiguracije proizvoda (SKP) imaju važnu ulogu u efikasnom obezbeđivanju personalizovanih proizvoda. Literatura u oblasti opisuje veliki broj strategija razvoja SKP, ali ne identifikuje različita polja njihove primene. Ova tema je posebno važna za kompanije koje projektuju po narudžbini i podržavaju postepenu implementaciju SKP zbog velike raznovrsnosti proizvoda, kao i višestruko veće složenosti proizvoda i procesa. Na taj način proces SKP može biti razložen, a rizici svedeni na minimum. Ovaj rad predlaže okvir u tri koraka koji identifikuje različite primene SKP i uključuje sledeće korake: (1) identifikacija potencijalnih SKP, (2) usklađivanje IT razvoja i (3) utvrđivanje pregleda primene SKP. Ovo istraživanje je podržano rezultatima studije slučaja u kojoj je predloženi okvir testiran. Rezultati potvrđuju primenljivost okvira, koji vodi do strateških i mudrih odluka koje se tiču implementacije SKP.*

Ključne reči: sistem konfiguracije proizvoda (SKP), *projektovanje po narudžbini, primena*

APPENDIX F

Framing business cases for product configuration system project success

S. Shafiee, K. Kristjansdottir, L. Hvam, A. Haug, C. Forza and E. Sandrin

Abstract. In recent years, product configuration systems (PCSs) have received increased attention as a means to provide customised products that bridge the gap between customers' requirements and products variants. As for most types of projects, creating well-defined business cases (BCs) before initiating PCS projects increase the chances of project success. The BC supports the arguments or rationales on why the organization should accept and invest in PCS. However, the existing literature fails to offer structured frameworks to guide PCS projects or analyse the projects' success factors. Therefore, based on a review of BC literature, this paper aims to provide such a framework. The proposed framework comprises the following four steps: (1) analyse the goals and benefits, (2) determine the stakeholders' expectations, (3) analyse the current process to propose scenarios in which PCSs increase the efficiency of the process, and (4) evaluate the new scenarios based on cost-benefits, sensitivity and risk analysis. The proposed framework was tested in three PCS projects at two engineering companies and use a qualitative exploratory design based on multiple data sources – documentation, workshops and participant observation – to evaluate the framework. These studies demonstrated the applicability of the proposed framework.

Keywords: *Product configuration system (PCS); business case (BC); IT projects; cost-benefits; risks analysis*

1. Introduction

One of the main characteristics of the modern economic systems is the increase of product varieties offered by different manufacturers (Forza and Salvador, 2007). Growing product variety at companies has led to an increased complexity of products and processes, which requires better stakeholders' coordination when generating product specifications (Forza and Salvador, 2007). Product configuration systems (PCS) enable companies to develop product alternatives to facilitate the sales and production processes (Felfernig, Hotz, et al., 2014) by incorporating information about product features, product structure, production processes, costs and prices (Forza and Salvador, 2007). Widely used in various industries, PCS can bring substantial benefits, such as shorter lead times for generating quotations, fewer errors, increased ability to meet customers' requirements regarding product functionality, the use of fewer resources, optimised product designs, less routine work and improved on-time delivery (Ardissono et al., 2003; Barker et al., 1989; Hvam et al., 2006; Petersen, 2007).

The advantages of PCS are evident but there are still some difficulties associated with high cost of development and chances of failure in PCS projects (Forza and Salvador, 2007). The complexity of PCS projects is discussed in the literature (Ardissono et al., 2003; Salvador and Forza, 2004), which can be clarified in terms of (1) a diverse set of process elements (e.g. machines, operations), (2) a high variety of component parts and assemblies, and (3) a large number of constraints and rules (Zhang and Rodrigues, 2010). This complexity leads to challenges on the initial analysis and cost estimation of investments because the configuration team lacks the adequate resources and knowledge, the acquired knowledge is subjective, and the project does not have a defined scope and extension (Haug and Hvam, 2008; Nonaka, 1994; Studer et al., 1998). Furthermore, as PCS projects typically involve a various range of different stakeholders with different expertise (Haug, 2010; Hvam et al., 2008), it is difficult to anticipate the expectations and implementation costs beforehand (Friedrich et al., 2014). To address these challenges, it is essential to develop a structured PCS project plan and establish a well-structured business case (BC) (Shafiee et al., 2016).

The BC is concerned with the primary question (Salzmann et al., 2005): What do the business community and organizations get out of this investment? More specifically, the BC is a 'description of a situation or sequence of events confronting an individual, a set of individuals, or an organisation; while it includes a detailed story of the events leading to a conclusion' (Matejka and Cosse, 1981). The BC refers to the bottom-line financial and other reasons for businesses pursuing PCS. Information included in a formal BC could be the background of the project, such as: the expected business benefits, the considered scenarios (with reasons for rejecting or carrying forward each option), the expected costs of the project, a gap analysis and the expected risks (Bentley, 2005). Turley (2007) describes the BC as a document that explains the reasons (why) for the project, in terms of cost, risks and benefits. BC explains in detail why the project should be done and why the final outcome is desired. During the project lifetime, whenever a risk appears, the odds should be weighed against the BC to check if the benefits still exist within the expected time and cost constraints (Turley, 2007).

Some studies have highlighted tools or frameworks available for BC in IT projects in general (Gambles, 2009; McNaughton et al., 2010; Nielsen and Persson, 2016), and still others have discussed different topics related to BCs in PCS projects, such as stakeholders' analysis (Tiihonen et al., 2014; Zhang, 2014) and process evolutions (Felfernig et al. 2014; Zhang 2014). However, existing literature fails to provide a systematic framework to guide the definition of BCs for PCS projects.

To address the mentioned gap in the literature, this paper proposes a framework that identifies the most important steps in BC development for PCS projects. This framework is built on generic BC frameworks designed for the IT projects and available steps and tools related to BC of PCS projects. By using this framework, companies can improve the quality to determine the business value on PCS projects and reduce the complexity by limiting the scope to stakeholder's requirements, evaluate the current process and assess the future scenarios with the return on investment (ROI). The proposed framework is tested in three case projects.

The remainder of the paper is structured as follows. Section 2 describes the research method, and Section 3 reviews and discusses the relevant literature. Based on the literature, Section 4 develops a BC framework for PCS projects, and Section 5 discusses the results of the empirical studies. The paper ends with discussion and conclusions in Section 6 and 7.

2. Literature study

First, the literature review discusses the specific requirements and tools for BCs in PCS projects and the lack of suitable frameworks. The recommended tools help the companies to overcome specific challenges in different phases of PCS projects related to BC (e.g. Felfernig, Bagley, et al., 2014; Felfernig, Hotz, et al., 2014; Heiskala et al., 2007; Hvam et al., 2008; Kristjansdottir, Shafiee and Hvam, 2016a; Mortensen et al., 2008).

Next, BC frameworks developed for IT projects, in general, are identified in order to determine whether any of them are applicable to configuration projects (e.g. Gambles, 2009; McNaughton et al., 2010; Nielsen and Persson, 2016). Moreover, comparing different studies led to conclusions about a basic BC framework for IT projects.

Finally, the differences between the required BC frameworks for IT projects in general and configuration projects are identified. This comparison highlighted the need for BC frameworks tailored for configuration projects (see, e.g., Basili and Weiss, 1984; Forza and Salvador, 2002; Friedrich et al., 2014; Tiihonen et al., 1996). Nevertheless, BC frameworks for IT projects could serve as a foundation for developing BC frameworks for configuration projects and for proposing ad hoc frameworks.

2.1. PCS and BC challenge

The BC explains the level of value creation of the configuration systems from different perspectives (Ward and Daniel, 2006). Despite the importance of BCs in PCS projects, there are few researchers and studies related to different steps of BC with a specific application in PCS projects. Although existing PCS literature fails to provide a detailed definition of BCs, some aspects that involve BCs have been described. Existing literature that focuses on PCS projects reflects different steps and tools separately required; however, there is a need for academic and practitioners to combine these steps in a framework.

Benefit analysis is essential for PCS projects because it determines the requirements of the project and sheds light on the project scoping (Hvam et al., 2008; Shafiee et al., 2014). Some goals are suitable for all PCS projects (Ardissono et al., 2003; Petersen, 2007); while others are suited to individual projects (section 4.1). The goal of the project typically determines the expected outputs from the PCS project, helps manage the knowledge and determines the stakeholders (Felfernig, Bagley, et al., 2014; Forza and Salvador, 2002; Heiskala et al., 2007; Kristjansdottir, Shafiee and Hvam, 2016; Mortensen et al., 2008)

Stakeholders' analysis examines the users' expectations and requirements for the system, which increase as the PCS projects become more successful and popular among users (Barker et al., 1989). Stakeholders' analysis is usually described as one of the most difficult components of PCS projects planning because the stockholders vary considerably and they have different levels of expertise (Forza and Salvador, 2002). Furthermore, the existing literature contains limited suggestions of available tools or methods for communicating with the stakeholders. Customer needs elicitation entails a process of identifying what a customer wants (Zipkin, 2001). Determining the stakeholders and analysing their requirements before starting the projects enables decisions to be made that save time and resources (Felfernig, Hotz, et al., 2014; Mortensen et al., 2008; Salvador and Forza, 2007; Shafiee et al., 2014).

Process analysis is a major step to perform before initiating a PCS project because it typically involves analysing the current sales and engineering processes and redesigning them to increase the efficiency by the help of PCS (Forza and Salvador, 2007). Future process analyses could include IT architecture and IT requirements if needed. A GAP analysis is then conducted to measure the performance of the current process and set goals for the target performance. Furthermore, the GAP analysis can show how the different scenarios contribute towards the targeted performance (Hvam et al., 2008; Shafiee et al., 2014; Tidstam and Malmqvist, 2010).

A cost and risk analysis is carried out to compare the different scenarios. Existing literature has conducted cost estimations to evaluate the savings from the PCS and performed a sensitivity analysis to analyse the costs and risks of the PCS project before the planning phase (Kristjansdottir, Shafiee, Hvam, et al., 2016). These risks are categorized for PCS projects in the literature (Hvam et al., 2008).

Table 1 summarizes and groups the relevant literature based on the introduced steps. While the existing PCS project literature includes different aspects related to BCs development elaborated in section 4, a structured framework that incorporates these aspects into a structured and sequential manner does not yet exist.

Table 1. Available literature for BC in configuration projects

	Benefit analysis	**Stakeholders' analysis**	**Process analysis**	**Cost and risk analysis**
(Barker et al., 1989)		✓		
(Zipkin, 2001)		✓		
(Forza and Salvador, 2002)		✓		
(Ardissono et al., 2003)	✓			
(Petersen, 2007)	✓			
(Mortensen et al., 2008)	✓			
(Heiskala et al., 2007)	✓			
(Forza and Salvador, 2002, 2007)	✓	✓	✓	
(Hvam et al., 2008)	✓	✓	✓	✓
(Shafiee et al., 2014)	✓	✓	✓	
(Felfernig et al., 2014)	✓	✓		
(Kristjansdottir, Shafiee, Hvam, et al., 2016)	✓			✓

2.2. Business cases for IT projects

Studies show that many information technology (IT) projects fail to achieve their goals or stay within deadlines and budgets (Berghout and Tan, 2013; Gulla, 2011; Mieritz, 2012; Wiklund and Pucciarelli, 2009). However, the right IT investments have a positive effect on technical efficiency (Shao and Lin, 2000, 2001, 2002), leading to improved financial performance and other tangible benefits (Stratopoulos and Dehning, 2000; Taylor et al., 2012; Van Der Zee and De Jong, 1999). In this context, it has been shown that investing time to identify the benefits, expectations, financial needs and risks of an IT project can minimise the chance of project failure (Whittaker, 1999). Most IT project failures can still be explained by a lack of project planning and weak BC (Kozak-Holland, 2005; Whittaker, 1999). Therefore, structured BC framework can guarantee the success of the IT projects. More specifically, BCs determine the success of IT investments by empowering organizations to: (1) undertake informed decisions regarding IT projects; (2) monitor the progress of investment projects; and (3) evaluate project outcomes upon completion (Barnes, 1995; Remenyi and Sherwood-Smith, 2012; Ward et al., 2008). Studies indicate that the richness of BCs will result in the identification of initial costs to be invested in IT projects, thereby conserving resources for the organization through informed investment decisions (Berghout and Tan, 2013).

As Table 2 shows, multiple frameworks for BCs have been developed for IT projects, many of which contain overlapping elements. Some authors focus on the steps of BC development at a high level of abstraction (Ashurst et al., 2008; Taylor et al., 2012) while others are more detailed (McNaughton et al., 2010; Nielsen and Persson, 2016). Furthermore, some researchers use different terms to describe the same steps, such as 'cost modelling' and 'cost estimation' (Ashurst et al., 2008; Gambles, 2009). Based on the literature, the main elements for BCs in IT projects can be described as (1) benefit analysis, (2) stakeholder's analysis, (3) IT requirements and (4) risk and cost analysis. However, these frameworks have limited usefulness for supporting the definition of BCs in PCS projects because of the differences between general IT projects and PCS projects. This is discussed further in the following section.

Table 2. Main elements of business cases in IT projects

Researcher	Main elements of BCs in IT projects
(Gambles, 2009)	(1) Strategic fit, (2) Stakeholders' analysis, (3) Benefits mapping, (4) Cost modelling, (5) Risk analysis
(Ashurst et al., 2008)	(1) IT gap analysis, (2) IT scenario analysis, (3) Cost estimation
(Häkkinen and Hilmola, 2008)	(1) Benefits analysis, (2) Stakeholders' analysis, (3) IT requirements and gap analysis, (4) Risk analysis
(McNaughton et al., 2010)	(1) Benefits analysis and objectives, (2) Stakeholders' analysis, (3) IT requirements, (4) Cost modelling
(Taylor et al., 2012)	(1) Stakeholders' analysis, (2) Technical requirement, (3) Cost modelling, (4) Risk management
(Bechor et al., 2010)	(1) Benefits analysis, (2) Stakeholder' requirement, (3) IT gap analysis, (4) IT scenario analysis, (5) Risk analysis, (6) Cost estimation
(Nielsen and Persson, 2016)	(1) Objectives and motivations, (2) Benefits, measures, and stakeholders, (3) Structure and benefits, (4) Costs and risks

However, these frameworks have a limited ability to support the BC process in configuration projects because of the differences between IT and configuration projects, which are explained in detail in the following section.

2.3. Comparing IT and PCS projects

There are several differences between IT projects and PCS projects compared to other IT projects as the reasons for having a separate research area for PCS (illustrated in Figure 1).

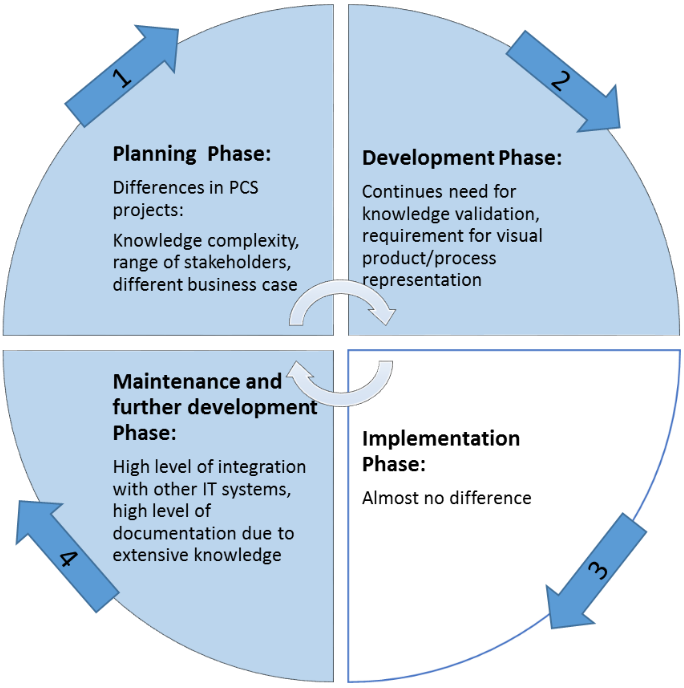

Figure 1. Different phase of PCS projects and differences from IT projects.

Because of the knowledge complexity and extensions in PCS, it is essential to determine the scope of the project in the early phases in order to determine the entire flow of the project. This is done by identifying the requirements, evaluating the time and budget, and prioritising the different products and functions depending on the variety and complexity of the knowledge, the required tasks and the resources for the project development (Shafiee et al., 2014). The scope of IT projects is determined differently because not all of them necessarily involve with extensive product knowledge. In PCS projects, goals and stakeholders' requirements from the first steps have to be clarified; due to the complexity of the involved knowledge, the range of stakeholders, and special system requirements (Studer et al., 1998).

In PCS projects, the goals and the stakeholders' requirements need to be clarified more detail in the first steps because of the complexity of the involved knowledge, the range of stakeholders and the special system requirements (Studer et al. 1998). The extensive and complex nature of the knowledge required for PCS projects highlights the need to scope the project in the very early phases (Shafiee et al. 2014).

While the knowledge required for IT projects typically does not need to be communicated, updated and validated continually (Coram and Bohner 2005), in PCS projects, the configuration team[1] needs to

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[1] The team working on configuration projects include knowledge engineers, modellers, developers and project managers (Hvam et al., 2008).

communicate with the domain experts[2] regularly to validate the vital and extended product knowledge (Forza and Salvador 2002). Hence, all available solutions need to be visualised before planning the PCS project to evaluate the best option (Hvam et al. 2008).

The reported risks for PCS projects are different from those for IT projects in terms of underestimating the required development and maintenance time and resources (Haug and Hvam 2007). The knowledge has to be clear and understandable to all stakeholders in non-IT language for many reasons. The knowledge required for configuration projects is normally very specialised product knowledge that lies beyond the configuration team's expertise (Haug and Hvam, 2008; Studer et al., 1998). For example, a knowledge engineer needs to learn the different domain aspects from the experts to model a medical equipment. In addition, the frequent changes in product knowledge necessitate continual updating and maintenance of the knowledge (Tiihonen et al. 1996a; Alexander Felfernig et al. 2000; Friedrich et al. 2014). Additionally, PCS projects have a high level of integration with other IT systems (Felfernig et al. 2014), which implies a particular need for IT development, testing and collaboration. (Haug and Hvam, 2007), which might be explained by the complexity of the involved knowledge, the range of stakeholders, special system requirements, specific risks and different cost estimations (Hvam et al. 2008; Studer et al. 1998).

To conclude, while PCS projects are categorised as IT projects, some fundamental differences exist, including different evaluations of the time and resources to be allocated to these projects. Specific BC frameworks are therefore required for PCS projects in which the specific steps of the framework support the specific needs of the PCS projects.

3. The proposed framework

3.1. Framework development

The development of the framework was based on (1) the literature review, (2) analytical thinking and (3) iterative design method through interactions with industrial partner.

From the literature review, we obtained the following tools and methods for the individual phases of BC in configuration projects: (1) benefit analysis, (2) stakeholders' analysis, (3) process analysis, scenario making and gap analysis, (4) scenarios evaluation including cost-benefit, sensitivity and risk analysis.

Analytical thinking breaks the problem down into smaller sections, and the authors' experiences from working with over 20 industrial partners on different PCS projects are used to make the framework more comprehensive. Categorizing different aspects of BC in the literature supported the organization of concepts into hierarchical components and the consequent investigation of keywords for each section.

The iterative design method, which blends the activities of designer and user, creator and player, is based on a cyclical process of prototyping, testing, analysing and refining a work in progress (Zimmerman, 2003); The developed framework is then tested, discussed and outlined within one case company over 6 months. The framework development is based on the results of the literature review, analytical thinking and

[2] The experts who provide domain knowledge of the process of performing the task and the data content, as well as quality assurance, verification support (Barker et al. 1989).

interactions with an industrial partner (case company). The industrial partner for developing the framework was an experienced team that has experienced both successes and failures in configuration projects.

3.2. Framework overview

Although, the framework suggested in this paper is based on currently available BC frameworks for IT projects, it is different from general BC frameworks for IT systems. More specifically, although the literature indicates that it is possible to use the sequence and core of the available BC frameworks designed for IT projects (benefit analysis, stakeholder's analysis, IT requirements, and risk and cost analysis) in PCS projects, there are some central differences. For example, PCS projects latter call for a stronger process evaluation and reporting of challenges for more accurate cost estimation (Forza and Salvador, 2007). In most cases, the IT structure and platform for the PCS projects is decided when the concept of PCS is established in the company (Hvam et al., 2008) and there is no need to discuss the IT architecture in each BC every time. Hence, based on existing literature, discussions and initial testing, the IT requirement step is merged with the process analysis, scenario making and gap analysis, which can include IT architecture discussions in the decided future scenario if necessary. Because of the reports on inaccurate cost estimations in PCS projects both from academia and industry, a sensitivity analysis step (Hvam et al., 2008) is introduced. On this basis, the following are the main steps for a BC framework in PCS projects:

(1) Benefit analysis
(2) Stakeholders' analysis
(3) Process analysis, scenario making and gap analysis
(4) Scenarios evaluation:

- Cost-benefit analysis
- Sensitivity analysis
- Risk Analysis

Table 3 subsequently summarizes the tools described in literature for IT projects in general and for PCS projects with respect to the proposed framework.

Table 3. The contribution of proposed framework in the field of business cases in configuration projects

	BC literature and Tools for IT projects:	**The BC proposed framework Configuration projects**
1. Benefit analysis	No specific tool	We consider it as the first step as it defines the next requirements. Interview and workshop sessions help in gathering and deciding about the tools and align them with the overall strategy in case companies.
2. Stakeholders' analysis	Unified modelling language tools including Use case diagrams, MoSCoW tables	After determining the goals of the project, stakeholders should be introduced. We promote the use case diagrams to define the requirements and MosCoW rules to prioritize them. The requirements gathered and prioritized during the workshops.
3. Process analysis, scenario	Process flowcharts, gap analyses	In this step, AS-IS and TO-BE flowcharts demonstrated the current and future process of the

making and gap analysis			project. Then gap analysis introduced in order to illustrate the current situation and future situation differences in terms of: lead time, quality, resources, and sales.
4. Scenarios evaluation	Cost-benefit analysis	ROI	We used the ROI to calculate and demonstrate the profitability of the projects.
	Sensitivity analysis	Sensitivity analysis	Sensitivity analysis was conducted to measure the parameters frequency used to calculate the savings and its effects on the overall expected savings. If many factors have uncertainty, the sensitivity analysis can warn the managers of possible changes in the project's profitability.
	Risk Analysis	Formulas, analytical frameworks, checklists, process models, risk response strategies	We used checklists to list up all the probabilities regarding different threats for the projects including the change management to the loose of resources.

3.3. Benefit analysis

The literature emphasises the various benefits gained by using PCSs in different organisational settings. The most common benefits from PCS can be listed in terms of reduced lead times, reduced resource consumption, higher quality of specifications, higher independency from domain experts, better decision-making in the early phases of sales, accurate and error-free quotations, less rework and higher customer satisfaction (Ardissono et al., 2003; Barker et al., 1989; Forza and Salvador, 2007; Hvam et al., 2008; Petersen, 2007; Tenhiälä and Ketokivi, 2012; Trentin et al., 2012).

Based on the commonly described benefits, the goals of the implementation must be aligned with the company's current strategy and difficulties. Identifying the goals and the desired benefits from the implementation of the PCS is highly important because it will guide the next steps.

3.4. Stakeholder analysis

Identifying the main stakeholders' requirements helps to understand the goal of the project (Basili and Weiss, 1984). Existing literature conducts stakeholder analysis for IT (Bittner, 2002; Ebert, 1997; Jiao and Chen, 2006; Lim et al., 2011) and PCS projects (Friedrich et al., 2014; Hvam et al., 2008; Mortensen et al., 2008; Nellore et al., 1999). For IT projects, the project requirements can be divided into two types: functional and non-functional. A non-functional requirement describes not what the software will do, but how the software will do it (Ebert, 1997), and a functional requirement specifies each of the functions that a system must be capable of performing (Ebert, 1997). Use case diagrams express the requirements and define the actors involved in the project (Kruchten, 2007). The demand for better communication among the stakeholders, specifically in PCS projects, led to illustrating and prioritising the requirements with use case diagrams (Hvam et al. 2008; Shafiee et al. 2014). The MoSCoW rule, meaning Must have (Mo), Should have (S), Could have (Co), Want to have (W), is also beneficial for prioritising the stakeholders' requirements (Bittner, 2002).

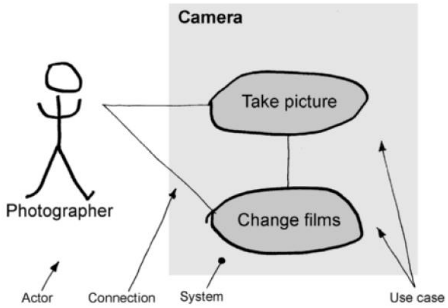

Figure 2. Example of a use-case diagram (Hvam et al., 2008).

3.5. Process analysis, scenario making and gap analysis

An analysis of the specification process at the company can be conducted to obtain an overview of the most important activities, their sequences and connections, and to list the persons responsible for the different activities, information flows and the processes' inputs/outputs (Hvam et al., 2008). Understanding the current processes is fundamental for designing how the future processes should look when PCS is incorporated.

Multiple tools are available for this purpose, such as flowcharts with Business Processes Modelling Notation (BPMN) (White, 2004). Gap analysis is recommended for comparing the operational performance with the target goals and identifying the gap that needs to be bridged (Hvam et al., 2008). Once the gap is identified, different scenarios can be generated to demonstrate how a PCS can be used to ensure the current situation reaches the targeted performance (Hvam et al., 2008).

3.6. Scenario evaluation

The last step of the framework evaluates the proposed scenarios based on the following analyses (Hvam et al., 2008; Shafiee et al., 2014):

- Cost-benefit analysis
- Sensitivity analysis
- Risk analysis

Discussions concerning the complexity and unpredicted costs of PCS projects indicate that the rough estimations involved in cost and risk analysis for BCs are considered a challenge that needs more attention from academia (Shafiee et al. 2014).

The financial benefits of PCS projects should be clear from the beginning, and cost evaluation is important when conducting BCs. Cost-benefit analysis is used to compare the expected costs and benefits for different scenarios and the results from a variety of actions (Haddix et al., 2003). Return On Investment (ROI), which is commonly used as a cost-benefit ratio, is a performance measure used to evaluate the efficiency of a number of different investments (Phillips and Phillips, 2010), and it has been used to determine the profitability of PCS projects (Kristjansdottir et al., 2016). The ROI is calculated as demonstrated in Equation (1) (Phillips and Phillips, 2010).

$$ROI = \frac{\text{Gain from investment} - \text{Cost of investment}}{\text{Cost of investment}} \quad (1)$$

Sensitivity analysis is conducted to measure the uncertainty or changes in different parameters and increase the accuracy of the cost analysis. Sensitivity analysis represents the certainty which can be apportioned to different sources of uncertainty in its output (Saltelli, 2002); and is grouped into four main categories: decision-making or development of recommendations for decision makers, communication, increased understanding or quantification of the system, and model development (Pannell, 1997). In this research study, sensitivity analysis is mainly used to perform cost estimation to improve the cost estimation and calculate the uncertainties in ROI.

IT project risk analysis aims at improving the chances of achieving a successful project outcome and/or avoiding project failure by identifying, analysing and managing risk factors (Boehm, 1991). Mathematically, R = P*I, where R is the risk exposure attributable to a particular risk factor, P is the probability the undesirable event will be realised, and I is the impact or magnitude of the loss if the event occurs (Boehm, 1991). Four inter-related approaches to risk analysis are checklists (Boehm, 1991; Johnson et al., 2001), analytical frameworks (Cule et al., 2000), process models (Boehm, 1991) and risk response strategies (DeMarco and Lister, 2013). In the context of PCS use, a scenario's risks can be divided into risks associated with (1) developing a PCS (knowledge management, system ownership, modelling issues, complicated systems), with (2) risks associated while deploying and using a PCS (lack of training, inadequate testing, lack of motivation for users) and with (3) maintenance, and further development of a PCS (neglecting documentation, lack of commitment for further developments, out of date system) (Hvam et al., 2008).

4. Research method

4.1. Method setting

To test the developed framework, a case study approach was used. Case study research seeks to find logical connections among observed events, relying on knowledge of how systems, organisations and individuals work (Kaplan and Duchon, 1988; McCutcheon and Meredith, 1993). However, the framework's actual practical performance can be proved by applying it to several real cases. For this reason, we decided to apply our framework to case companies. Understanding the 'how' and 'why' is one of the main reasons for using multiple case studies in several disciplines, such as explanatory studies in operations management and technology management (McCutcheon and Meredith, 1993; Yin, 2013). However, because applying a framework requires not only a company's availability but also considerable time and resources in the organisation, we were able to apply the frameworks in only four projects at two companies. The study of a limited number of case applications allowed us to conduct a detailed assessment of how the framework works and to understand why it may present challenges in application. The research team observed the participants and recorded the documents during the projects by focusing on framing the business cases.

When conducting multiple case studies in this type of research, attention should be given to data triangulation as well as observer triangulation (Creswell and Clark, 2011; Johnson et al., 2007; Yin, 2013). Multiple benefits can be gained from triangulation, such as complementary insights, which enhance the richness and convergence of observations, which in turn enhance confidence in the findings. For example, interviews can be conducted by two persons, with one researcher handling the interview questions and the other taking notes and recording observations (Eisenhardt, 1989). In this research, multiple researchers were involved in handling and recording the observations and feedbacks. The researchers had the outsider perspective to prevent the personal interpretation in the research (Van de Ven, 2015).

4.2. Selection of the cases

The proposed framework for BCs of PCS projects was tested in two engineering companies with the configuration projects as a unit of analysis. The first company (Company A) specialises in the production of heterogeneous catalysts and the design of process plants, while the latter company (Company B) specialises in the construction industry. The case companies were chosen because of their global operations, their highly engineered and complex products and because they were in the process of implementing PCSs to support their sales and engineering processes. They both faced challenges in defining the BCs and analysing different factors before the initiation of the project. Company A tested the presented framework in two projects and Company B in one project. All the companies established and defined their IT architecture based on a commercial constraint-based platform.

4.3. Framework testing

The research teams formed in each case company included two researchers and two configuration engineers from the company (Table 4). Workshops were conducted to introduce the proposed framework and the tools suggested in the individual steps to all the stakeholders. Finally, feedback meetings were held as semi-structured interviews to collect knowledge about the team's satisfaction with the new framework. Each meeting lasted 30 minutes and included members of the configuration teams ranging from project managers to developers and from end users and top managers. The purpose of the interviews is to assess the framework from all involved stakeholders in the project. The interview questions aim to obtain a general evaluation of the benefits and challenges associated with the framework's performance.

Table 4. Background information on the case companies

Companies	**Company A (catalyst and chemical technology), 3,000 employees**		**Company B (construction), 20,000 employees**
Projects	**Project 1**	**Project 2**	**Project 3**
Estimated timeframe for development of the PCS (months)	24	6	12
Estimated complexity of the PCS (number of attributes and constraints in the PCS)	Great	Medium	Great/Medium

No. of employees involved in testing the proposed framework	10	4	6
No. of workshops	6	3	4
No. of feedback meetings	15	4	4

5. Results from tests of framework

5.1 Step1 and 2: Benefit and stakeholders' analysis

5.1.1 Framework application

Interviews with the domain experts revealed that in the PCS projects were usually determined in unstructured meetings with the main stakeholders. However, the various requirements of stakeholders were not identified and clarified before starting the projects. Some of the requirements were ignored due to a lack of communication and tools, such as requests for outputs, user interfaces and additional IT automation.

The tools proposed in this phase to prioritise the requirements of the project are use case diagrams and the MoSCoW rule. The benefits of using these methods are (1) a full understanding of stakeholders' requirements and (2) improved communication and task delegation, which results in saving resources and time.

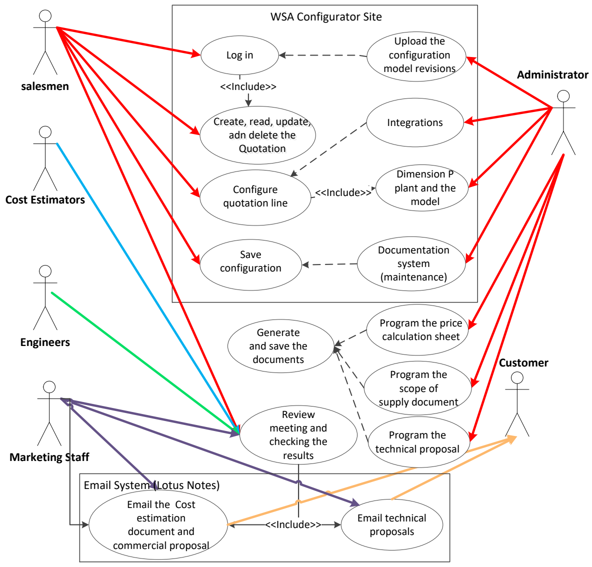

Figure 3. Example of use-case diagram.

The example of the used of use case diagram is shown in Figure 3, and an example of utilization of the benefits of MoSCoW rules is demonstrated in Table 5.

Table 5. Examples of stakeholder-requirement prioritisation.

List of requests	Must have	Should have	Could have	Want to have
Combining document snippets into full technical or commercial proposals (salespeople and cost estimators)		✓		
Loading data from the PCS into tables in the technical and commercial (sales, cost estimators and marketing group)			✓	
Price calculation, bills of material and scope of supply (all stakeholders)	✓			
Having colours for different components in user interface				✓

5.1.2 Cross-case comparison

The determined goals differ for the companies because they reflect the companies' current operational challenges. The stakeholders reported the main obstacle in this step as the unfamiliarity with the introduced tools. Table 6 lists the main results from the cases in the first two phases.

Table 6. Phases 1 and 2: Results of the benefit and stakeholder analysis

Case 1	Empower the sales offices around the world, generate proposals faster to increase the hit rate and increase sales. The *main stakeholders* included the general managers and the engineers from the sales and process design departments, including cost estimators, process engineers and mechanical engineers. The *main requirements* included two integrations with the simulation and CAD tools at the company to support the full automation of the process. The requirements were communicated through use case diagrams and prioritised according to the MoSCoW rule.
Case2	Save time and resources and increase quotations accuracy to increase competitiveness. The *main stakeholders* included the general manager of the engineering department and two senior engineers, who are the cost estimators in the sales department. The *main requirements* included a user-interface allowing interactions with other IT systems used internally at the company to make the system functional. The requirements were communicated using use case diagrams and prioritised according to the MoSCoW rule.
Case 3	Save resources, reduce the complexity causing redesign loops in the current process and to make experts' knowledge more available to all employees The *main stakeholders* included the project leader of design, project leader of production, architects, engineers, cost calculation manager and IT experts. The *main requirements* were a user-friendly interface with visualisation, optimisation of the design and accurate calculations. The requirements were communicated using use case diagrams.

Awareness of project goals and of the importance of stakeholder requirements before starting the project proved helpful for the project team. The benefits of using the methods for the benefits and stakeholder analysis can be mentioned as: Improved understanding of the stakeholders' requirements for the system; visualising their needs established a common understanding, reduced time needed for the meeting with experts as a result of clear goal setting in the first step, improved communication and task delegation between the resources, which reduced the consumption of time and resources.

Obstacles included unfamiliarity with the tools, amount of time needed to change the current way of working and the needed time and resources for workshop preparations. In Company A, it was difficult for the team to use and see the purpose of the use-case diagrams at first because it is difficult to change their habits and enable them to see the value of using illustration tools. However, the workshops proved to be helpful, because they provided step-by-step training for the configuration team and domain experts. However, Company B refused to incorporate use-case diagrams, because the managers considered it time-consuming and preferred to use MoSCoW tables when communicating with stakeholders. The configuration team recognised the benefits as a result of discussions with different stakeholders about how to prioritise the requirements.

5.2 Process analysis, scenario making and gap analysis

5.2.1 Framework application

The tools proposed in this step are process mapping and gap analysis (Hvam et al., 2008). In Table 7 an example of gap analysis is assessed while calculating the gap between the current situation and the future scenario.

Table 7. Example of gap analysis

	Current	**Target**	**Gap**
Lead time	168 hours (1 week)	0.5 hours	167.5 hours
Mistakes in offers	5%	1%	4%
Resource consumption	2 full time sales-persons	0 salespersons	2 salespersons
Product sales	25/month	30/month	20%

5.2.2 Cross-case comparison

Table 8 lists the main results from the cases in this phase.

Table 8. Phase 3: Results of the process analysis, scenario making and gap analysis

Case 1	The *current situation* is complex and wastes time by spreading responsibilities across departments. The current process generated *two scenarios*. In scenario 1, the system is used as an improved user interface, where the main aim is to empower the sales offices around the world. In scenario 2, the system includes all the required integration to generate accurate proposals and process drawing templates in more efficient manners. Gap analyses demonstrate how these scenarios contributed to the targeted goals.
Case2	Based on the c*urrent situation* in the engineering department, the team proposed a scenario for automating the sales and engineering process. The current situation includes too many iterations and a lengthy waiting time when generating the specifications. In scenario 1, the system is used as an improved user interface, where the main aim is to reduce the resources and time for generating proposals. In scenario 2, the system includes more plugins for a better user interface aligned with more development tasks to enable more selections and options for the product. Gap analyses demonstrate how these scenarios contributed to the targeted goal.
Case 3	The main challenge in the *current process* is its complexity and the need for experts' information, resulting in a great number of redesign loops. Two scenarios were proposed for the future processes. In scenario 1, the PCS is used only to support the engineering design process, but in scenario 2, it is also used to support the generation of specifications for the production planning. Finally, gap analyses demonstrate how these scenarios contributed to the targeted goals.

A common understanding of the current processes provided learning points for the stakeholders. Especially in Case 1, which involved a number of departments, the team gained a deep understanding of the current process which allowed them to anticipate all the integrations required for the future processes. In all cases, the numbers of redesign loops were noticed due to an insufficient flow of information in the various steps of the processes. Furthermore, the gap analysis provided an effective overview of the future state of the companies. Training sessions were prepared to ensure employees knew how to use the new methods; however, stakeholders considered this a time-consuming process. Furthermore, the learning points from analysing the current process (such as clarification in tasks and challenges in current) and the possible future scenarios were reported to be very effective. The project teams in all cases found the gap analysis a beneficial and easy tool that provides a helpful demonstration of how different scenarios contribute to the goals. The gap analysis also helped to communicate the need for implementing the PCSs in all cases and thereby increases the stakeholders' commitment to the project.

5.3Scenario evaluation

5.3.1 Cost-benefit analysis

Table 9 presents the main results for the cases in this phase.

Table 9. Phase 4.1: Results of the cost-benefit analysis

		Scenario 1	**Scenario 2**
Case 1	Project cost (EUR)	399,785	470,335
	Yearly cost savings (based on selling one more plant)	1,007,862	1,068,468
	ROI in the first year	152,10%	127,17%
		Scenario 1	**Scenario 2**
Case 2	Project cost (EUR)	99,600	100,253
	Yearly cost savings (increased sales)	199,774	199,985
	ROI in the first year	100,6%	99,5%
		Scenario 1	**Scenario 2**
Case 3	Project cost (EUR)	154,666	200,160
	Yearly cost savings (increased sales)	407,997	487,128
	ROI in the first year	163,7%	143,36%

This step estimates the financial benefits of PCS projects calculating the ROI. For Case 1, the expected time savings created by automating the process will not cover the cost of man-hours saved because the quantity of plants sold every year is too low. Therefore, the savings are calculated based on selling one more plant per year. However, Cases 2 and 3 will save on man-hours because of the higher quantity of products or processes sold each year. The cost is calculated as the project cost, which includes the development and implementation and the yearly running cost, such as licenses and maintenance activities. The main challenge in this step is quantifying the future savings, which was faced great interest from the stakeholders.

5.3.2 Sensitivity analysis

Sensitivity analysis was conducted to see if one of the parameters used to calculate the savings would change and examine the effects on the overall expected savings from the implementation of the PCS. If many factors have uncertainty, the sensitivity analysis can warn the managers of possible changes in the project's profitability Table 10 presents the yearly benefits from implementing the systems in terms of the lower bound, most likely and upper bound.

Table 10. Phase 4.3: Results of sensitivity analysis

		Scenario 1	Scenario 2
Case 1	Lower bound (EUR): saved man-hours	189,569	191,256
	Most likely (EUR): selling one more plant	1,007,862	1,068,468
	Upper bound (EUR): selling one more plant and saved-hours	1,197,431	1,259,724
Case 2		**Scenario 1**	**Scenario 2**
	Lower bound (EUR): saved man-hours	150,521	149,256
	Most likely (EUR): increased sales	199,600	199.774
	Upper bound (EUR): increased sales and saved man-hours	349,000	350,000
Case 3		**Scenario 1**	**Scenario 2**
	Lower bound (EUR): saved man-hours	209,091	244,631
	Most likely (EUR): increased sales	407,997	487,128
	Upper bound (EUR): saved man-hours and increased sales	617,088	731,759

Sensitivity analysis are a critical aspect of the management because it increases the credibility of the anticipated savings from implementing the PCS. The calculations in Case 1 are an example of the expectation that the company sells one more plant. For the lower band, the assumption is that the company just save man-hours by using PCS without increase in sales, and in the upper band, we calculate the savings based on selling one more plant type plus the saved man-hours, while the most likely scenario is to sell one more plant; while the decrease in man-hours is not really significant.

5.3.4 Risk analysis

Table 11 presents the results of the risk analysis.

Table 11. Phase 4.3: Results of the risk analysis

Case 1	Scenario 1: There is a high risk of system avoidance. Another risk concerns the right documentation and validation because the system tends to be large and complex. Scenario 2: The same risk factors as Scenario 1 but at a lower scale because the delivered system is more accurate, reliable and fully automated because it is integrated with all the other systems. The extra risk concerns the IT process, which could be challenging and time-consuming, and the need for resources (experts from the business) to test the system.
Case2	Scenario 1: Internal resistance to using the system and a lack of resources could be the biggest risks for the project. Scenario 2: The same risk factors as Scenario 1 but to a greater extent because of the greater number of stakeholders involved.

Case 3	Scenario 1: Retrieving the relevant knowledge and structure in PCS and anticipated internal resistance of using the system. Scenario 2: The same risk factors as Scenario 1 but to a greater extent because more knowledge has to be incorporated into the system and a greater number of stakeholders are involved.

As mentioned in the literature on PCS projects, the risk of system avoidance from users highlighted the need for good management to change employees' mind-sets. The solution was to involve all future system users from the beginning of the project to create a feeling of ownership and commitment. Another risk relates to the benefits realisation of the project and trust in the accuracy and stability of the calculations. The solution was to present visualisations of all the data and formulas in the system to the domain experts and to involve them in testing the system. In all cases, checklists were prepared based on the literature and experiences of working with PCS. The risk response strategies regarding avoidance and acceptance were evaluated.

In Case 1, based on the gap analysis, expenses and savings from the project implementation, the Scenario 2 was accepted by stakeholders. The evaluated risks prompted the project team to create a backup plan while the management team planned to move smartly and restrict their involvement in the project. In Case 2, Scenario 2 was accepted as the risks and ROI compromise. Finally, in Case 3, Scenario 1 was chosen because it had a higher ROI and less associated risk. Furthermore, by implementing Scenario 1, the project can be extended in the future when the usability of the system has been proven.

The cross-case comparisons show that the framework affects the companies differently, which may derive from the different cultures of Companies A and B. Company A took the risk of experimenting with new tools and techniques, and the employees reported that many benefits and challenges resulted from employing them. Company B's management board achieved efficiency by keeping up with routine work while making minor changes. In comparison, Company A's management board aimed to improve the current workflow by accepting the changes and modifications recommended by researchers.

6. Discussions

In the first part of the discussion section, we discuss the framework development, which was based on the literature. In the second, we discuss the framework evaluation and the results of the interviews for evaluation.

6.1. Comparing the framework with the current literature

By analysing the literature, our study has been shown that the BC analysis in PCS projects is a challenging task due to the complexity and unpredictable extensions during the projects (Shafiee et al., 2014). The available framework for IT projects do not meet the challenges of PCS projects and need modifications (Studer et al., 1998). Before initiating PCS projects, the communication between domain experts and the configuration team, analysis of different dependent factors, and evaluation of different scenarios is required (Shafiee et al., 2017). Without a clear BC framework, the investment and the complexity of the PCS, however, caused the failure or abandonment of the project (Forza and Salvador, 2007).

Furthermore, it is difficult to analyse the stakeholders' requirements, investment costs and risks of the PCS projects beforehand (Friedrich et al., 2014). Moreover, we mentioned that PCSs are IT based and that some IT-oriented BC frameworks can inspire BC frameworks modification in PCS projects (Gambles, 2009; McNaughton et al., 2010; Nielsen and Persson, 2016). Besides, literature on PCS projects have investigated BC tools and steps in PCS projects (Felfernig, Hotz, et al., 2014; Heiskala et al., 2007; Hotz et al., 2014; Salvador and Forza, 2007).

The proposed framework includes four BC steps for PCS projects based on the BC framework literature in IT projects (e.g. Gambles, 2009) and on BC steps introduced in the literature in PCS projects (e.g. Forza and Salvador, 2007). The first step determines the goal of the project which should be aligned with the challenges in the company (e.g. Ardissono et al., 2003; Petersen, 2007; Tenhiälä and Ketokivi, 2012; Trentin et al., 2012). The second step proposes tools and techniques to identify and analyse the stakeholders and their requirements (e.g. Friedrich et al., 2014; Hvam et al., 2008; Mortensen et al., 2008; Nellore et al., 1999). Available tools for the process analysis step are mentioned, and the future scenarios are introduced (e.g. Hvam et al., 2008; White and Corp, 2004). The last step concerns the different analysis of the proposed scenarios including cost analysis, sensitivity analysis and risk analysis. ROI is selected to analyse the costs (e.g. Haddix et al., 2003; Phillips and Phillips, 2010) and sensitivity analysis helped to measure the uncertainty or changes in different parameters and increase the accuracy of the cost analysis (e.g. Pannell, 1997; Saltelli, 2002). A different approach to calculate the risks of the PCS projects is presented as the final analysis of the fourth step (e.g. Boehm, 1991; DeMarco and Lister, 2013; Johnson et al., 2001). Departing from the existing literature on PCSs, the proposed framework integrates the proposed steps into a specific sequence in order to fulfil the need for a standard process for BC analysis.

6.2. Evaluation of research

The suggested framework was tested on three configuration projects in two ETO companies. The configuration projects were engineering projects in which vast, complicated PCS projects had to be managed. The proposed framework helped the companies address the main BC analysis for PCS projects. The scope of the projects was determined and kept limited (whereas before they were continuously expanded); this limitation supported the control of the project risks, thus reducing the difficulties associated with calculating the costs. Consequently, the companies witnessed a standard strategy for prioritizing the PCS projects and a reduction of the time and resources needed for scoping.

The configuration teams involved in the development and testing of the framework expressed a willingness to use the framework in future projects to save both time and resources. Domain experts at the company also appreciated their involvement in stakeholders' requirements identification. These results indicate both the effectiveness of the framework and its positive involvement effects on the people engaged in the configuration project.

The main obstacle for the configuration team's use of the framework was their lack of familiarity with the suggested tools. An introduction of the tools in workshops significantly reduced their resistance to the

framework. Using the framework and suggested tools did not introduce additional burdens or costs, and the training for configuration engineers and domain experts was carried out in a short amount of time.
To evaluate the framework, three engineers who have been working with the BC framework were interviewed. The interviews focused on the applicability of the proposed framework (Table 12).

Table 12. Interviews result of final evaluation of the framework

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
Do you expect it will require little effort to learn to understand the information on the BC framework?			1		2
In your opinion, would it be realistic to use the BC framework in others industrial company?				2	1
Would the framework help you in defining the stakeholders' requirements more precisely?					3
In your opinion, would the BC framework be useful to compare different scenarios of a future specification process?				1	2
In your opinion, would the BC framework help in prioritizing the projects and reducing the risk of failure?				1	2
Do you think that the BC framework would provide additional insight into scoping and planning the project?					3
Do you think that this BC framework has improved your previous way of working regarding efficiency and accuracy?				1	2

As can be seen, the interviews assessed that the BC framework is helping to scope and plane PCS projects. This framework has been mentioned as a straightforward and easy way to assess the situation of the projects in a high level of abstraction with the little effort for training and change.

7. Conclusions

Existing literature regarding PCS discusses the necessary steps for BCs involved in PCS projects before starting the project planning; however, no structured framework exists to help practitioners evaluate PCS projects based on BCs. However, BCs are addressed in the literature to be of great importance to avoid any failures in IT projects. PCS projects are IT projects with greater complexity and unexpected costs, and a variety of risks are anticipated for each PCS project. Having a structured framework and being knowledgeable about the risks and benefits of the PCS project has a remarkable effect when choosing the project and making decisions in the early phases of the project.
This paper proposed a framework for developing BCs for PCS projects, based on the available literature for IT and PCS projects. The framework was developed using an iterative process in one case company and based on the experiences obtained from implementing PCS in multiple case studies. The suggested framework and the suggested tools should help the whole team to focus on and prioritise the goals, specific

stakeholders' requirements, analysis and design of the current and future processes where PCS is used, and the evaluation of future scenarios based on cost-benefit analysis, and sensitivity and risk analysis.

The framework tested in three PCS projects at two engineering companies proved the application of the framework in different projects and in different companies. To validate the framework, we have clarified the application of the framework and the different steps involved. All three projects aimed to reduce the complexity of the current processes and achieve economic benefits from implementing a PCS. The results from testing the framework and observations of the case studies show the interest among the whole team in using suggested BC framework as well as its challenges at the company.

The use of cases allowed us to assess – in depth, in detail and in real-world contexts – the proposed framework's effectiveness. However, we were able to apply the framework only in a limited number of projects and companies, and this limits the generalisability of our results. The ability of the framework to cope with highly engineered, complex products in ETO companies indicates that it could also be used in configuration projects of less complexity. However, the necessity of applying such a structured framework in smaller projects is questionable and needs further testing. Further testing of the suggested framework is required in other industries. Further studies of the ROI or risks expected for different PCS projects in different types of industries and for different applications would also be beneficial.

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APPENDIX G

International Journal of Production Research, 2018
https://doi.org/10.1080/00207543.2018.1436783

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The impact of applying product-modelling techniques in configurator projects

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(*Received 17 February 2017; accepted 24 January 2018*)

This paper aims to increase understanding of the impact of using product-modelling techniques to structure and formalise knowledge in configurator projects. Companies that provide customised products increasingly apply configurators in support of sales and design activities, reaping benefits that include shorter lead times, improved quality of specifications and products, and lower overall product costs. The design and implementation of configurators are a challenging task that calls for scientifically based modelling techniques to support the formal representation of configurator knowledge. Even though extant literature has shown the importance of formal modelling techniques, the impact of utilising these techniques remains relatively unknown. Therefore, this article studies three main areas: (1) the impact of using modelling techniques based on Unified Modelling Language (*UML*), in which the phenomenon model and information model are considered visually, (2) *non-UML-based modelling techniques*, in which only the phenomenon model is considered and (3) *non-formal modelling techniques*. This study analyses the impact to companies from increased availability of product knowledge and improved control of product variants. The methodology employed is an exploratory survey, followed by interviews with 18 manufacturing companies providing customised products. The results indicate that companies using UML-based modelling techniques tend to have improved documentation of their product knowledge and an improved ability to reduce the number of product variants. This paper contributes to an increased understanding of what companies can gain from using more formalised modelling techniques in configurator projects, and under what circumstances they should be used.

Keywords: information systems; product-modelling; product configurators; documentation; object-oriented modelling; knowledge management

1. Introduction

In today's business environment, customers increasingly demand high-quality, customised products with short delivery times at competitive prices (Forza and Salvador 2007; Hvam, Mortensen, and Riis 2008; Zhang 2014). To respond to these challenges, configurators are used to support design activities, which involve gathering information from customers and generating the required product specifications (Forza and Salvador 2002a, 2007). A configurator is a knowledge-based system that supports the user in the specification process of personalised products by providing design choices, in which a set of components, along with their connections, are pre-defined and constraints are used to prevent unfeasible configurations (Felfernig, Friedrich, and Jannach 2000; Zhang and Rodrigues 2010; Eigner and Fehrenz 2011; Long et al. 2016). Thus, the use of configurators means that the generation of product specifications (e.g. quotes, sales prices, bills of materials, CAD models) can be automated (Hvam, Mortensen, and Riis 2008).

Configurator projects can be defined regarding the tasks required to build a configurator, which includes analysis and redesign of the business processes, modelling of the product range, selection of configurator software, programming of the configurator, implementation and maintenance (Hvam, Mortensen, and Riis 2008). In configurator projects, one of the primary tasks is to structure and represent the knowledge of the configuration model (Aldanondo, Rougé, and Véron 2000; Forza and Salvador 2002a; Felfernig et al. 2004, 2014; Hvam 2006; Stark 2007; Ardissono et al. 2003; Shafiee et al. 2017). However, if companies are highly dependent on domain experts' knowledge, there is a risk of incomplete communication or cognitive conflicts, which can result in loss of knowledge, making it difficult to formalise and document (Tseng, Chang, and Chang 2005). Furthermore, with configurator projects, there is a risk that the documented knowledge is low-quality or not properly maintained (Tiihonen et al. 2013; Shafiee et al. 2017). Research has shown that a configuration model without adequate documentation can lead to a lack of overview and even require restructuring of the configurator (Haug, Hvam, and Mortensen 2009). Furthermore, past studies emphasise the importance of

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standard-knowledge representation in configurator projects for an effective integration of configuration technologies into software environments that deal with highly complex products (Felfernig 2007). Tiihonen et al. (1996) describe the challenges of configurator projects concerning knowledge: (1) knowledge is rarely documented systematically and (2) long-term management of knowledge is difficult, as knowledge changes over time to be aligned with companies' product offerings. Furthermore, the need for a general methodology supporting the representation of the configurators' product models is emphasised (Tiihonen et al. 1996).

Product modelling focuses on representing structure and product knowledge to ensure that it is understandable to all parties involved, which, in configuration processes, includes both domain and configuration experts (Hvam, Mortensen, and Riis 2008). In configurator projects, four basic representations are proposed for structuring configurator knowledge, as Figure 1 shows (Duffy and Andreasen 1995). First, the real world represents the product knowledge available within a company, in which a formal representation of the knowledge has not been established. Second, the phenomenon model describes a product's structure, function and other properties, including the product's lifecycle, in a way that can be communicated to domain experts. Third, the information model is formalised, which is an IT representation of the phenomenon model, often supporting Unified Modelling Language (UML) notation (Felfernig, Friedrich, and Jannach 2000; Hvam 2001; Hvam, Mortensen, and Riis 2008). Fourth, the actual computer model is built on the previously described representations of the product knowledge.

The literature describes modelling techniques for constructing the phenomenon model (e.g. Hegge and Wortmann 1991; Ulrich 1995; Erens and Verhulst 1997; Eppinger and Ulrich 2000; Stone, Wood, and Crawford 2000; Gonzalez-Zugasti, Otto, and Baker 2000; Dahmus, Gonzalez-Zugasti, and Otto 2001; Du, Jiao, and Tseng 2001; Fixson 2005; Huang, Zhang, and Liang 2005; Harlou 2006). Modelling techniques for building the phenomenon model and information model also have been detailed (e.g. Chao and Chen 2001; Felfernig, Friedrich, and Jannach 2001; Hvam 2001; Magro and Torasso 2003; Hvam, Mortensen, and Riis 2008). UML has been proposed as a way to represent the information model in configurator projects (Felfernig, Friedrich, and Jannach 2000; Hvam 2001; Hvam, Mortensen, and Riis 2008). UML is a visual modelling language that is used for visualising, specifying, constructing and documenting artefacts in software design (Booch, Rumbaugh, and Jacobson 2005). This article focuses on three different representations of knowledge in configurator projects: (1) *UML-based modelling techniques*, in which the phenomenon model and information model are considered in a visual way, (2) *non-UML-based modelling techniques*, in which only the phenomenon model is considered (e.g. structured bills of materials) and (3) *non-formal modelling techniques* (e.g. making a list of features in Word or Excel without any formal structure or modelling directly in the configurator). The Centre for Product-Modelling (CPM) procedure is a modelling technique that represents both the phenomenon and the information model using UML notation. To represent the phenomenon model, product variant master (PVM) and class responsibility collaboration (CRC) cards are used, and to represent the information model, class diagrams and CRC cards are used (Hvam 2001; Hvam, Mortensen, and Riis 2008). To represent UML-based modelling techniques, the CPM procedure is used in this study, partly because it is based on UML – also used to make phenomenon models – and partly because the authors have access to companies using the CPM procedure, along with companies using other methods (*non-UML*-based and *non-formal* modelling techniques).

Although the previously mentioned modelling techniques are proposed in extant literature, the impact of applying modelling techniques when making the phenomenon model and the information model remains relatively unknown (Hvam et al. 2014). Even though a few studies have analysed this impact, it is limited to single-case studies of one specific modelling technique (e.g. Stumptner, Friedrich, and Haselböck 1998; Chao and Chen 2001; Yang et al. 2009). Thus, a comparison of different modelling techniques is required both to compare their impact and to determine which circumstances require more formalised modelling techniques (e.g. supporting both the phenomenon and information models).

The literature describes numerous benefits that can be gained from utilising configurators, e.g. reduced work-hours to prepare specifications, routine work, lead time and improved quality, certainty of delivery, control of product variants and knowledge availability (Tiihonen et al. 1996; Forza and Salvador 2007, 2008; Hvam, Mortensen, and Riis 2008; Trentin, Perin, and Forza 2011; Tenhiälä and Ketokivi 2012; Zhang 2014; Myrodia, Kristjansdottir, and Hvam 2017).

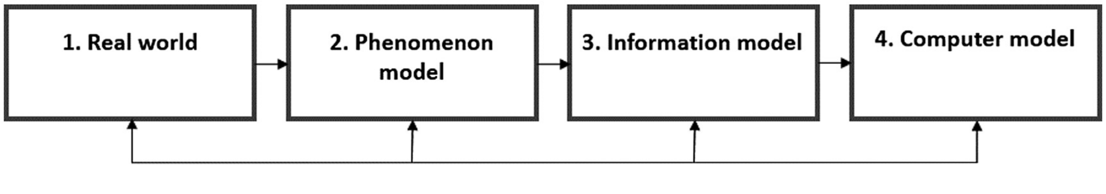

Figure 1. Four basic representations of product modelling for configurators. Revised from Duffy and Andreasen (1995).

However, the modelling techniques used in a configurator project impact knowledge availability, as knowledge is made more explicit and thereby more accessible to a greater number of employees within the company. Additionally, choice of modelling technique impacts the company's control of product variety by providing increased insight and overview of product variants and relations/constraints between components/modules. Thus, to explore the impact of utilising product-modelling techniques in configurator projects, the following propositions are presented, in which it is assumed that more formalised modelling methods (UML-based) will have a greater impact on both knowledge availability and control of product variants:

Proposition 1: The use of a UML-based modelling technique will result in increased availability of product knowledge in organisations.

Proposition 2: The use of a UML-based modelling technique will result in improved control of product variants.

Due to the exploratory nature of this study's objectives, the research methodology is an exploratory survey, followed by interviews (Yin 1989). All contacted companies manufacture customised products and use configurators to support their sales and design processes. The results presented in this paper include responses from 18 companies. Research has shown that small sample sizes are justifiable in the context of exploratory research, which this study employs (Isaac and Michael 1995; Dattalo 2007). Because of the small sample size, a statistical analysis on the findings does not provide reliable/informative data (Isaac and Michael 1995; Dattalo 2007). Instead, this exploratory study aims to provide further insight into the impact of using different modelling techniques in configurator projects.

The remainder of this paper is structured as follows: Section 2 discusses relevant extant literature and Section 3 elaborates on the CPM procedure. Section 4 explains the research method and Section 5 presents research results. Section 6 discusses the research results, and Section 7 concludes the paper, re-examining the research question and noting the study's limitations, which can be used as a starting point for further research.

2. Literature review

Configurators can be traced back to the 1980s, when the first configurators were developed as rule-based systems (Barker et al. 1989). However, the maintenance of those systems proved to be challenging due to the vast knowledge within the systems and frequent updates (e.g. Mailharro 1998; Felfernig 2007; Jannach and Zanker 2013). To address these challenges, researchers examined knowledge representation and conceptual modelling for configurators, which are further elaborated in this section.

Mittal and Frayman (1989) propose a generic component-port approach for solving configuration problems. Their approach of configurable systems is based on a pre-defined set of components, in which each component is described by a set of properties and ports that enable connections to other components, under certain constraints. The configuration task is restricted by functional architecture and key components. Their approach is still dominant and serves as the basis for many commercial configurators (Felfernig et al. 2004; Jannach and Zanker 2013).

Soininen et al. (1998) proposed a general ontology for configuration that combines connection-, resource-, product structure- and function-based approaches. The ontology aims to reuse and share configuration knowledge and allow for interacting among configurators' agents. Felfernig, Friedrich, and Jannach (2000) proposed another approach, in which UML is used to represent domain-specific notation, both to make the knowledge understandable for domain experts and to describe the formalism of the configurator. Under their approach, contextual diagrams are proposed for more complex domain knowledge (Felfernig, Friedrich, and Jannach 2000). Yang et al. (2009) proposed a similar approach, in which a method-based semantic web technology (Web Ontology Language [OWL] and Semantic Web Rule Language [SWRL]) supports reuse and modelling of configuration knowledge. Using OWL, which is based on description logic, well-defined logic semantics can be created that do not need any translation, unlike the UML approach (Yang et al. 2009).

Another essential aspect of configurator projects is to structure the configuration knowledge sufficiently so that components and their relations are defined (Zhang 2014). To this end, Stumptner, Friedrich, and Haselböck (1998) propose a method based on a constraint-satisfaction problem, known as a generative-constraint satisfaction problem. The method allows for reasoning of both existing components and of large and variable numbers of components. Furthermore, Mailharro (1998) defines a configuration problem as both a classification problem and a constraint-satisfaction problem, in which a framework based on object-oriented and constraint-satisfaction paradigms is proposed that focuses on domain-knowledge representation. To address the challenges of semantic web applications, Felfernig et al. (2003) analyse the applicability of commonly used languages based on description logic concerning configuration-knowledge representation. Their research shows that description logics are synonymous with consistency-based definitions and are thereby useful in configurator projects (Felfernig et al. 2003). In another study, Felfernig (2007) extends this work to support product-structure constraints and complex structural properties of configuration problems, proposing model-driven architecture (MDA) based on UML and object-constraint language (OCL) for configurators. This should enable more efficient communication with other software applications and facilitate technical support (Felfernig 2007). To address the challenges of distributed configurators, Ardissono et al. (2003) propose a framework and develop the configuration shell. Jannach and Zanker (2013) later added to this work, offering an approach based on distributed constraint satisfaction in which generative-constraint satisfaction is used to model the knowledge to solve the challenge of distributed configurators.

Conceptual modelling of configuration knowledge is a vital aspect concerning the structure of configuration knowledge. McGuinness and Wright (1998) propose a conceptual approach for structuring knowledge for configurators in which they emphasise the need for configurator accuracy over optimisation by proposing a modelling technique based on description logic. Peltonen et al. (1998) define concepts for modelling configurable products based on hierarchical product structure, with the configuration model divided into an explicit structure (based on bills of materials [BOM], with optional, alternative pars and parametric components; other constructs also can be described, such as connection ports) and constraints (which can be related to specifications, implementation or structure). Aldanondo, Rougé, and Véron (2000) propose a method that builds on a function-breakdown structure and a physical-breakdown structure that, in turn, build on an object-modelling technique that represents both functions and components regarding objects, dependencies and composition operators. Felfernig, Friedrich, and Jannach (2001) propose a conceptual modelling technique for configurators, which they built onto their previous research (Felfernig, Friedrich, and Jannach (2000), in which UML is used to structure the domain knowledge, and that work is further extended to incorporate functional architecture (Mittal and Frayman (1989). Magro and Torasso (2003) describe decomposition strategies for configurations to improve performance and support interactive configuration, in which frame parts and components are used to represent configuration-domain knowledge.

Chao and Chen (2001) introduce an assembly model that includes information regarding functionalities and components for assembly in configuration management in product-data management systems. Jinsong et al. (2005) propose a method aimed at make-to-order manufacturers, in which the product architecture usually consists of modules and standardised components. The method is based on knowledge components and attributes that capture and represent configuration knowledge (Jinsong et al. 2005). Hong et al. (2008) offer an approach to identify optimal product configuration for one-of-a-kind products based on customer requirements for products' cost and performance. The approach builds on modelling products' functions and structure through an AND-OR tree (Hong et al. 2008). Hong, Xue, and Tu (2010) expand this approach and present a customer-centric product-modelling scheme to model one-of-a-kind products in which customers are grouped by product and customer patterns. Tseng, Chang, and Chang (2005) suggest using a graph-based bill of material and case-based reasoning to construct a new BOM in the configuration processes, in which previous similar cases are identified and adjusted to meet the constraints for the product under design. Yang, Dong, and Chang (2012) propose a method to deal with structured product-configuration problems in which an object-oriented configuration model is transformed into dynamic constraint satisfaction problems. Finally, Zhang, Vareilles, and Aldanondo (2013) analyse the SAP^2 configurator, in which the production view is considered, in addition to functional and physical structure. In that study, the generic bill of functions, materials and operations (GBoFMO) is proposed to present the knowledge from different domains (Zhang, Vareilles, and Aldanondo 2013).

Alternative approach is offered by Hvam (2001) that is later extended by Hvam, Mortensen, and Riis (2008), or the CPM procedure for conceptual modelling of configurators. The approach builds on the concepts of, object-oriented modelling (Bennet, McRobb, and Farmer 1999; Booch, Rumbaugh, and Jacobson 1999; Felfernig, Friedrich, and Jannach 2000), systems theory (Bertalanffy 1968; Skyttner 2005) and modelling mechanical products (Hubka and Eder 1988; Schwarze 1996; Jiao, Simpson, and Siddique 2007). To support this method, Haug and Hvam (2007) and Shafiee et al. (2017) proposed IT tools to model, communicate and document product knowledge. The CPM procedure represents both the phenomenon and the information model using UML notation, in which the PVM and CRC cards represent the phenomenon model, and class diagrams and CRC cards form the information model. The CPM procedure is further explained in Section 3.

2.1 *Summary*

This section reveals that several researchers have addressed modelling techniques and knowledge representations for configurator projects. These studies benefit from different methods, providing both case studies (e.g. Stumptner, Friedrich, and Haselböck 1998; Magro and Torasso 2003 Tseng, Chang, and Chang 2005; Hong et al. 2008; Hong, Xue, and Tu 2010; Yang, Dong, and Chang 2012) and illustrative examples (e.g. Mailharro 1998; McGuinness and Wright 1998; Aldanondo, Rougé, and Véron 2000; Felfernig, Friedrich, and Jannach 2000, 2001; Chao and Chen 2001; Zhang 2014; Felfernig 2007; Yang et al. 2009; Zhang, Vareilles, and Aldanondo 2013). The impact of using different modelling techniques is discussed in terms of managing the complexity of the configurator (McGuinness and Wright 1998), reducing the time needed for development and maintenance of the knowledge base (Stumptner, Friedrich, and Haselböck 1998), increasing efficiency in product development (Chao and Chen 2001), reusing product-configuration knowledge (Yang et al. 2009), and saving time and resources while improving configurator quality (Shafiee et al. 2017). However, none of the studies compares the actual impact of using different modelling techniques, such as UML-based, non-UML-based or non-formal modelling techniques, on configurator projects. Thus, a comparison of different modelling techniques is required both to compare their impact and to see under which circumstances more formalised modelling techniques (i.e. UML-based or non-UML-based) are necessary.

3. CPM procedure

The CPM procedure was first proposed by Hvam (2001) and has since been extended (e.g. Hvam, Riis, and Hansen 2003; Hvam and Ladeby 2007; Haug, Hvam, and Mortensen 2010). Hvam, Mortensen, and Riis (2008) offer the most comprehensive version of the procedure, on which this section builds.

The primary application of the CPM procedure involves a PVM and class diagrams associated with CRC cards. PVM is a modelling technique used to structure the phenomenon model visually so that it can be used to communicate with domain experts while supporting UML notation. The PVM structure includes product features on multiple product variants according to the customer, engineering and part/production views (Andreasen 1994; Harlou 2006). This is aligned with (e.g. Deciu et al. 2005; Zhang, Vareilles, and Aldanondo 2013), who recommend that product structures be modelled from different views (Section 3.1). Class diagrams are used in the CPM procedure to represent the information model, in which the structure corresponds to the PVM structure (Section 3.2). Finally, CRC cards, associated with the PVM and class diagrams, are used to describe the individual classes in more details (Section 3.3).

3.1 *Product variant master (PVM)*

To obtain an overall view of the products, the product range is drawn up in a PVM to represent the phenomenon model (Hvam 2001; Hvam, Mortensen, and Riis 2008). The PVM consists of two structures: the *part-of structure* and the *kind-of structure*. The part-of structure represents the parts that appear in the entire product family. The classes are defined as object classes, which include the name of the class, description, attributes and constraints. The kind-of structure describes the different variations that individual parts can have. Furthermore, the PVM contains a description of the most important connections between parts, i.e. the rules for how parts are permitted to be combined. To preserve the overview of the PVM, CRC cards are associated with the PVM to describe the individual parts in more detail (Section 3.1). The PVM represents knowledge from different domains, which include customers, engineering and part/production views (Harlou 2006). The causal connection then can be drawn between views to identify complexity and non-value-adding variety in the product range. Figure 2 provides an illustrative example of the PVM, which supports UML

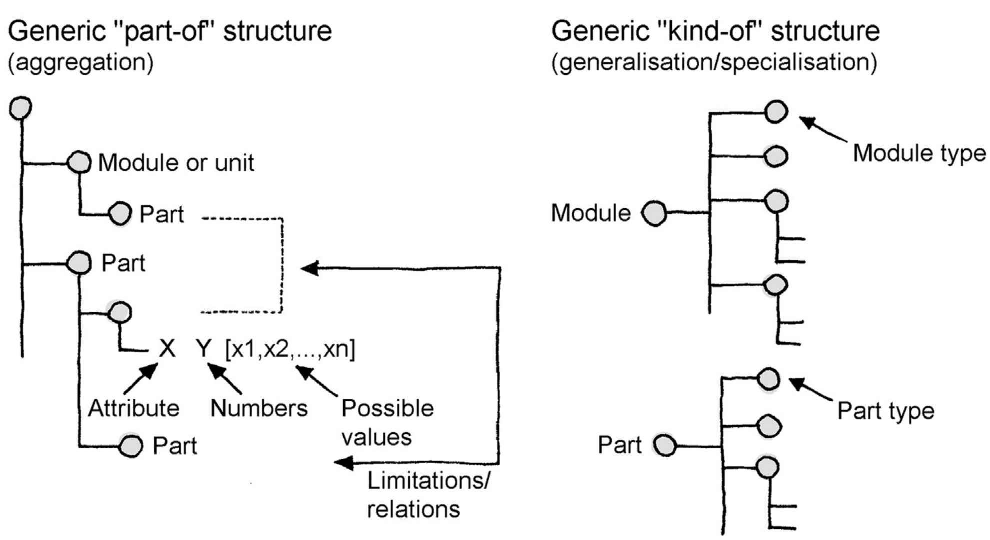

Figure 2. PVM structure regarding part-of and kind-of structure adjusted from (Harlou 2006; Hvam, Mortensen, and Riis 2008).

notation and thereby can be transformed into a class diagram, which is a UML-based modelling technique (as explained in Section 3.2).

3.2 *Class diagrams*

Class diagrams are used to represent the information model. Individual classes in the class diagram are defined from the PVM, in which a class in the PVM indicates a class in the class diagram.

Aggregation and association structures are used to indicate relationships between objects. The aggregation structure corresponds to the part-of structure in the PVM. The association structure is used if objects are associated with each other. Cardinalities can be used with the aggregation and association structures to represent the number of sub-parts needed to make a super-part (Hvam, Mortensen, and Riis 2008). Generalisation and package structures describe relationships between classes. The generalisation structure corresponds to the kind-of structure in the PVM. Figure 3 shows the relationship between the PVM and class diagrams. Since the PVM supports UML notation, a class diagram can be generated directly from its structure.

3.3 *Class responsibility collaboration (CRC) cards*

The CRC cards, which are associated with both the PVM and the class diagrams, describe classes in more detail. The CRC card was first proposed as a way to teach object-oriented thinking (Beck and Cunningham 1989). Later, they were developed for use in configurator projects, in which they describe individual object classes of PVM and class diagrams in more detail (Hvam, Riis, and Hansen 2003; Hvam, Mortensen, and Riis 2008). In other words, the CRC card defines the class, including the class name and its possible place in the hierarchy, along with a date and the name of the person responsible for the class. Also, class task (responsibility), class attributes and methods, and collaboration classes are provided. Furthermore, a sketch of the product part represented by the class is included. CRC cards' purpose is to document detailed knowledge about the attributes and methods for individual object classes, as well as describe classes' mutual relationships. CRC cards serve as documentation for both domain experts and system developers. Thus, together with the PVM and class diagram, CRC cards become an essential means of communicating and documenting knowledge in configurator projects, thereby supporting UML-based modelling, along with the PVM and class diagrams. Figure 4 provides an example of a CRC card.

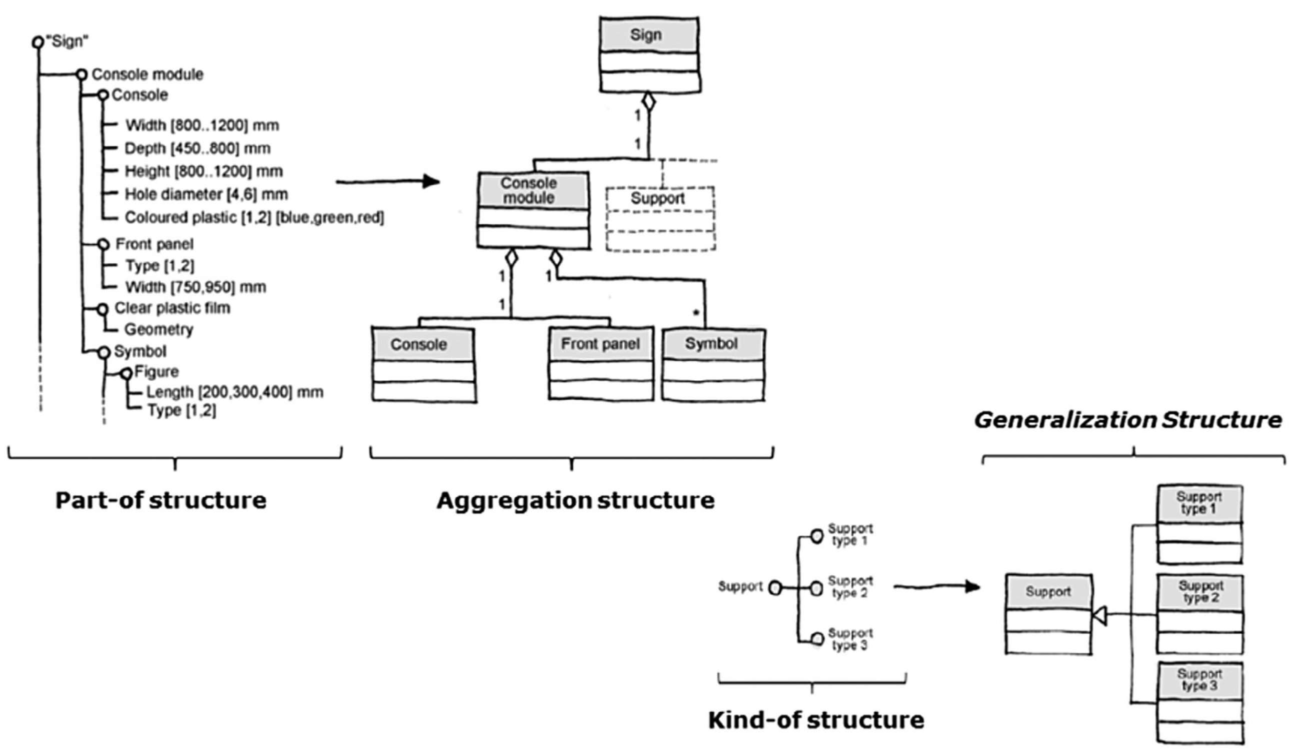

Figure 3. Class structures concerning the PVM adjusted from (Hvam, Mortensen and Riiss 2008).

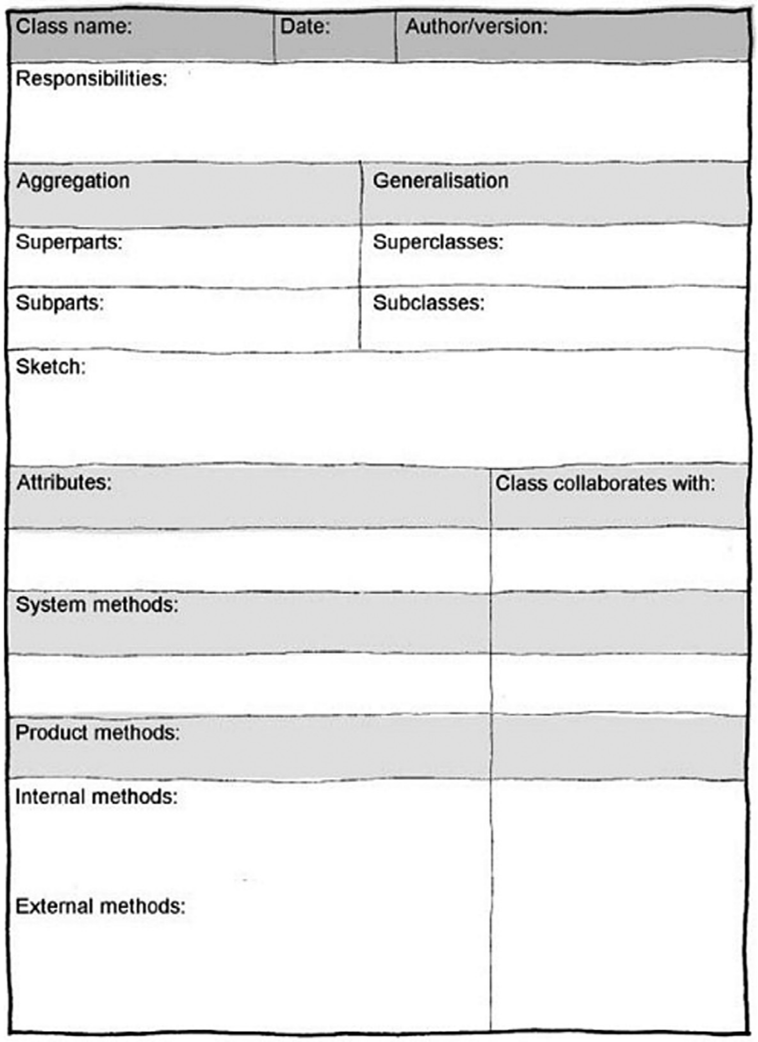

Figure 4. CRC card (Hvam, Mortensen, and Riis 2008).

4. Research method

Due to the exploratory nature of the research objective, the chosen research method is an exploratory survey followed by interviews (Yin 1989; Bradburn, Sudman, and Wansink 2004). A survey supported by interviews offers the advantages of structured and standardised questions, while also allowing for qualitative explanations and a deeper understanding of companies' settings. A further advantage of this kind of research design is the ability to ensure that respondents understand the survey's questions and to clarify any misperceptions. This approach proved to be particularly helpful because of respondents' varying backgrounds and target organisations' differing industrial settings, definitions and practices. The following sections provide a more detailed explanation of the sample population, respondents, questionnaire design, data collection and data analysis.

4.1 *Population and sampling*

The selection criteria were that organisations had to be manufacturing companies providing customised solutions with experience using configurators to support their specification processes. To identify companies that fulfilled the selection criteria, the Danish Association for Product Modelling was consulted. To identify additional companies, a brainstorming session was conducted during the interviewing process in which respondents were asked for a reference list of other companies that might fulfil the criteria. A total of 18 companies provided valid answers to the questions included in the study, i.e. qualifying corporate respondents explained the modelling techniques that their companies used and stated the impact of using such modelling techniques. Research has shown that small sample sizes are justifiable in the context of exploratory research and pilot studies, under which this study falls (Isaac and Michael 1995; Dattalo 2007). Because of the small sample size, applying statistical-significance tests might not be very reliable/informative (Isaac and Michael 1995; Dattalo 2007). However, this is not the aim of this paper due to its exploratory nature.

The sample used in this study can be characterised by the size of the company in terms of number of employees, product types offered, number of configurators in use and experience working with configurators (Tables 1–3).

4.2 *Respondents*

At each company, only one person was responsible for completing the survey and agreeing to an interview. Aligned with the study's focus, the companies' respondents were selected based on their familiarity with configurators. It was decided that in-depth knowledge of configurators was required, which top-level management at the companies might not have.

4.3 *Design of questionnaire*

In the design phase, a rough draft of the questionnaire was developed from the literature review. Hereafter, a brainstorming approach was used to specify the survey's primary constructs. The questionnaire was divided into three sections, as summarised in Table 4.

To establish external validation of the questionnaire and ensure that the respondents were familiar with how the questionnaire worked in practice, three pilot studies were conducted. The criteria for selecting the subjects for the pilot studies were that the respondents should be sufficiently experienced with configuration and represent an organisation with a distinct configuration setting. Thus, one selected company was a manufacturer of consumer electronics, one was a one-of-a-kind manufacturer, and one was a manufacturer of industrial equipment. These criteria were established to test the applicability of the questionnaire for the configuration settings of different types of industries. The questionnaire was first e-mailed to the companies' respondents, then follow-up interviews were conducted. The pilot studies focused partly on testing the relevance of the questions and instruments – particularly whether the questions made sense, the formulations were accurate, and the assumptions made were explicit – and partly on discussing configuration practices at the companies to identify further relevant topics for the questionnaire. The pilot studies led to a moderate update of the questionnaire concerning wording to increase clarity.

4.4 *Data collection*

The first step was to e-mail the questionnaire to the respondents with a description of the study's purpose, the interview procedure and a follow-up notification. Appointments were made for phone interviews. One person conducted the interviews to increase consistency. The interview process provided room for clarification and elaboration of questions to ensure accurate and consistent interpretation of the questions listed in the questionnaire and for the interviewer to gain a complete understanding of the companies' settings. Immediately after each interview, the completed questionnaire was e-mailed to each respondent for verification while the interview was still fresh in the respondent's mind. Few interviewees used the opportunity to modify registered answers. The interviews took 40–90 min each, depending on the complexity of the configuration setting and the organisation's situation.

Table 1. Companies' size in terms of numbers of employees.

Distribution	Number of employees
Minimum	20
≤25%	400
≤50%	600
≤75	5600
Maximum	15,000

Table 2. Product types that the companies offer.

Product types	Number of companies
Agricultural systems	2
Boiler systems	1
Building systems	5
Components and systems	1
Control boards	1
Control systems and components	1
Heating systems and components	1
Hydraulic components	1
Mechanical systems	1
Plants and electronic systems	1
Plants and machines	1
Tools and components	1
Ventilation systems	1

Table 3. Years since the first configurator was implemented and number of configurators used.

Distribution	Number of years since the first configurator became operational	Number of configurators used at the companies
Minimum	3	1
≤25%	7	1
≤50%	9	2
≤75%	13	3
Maximum	25	20

4.5 *Data analysis*

In the analysis phase, interviews were cross-checked for data-entry errors before answers were analysed. Concerning the complexity of the configurator, company No. 6 and No. 15 did not provide all the required information. No. 6 could not estimate the number of rules and attributes, and No. 15 provided answers only on number of attributes and not rules. Finally, No. 1 did not provide answers to whether the use of modelling techniques influenced the improved control of product variants. However, it was decided to keep these companies in the data sample, as the exploratory nature of the research aim meant that their responses still provided vital insights. Out of the companies included in this study, one company is identified as an outlier regarding its large numbers of rules and attributes, the reason being that the company's configurator consists of several sub-configurators. To validate the findings, the analysis was repeated by excluding this company to evaluate the impact on the overall results. However, it did not change the overall results, so the company remained in the sample.

5. Results

This chapter presents the primary results of the research regarding the modelling techniques used by the companies included in the sample.

5.1 *Modelling methods used at the companies and characteristics of the configurators and companies*

The companies were divided into three groups, based on the modelling techniques applied: a UML-based modelling technique (CPM procedure), a non-UML-based modelling technique (e.g. structured bills of materials) or a non-formal modelling technique (e.g. making a list of features in Word or Excel without any formal structure or modelling directly in the configurator).

In the first group, six companies were using UML-based modelling methods, meaning they used the CPM procedure, which is based on UML notation both for the representation of the phenomenon model (the PVM and CRC cards) and the information model (class diagram and CRC cards). The companies in this category used either PVM, class diagrams and CRC cards, or at least either the PVM or class diagrams. The second group consisted of six companies that utilised non-UML-based modelling techniques or structured BOM in addition to Excel spreadsheets, Word documents

Table 4. Design of questionnaire.

	Description/Key areas	Examples
Section 1	Industrial settings and size of companies' configuration areas	• Number of employees [open] • Number of employees working on configurator projects [open] • Number of users [open]
Section 2	Complexity of configurators used at companies. If the companies had more than one configurator in use, the respondents' answers were based on the most complex configurators	• How many attributes? [0–199, 200–499, 500–999, 1000–2000. If more, how many?] • How many constraints? [0–199, 200–499, 500–999, 1000–2000. If more, how many?][a] • Is the configurator integrated with the following systems: ERP, CRM, CAD, PLM, calculation system and/or 'other'? If 'other', what?]
Section 3	Gain understanding of modelling techniques used by companies in configurator projects and the impact of using them	• Were modelling techniques used during development and maintenance of the configurator? [Yes or No] • If modelling techniques were used, please indicate whether some of the following techniques were used: class diagrams, product variant master (PVM), CRC cards, structured bills of materials, flowcharts and/or 'other'. If 'other', what? • To what extent do you agree that the company has obtained the following benefits (on a five-point scale, with one representing 'strongly disagree', three 'neither agree nor disagree', and five 'strongly agree')? ○ Improved documentation of knowledge ○ Improved availability of product knowledge ○ Reduction of product variants (item numbers) ○ Increased use of standard parts ○ Improved quality of products

[a]This includes any kind of rule-based formalisation.

and modelling tools provided by the configuration software. Finally, the remaining six companies said they did not use any formal modelling techniques outside of configuration software besides spreadsheets and Word documents. Table 5 summarises how the different modelling techniques are used at the companies.

To determine the companies' characteristics and the configurators used at each company, respondents were asked to provide the number of employees at their companies to represent company size. To describe the size of the configuration areas at the companies, the respondents were asked to provide the number of configurators utilised at their companies, the number of employees working on configurator projects and the number of configurator users. Finally, they were asked to describe the configurators' complexity that is based on, rules, attributes and integrations. In Table 6, this information is grouped according to the approach used for the companies' product modelling.

According to the results presented in Table 6, companies using UML-based modelling techniques are characterised as having more employees than companies listed in other groups, thereby indicating more formalised modelling techniques are required at larger companies. Furthermore, these companies also have more configurators in operation, and the configurators are characterised as being more complex regarding the number of attributes, rules and integrations with other software applications. In three of the six companies using UML-based modelling techniques, the respondents reported that they started to model their configurators using non-formal modelling techniques. However, as the configurators grew bigger and the number of people involved in the configurator projects increased, the companies realised the necessity of working in a more structured way and taking more control of the models implemented in the system. Therefore, in these cases, UML-based modelling techniques were applied at a later stage in those configurator projects.

Table 5. The types of modelling methods used to represent the knowledge in configuration projects.

Number of companies	Company ID	UML-based modelling techniques	Non-UML-based modelling techniques	Non-formal modelling techniques
6	1, 3, 4, 5, 7, 8	x		
6	2, 6, 9, 10, 11, 13		x	
6	12, 14, 15, 16, 17, 18			x

Table 6. The use of different types of modelling techniques related to configuration area size and configurator complexity.

	No. employees	No. configurators	Number of employees involved in configurator projects	Number of users	No. attributes	No. constraints	Total integrations
Companies using UML-based modelling techniques							
Average	7833	4.2	7	190	2725	2391	3.2
Companies using non-UML-based modelling techniques							
Average	4600	2.3	6	130	720	730	1.7
Companies using non-formal modelling techniques							
Average	370	1.3	3	37	1000	708	1.7

Comparing the companies using UML-based modelling techniques with the companies using non-UML-based or non-formal modelling techniques reveals that the latter companies are smaller in terms of numbers of employees and system users, and the configurators are less complex with respect to numbers of rules, attributes and integrations. However, the results show that companies using non-UML-based modelling techniques were larger than those using non-formal modelling techniques and have more configurator users, but the configurators were similar in terms of complexity. These results could indicate that for a minor configurator project that does not involve too many employees, the product modelling can be managed using non-UML-based or non-formal modelling techniques.

5.2 *The impact of applying different modelling techniques*

The impact of using UML-based modelling techniques compared with non-UML-based or non-formal modelling techniques is analysed concerning the propositions or availability of product knowledge and control of product variants. The respondents rated the impact on a five-point scale, with 'one' indicating they strongly disagreed with the statement and 'five' indicating they strongly agreed with the statement. Table 7 provides the results concerning the propositions, and the values given in the table are based on a five-point scale representing to what extent the companies agree with the obtained benefits.

First, increased availability of product knowledge is measured through ratings of improved documentation of knowledge and improved availability of product knowledge. The companies using a UML-based modelling technique gave higher ratings to improved documentation of knowledge, improved availability of knowledge and improved availability of product knowledge. Furthermore, companies using non-UML-based modelling techniques gave a higher rating than companies using non-formal modelling techniques. This indicates that the more formalised the method, the more the availability of product knowledge increases. However, especially between companies using UML-based and non-UML-based techniques, there is only a small difference in responses.

Second, improved control of product variants is measured through ratings of reduction in product variants (item numbers), increased use of standard components and improved product quality. Companies using a UML-based modelling technique claimed to be better able to reduce the number of product variants than companies not using UML-based modelling techniques, which may be related to an increased ability to document and gain access to product knowledge. Furthermore, the companies using UML-based modelling techniques rated higher with respect to benefits from increased use of standard parts and improved product quality. The findings in relation to improved control of product variants align with results of increased availability of knowledge, or the control of product variants increases as more formal modelling technique is used.

Table 7. Comparison of the impact of using different types of modelling techniques in configurator projects concerning propositions (in which 'one' represents strongly disagree and 'five' represents strongly agree).

	Increased availability of product knowledge		Improved control of product variants		
	Improved documentation of knowledge	Improved availability of product knowledge	Reduction of product variants (item numbers)	Increased use of standard parts	Improved quality of products
Companies using UML-based modelling techniques					
Average	4.7	4.7	4.0	4.7	4.4
Companies using non-UML-based modelling techniques					
Average	4.3	4.5	2.5	4.3	4.2
Companies using non-formal modelling techniques					
Average	3.7	3.8	2.2	4.0	3.8

6. Discussion

The literature emphasises the need for formal modelling methods to structure and formalise knowledge in configurator projects (Aldanondo, Rougé, and Véron 2000; Forza and Salvador 2002a; Felfernig et al. 2004; Hvam 2006; Stark 2007; Ardissono et al. 2003; Felfernig et al. 2014; Shafiee et al. 2017). However, the impact of utilising modelling techniques in configurator projects remains relatively unaddressed. Studies addressing the impact of utilising modelling techniques in configurator projects show that reduced time for development and maintenance, increased efficiency of product development, reuse of knowledge and better utilisation of employees in configurator projects can be achieved (McGuinness and Wright 1998; Stumptner, Friedrich, and Haselböck 1998; Chao and Chen 2001; Yang et al. 2009; Shafiee et al. 2017). However, these studies are all based on case studies in which the impact of applying the method is compared with when a structured modelling technique was not used. In contrast, this study explores the impact of using different modelling techniques within 18 companies.

In this study, which examined three types of modelling techniques – UML-based, non-UML-based and non-formal, the findings show that the importance of using more formalised modelling techniques increases when companies get larger and configurators' complexity (numbers of rules, attributes and integrations) increases. In support of this, the findings show that UML-based modelling techniques are used at larger companies and in configurator projects in which the configurators include greater numbers of rules, attributes and integrations. Furthermore, three of the six respondents from companies using UML-based modelling methods reported that they started to use them as the number of configurators and configurator projects grew and involved more people. This indicates that UML-based modelling techniques are required for larger companies to be successful in managing a set-up with several configurators in operation with high complexity and numerous employees involved (often geographically dispersed).

The impact of applying the different modelling techniques is analysed regarding improved availability of knowledge (Tiihonen et al. 1996; Slater 1999) and improved control of product variants (Forza and Salvador 2002b, Tenhiälä and Ketokivi 2012), which are commonly reported benefits from configurators that can be linked directly to companies' capability to formalise and represent knowledge. The findings show that companies utilising UML-based modelling techniques perform better concerning knowledge availability and control of product variants than the ones using non-UML-based and non-formal modelling methods. These findings indicate that by investing time in structuring knowledge using formalised modelling methods, companies can gain additional benefits aside from configurator aspects. This especially applies to larger companies with more complex configurators. The ability to keep the number of product variants low is an important enabler for reducing complexity and thereby keeping costs down in companies (Hvam, Mortensen, and Riis 2008; Lindemann, Maurer, and Braun 2008).

7. Conclusion

This paper aimed to investigate the impact of using different modelling techniques to structure and formalise knowledge in configurator projects. The exploratory nature of the research aim means an exploratory survey with in-depth follow-up interviews is employed. The findings show that out of a sample of 18 companies, six used UML-based modelling techniques, six used non-UML-based modelling techniques and the remaining six used non-formal modelling techniques. To represent UML-based modelling methods, the CPM procedure is used, in which both the PVM and class diagrams support a UML notation. Aligned with the study's focus on analysing the actual impact of using different modelling techniques, this paper analysed two propositions.

The first proposed that use of a UML-based modelling method would result in *increased availability of product knowledge in organisations*. This is measured through (1) improved documentation of knowledge and (2) improved availability of product knowledge. The results revealed that companies using a UML-based modelling technique scored the highest. However, there was only a small difference between those companies and the companies using non-UML-based modelling techniques. One explanation is that product knowledge is still documented in the latter group, even though the information model is not structured. Another factor influencing this finding is that the companies using non-UML-based modelling techniques have less-complex configurators concerning numbers of rules, attributes and integrations, making the complexity more manageable.

The second proposition was that the use of a UML-based modelling technique would result in improved control of product variants. This is measured through (1) reduction of product variants (item numbers), (2) increased use of standard parts and (3) improved quality of products. The companies using UML-based modelling techniques were more in control of their product knowledge and product variants than the companies using non-UML-based or non-formal modelling techniques. This may be partly due to an increased ability to involve domain experts in the modelling process, thereby ensuring that the right decisions are being made regarding which product variants to include in the configurators. Furthermore, a UML-based modelling technique makes it possible to keep track of product variants, features and rules implemented in the configurators.

This paper contributes novel insights to the research community and practitioners by analysing the impact of different modelling methods used in configurator projects based on the availability of product knowledge and control of product variants. Furthermore, the findings can be used to determine a sufficient level of documentation, e.g. at larger companies with complex configurators, more formal documentation is required, making UML-based techniques more desirable. Finally, the results presented in this paper can be used to guide further studies in this area of configurator research.

7.1 *Limitations and further research*

As this research is exploratory, the focus was on gathering in-depth information from companies, instead of having a large sample size that does not allow for the same in-depth information gathering. Thus, both survey and interview methods were used to ensure high-quality data. To be able to generalise from these findings based on a statistical analysis, a larger sample of companies is needed, providing an avenue for further research.

In this study, the CPM procedure is used to represent UML-based modelling techniques. The CPM procedure has been used by the authors' research team for more than 16 years and has proven its usability in different industrial settings. The main reason for selecting the CPM procedure is accessibility, as the authors had worked with some of the companies in the past. However, to avoid bias in the results, the respondents chosen had not, prior to this study, worked with the research team. Therefore, further studies should include an analysis of other modelling techniques.

The impact of using different modelling techniques is based on preserved benefits rated on a five-point scale, so they are based on the respondent's perspective. Additionally, approximate values are used to represent numbers of rules and attributes when exact numbers were not available. This is aligned with the exploratory nature of the study, which aimed to determine whether there are any relationships between the constructs, thereby providing guidelines for further studies (descriptive or explanatory surveys), not to prove their existence or the relationships between constructs. Therefore, further studies should include more objective measures to quantify the impact (e.g. percentages of variant reductions (item numbers), numbers of product modelling/coding errors, or corrections and product-modelling workloads).

Disclosure statement

No potential conflict of interest was reported by the authors.

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APPENDIX H

How to scope configuration projects and manage the knowledge they require

Sara Shafiee, Katrin Kristjansdottir, Lars Hvam and Cipriano Forza

Abstract

Purpose – *This paper aims to explore the use of the knowledge management (KM) perspective for configuration projects. Configuration projects implement configurators as information technology systems that help companies manage the specification process of customised products. An effective method of retrieving and formalising knowledge for configurators is essential, because it can reduce the risk of unsuccessful implementation and the time and effort required for development. Unfortunately, no standard KM frameworks are available specifically for configuration projects. This study identifies the knowledge necessary for different phases of a configuration project (which knowledge, for what purpose and from what sources), examines how it is transformed during a configuration project (what KM activities and tools are used) and establishes how the knowledge can be documented for future maintenance and updates.*

Design/methodology/approach – *This paper proposes a four-step framework for making the KM process more efficient in configuration projects. The framework is based on the literature, developed in collaboration with industrial partners and tested on four configuration projects in two engineering companies. The framework is a structured KM approach designed to save time for both domain experts and the configuration team. The authors have used a qualitative exploratory design based on multiple data sources: documentation, workshops and participant observation.*

Findings – *The proposed framework comprises four steps: determination of the system's scope, to establish the project's goal based on stakeholders' requirements and prioritise the required products and processes; knowledge acquisition, to classify the knowledge according to the desired output and identify different knowledge sources; modelling and knowledge validation; and documentation and maintenance, to ensure that the KM system can be maintained and updated in the future.*

Research limitations/implications – *Because the framework is tested on a limited number of cases, its generalisability may be limited. However, focusing on a few case applications allows us to assess the effectiveness of the framework in detail and in depth to identify the practical challenges of applying it. The results of the tests support the framework's validity. Although the framework is designed mainly for engineering companies, other industries could benefit from using it as well.*

Practical implications – *The individual steps of the framework create a structured approach for the KM process. Thus, the approach can save both time and resources for companies, without the need for additional investment.*

Originality/value – *A standard framework is lacking in the literature on KM for configuration projects. This study fills that gap by developing a KM framework for configuration projects, based on KM frameworks developed for IT projects, and KM tools.*

Keywords *Knowledge management, Knowledge acquisition, Configuration projects, Product documentation, Product modelling, Scoping*

Paper type *Research paper*

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Received 12 January 2017
Revised 25 July 2017
6 October 2017
Accepted 17 November 2017

This work was conducted within the company Haldor Topsoe A/S. The granted project and the financial support are gratefully acknowledged.

1. Introduction

Configurators have entered a new stage of maturity and have recently received increased attention from both researchers and practitioners. Configurators support decision-making processes in the sales and engineering phases of a product, which can determine the most important decisions regarding product features and cost (Hvam *et al.*, 2008). Configurators

DOI 10.1108/JKM-01-2017-0017

enable companies to develop product alternatives to facilitate sales and production processes (Felfernig *et al.*, 2014) by incorporating information about product features, product structure, production processes, costs and prices (Forza and Salvador, 2007). This information is modelled into the configurators during their implementation (Forza and Salvador, 2007). Because configurators are implemented in the context of a project, we refer to this process as a "configuration project".

The variety and complexity of knowledge in configuration projects are discussed in the literature on configurators. Increased complexity of products increases the number of product features to be modelled and maintained in a configurator (Ardissono *et al.*, 2003). The configuration knowledge for different parts of a product is often spread among various experts in a company (Hvam *et al.*, 2008). Other valuable sources of knowledge are available in internal software systems, such as enterprise resource planning systems, calculation systems and spreadsheets (Friedrich *et al.*, 2014). Therefore, a knowledge acquisition and cleansing stage is required early in a configuration project's development phase (Friedrich *et al.*, 2014). Once the configurator is up and running, further knowledge may be necessary to keep it up to date. Therefore, knowledge is required throughout a configurator's life.

Knowledge management (KM) in configuration projects is one of the most time-consuming tasks for domain experts[1] and the configuration team[2]. KM is an integrated process incorporating a set of activities to create, store, transfer and apply knowledge to a knowledge business value chain (Aurum *et al.*, 2008). In configuration projects, KM is challenging because it involves the entire life cycle of knowledge, from acquisition (Hvam *et al.*, 2008; Tiihonen *et al.*, 1996) to modelling[3], validating, testing (Hansen *et al.*, 2012; Magro and Torasso, 2003; Tseng *et al.*, 2005; Yang *et al.*, 2009) and finally to documenting and updating. Project teams must have access to the knowledge required for configuration projects (Turley, 2007) to maintain awareness of the following issues when managing and modelling the configurator's knowledge (Studer *et al.*, 1998):

- Models are only approximations of the reality because the modelling process is open-ended.
- The modelling process is cyclical, and because new observations may lead to a refinement, modification or completion of the already built-up model, the model may guide further knowledge acquisition.
- The modelling process is dependent on the subjective interpretations of the knowledge engineer[4].

KM is critical to the development of centralised configurators (Fleischanderl *et al.*, 1998) because:

- knowledge must be shared among supply-chain participants and different reasoning mechanisms and tools must be integrated; and
- the adaptive user interface must be dynamically generated by the application of business rules and personalisation strategies based on the product knowledge stored in the knowledge base (Ardissono *et al.*, 2003).

Effective KM facilitates the creation and integration of knowledge, minimises knowledge losses and fills knowledge gaps throughout the project (Lech, 2014). The primary recommendation for achieving effective KM is to adopt a KM framework designed for the system context under consideration (Rubenstein-Montano *et al.*, 2001).

Unfortunately, no systematic framework currently exists for KM in configuration projects (Forza and Salvador, 2002a; Friedrich *et al.*, 2014). On the basis of the discussions above, the lack of such a framework leads to faulty KM processes for the following reasons:

- The modelling process depends on new observations in a cyclic course.
- The model requires continuous revision at all stages of the modelling process, so the configuration team lacks confidence in the adequacy of the knowledge.
- The acquired knowledge, which involves the project's entire life cycle, is influenced by knowledge engineers' interpretations, so its objectivity is questionable.
- The project does not have a defined scope and extension.
- The configuration team experiences difficulties when they have to manage knowledge for areas outside their expertise (Haug and Hvam, 2008; Nonaka, 1994; Studer *et al.*, 1998).

Some studies have suggested a general KM framework (Heisig, 2009), some have proposed individual steps for the KM of configuration projects (Felfernig *et al.*, 2014) and some have highlighted tools or frameworks available for KM in information technology (IT) projects in general (McGinnis and Huang, 2007), but not specifically for configuration projects. These indications and tools for generic KM and KM in IT projects can serve as the basis for a systematic methodological framework for KM in configuration projects.

This study proposes a framework that identifies the most important KM steps in configuration projects. This framework is based on generic KM frameworks and KM frameworks designed for IT projects. By using this framework, companies can improve the quality of acquired knowledge and reduce its complexity by limiting the knowledge to that needed for the stakeholders' requirements. The framework also offers methods for keeping the knowledge up to date.

The remainder of the paper is structured as follows. Section 2 explains the study's methodology (which is presented before the literature review because the literature review is an essential part of the framework development). Section 3 discusses the relevant literature, and Section 4 explains the framework development. Section 5 presents the results of the framework validation, and Section 6 discusses the results. Section 7 concludes the paper.

2. Research method

This study was performed in three main phases: literature review, framework development and framework validation. Hereafter, for each phase we have presented the method that was adopted.

2.1 Literature review

The relevant literature is reviewed to clarify the present study's position in relation to existing research. This allowed us not only to ascertain whether our research has the potentials to add something new but also to identify which parts of the available knowledge are relevant to our purpose.

First, we take a generalised view of KM frameworks to explain key KM concepts and discuss literature reviews on numbers of KM frameworks. Studies comparing different KM frameworks have resulted in decisions regarding the development of a general KM framework (European Committee for Standardization, 2004; Heisig, 2009). This general KM framework supports the decisions about the steps required for the framework proposed in the present article.

Second, we discuss the challenges of KM in configuration projects and identify existing methods that could be applied to overcome these challenges (McGinnis and Huang, 2007; Rodriguez and Al-Ashaab, 2005). This step reveals some KM-specific challenges and also sheds light on the available KM literature in configuration projects as well as the lack of suitable KM framework for configuration projects.

Third, we have considered KM frameworks developed for IT projects in general to determine whether any of those is applicable to configuration projects (Lech, 2014; Reich *et al.*, 2012). Moreover, comparing different studies led to conclusions about a generic KM framework for IT projects.

Fourth, the differences between the required KM framework for IT projects in general and configuration projects are identified. This comparison highlighted the need for KM frameworks tailored to configuration projects (Basili and Weiss, 1984; Forza and Salvador, 2002a, 2002b; Friedrich *et al.*, 2014; Tiihonen *et al.*, 1996). Nevertheless, KM frameworks for IT projects could serve as a foundation for developing KM frameworks for configuration projects and for proposing *ad hoc* frameworks.

2.2 Framework development

The framework development was based on the literature review, analytical thinking and interactions with industrial partners (case company).

From the literature review, we obtained the following tools and methods for the individual phases of KM in configuration projects:

- identifying stakeholder requirements;
- prioritising products and product features to include in the configurators;
- identifying knowledge resources;
- modelling and validating knowledge; and
- documenting configurators and maintaining knowledge.

Analytical thinking was used to break the problem into smaller sections. Categorising different aspects of KM in the literature supported the organisation of concepts into hierarchical phases. Afterwards, we used these phases to investigate the keywords for each section.

On the basis of the relevant information in the literature, the team then identified the key issues. Iterative design method, which blends the activities of designer and user and creator and player, is based on a cyclical process of prototyping, testing, analysing and refining a work in progress (Zimmerman, 2003); thus, we developed the framework through an ongoing dialogue between the researchers and configuration teams. In other words, the framework was developed and validated in an iterative process in one company which allows us to benefit from the strength of using the case study method (McCutcheon and Meredith, 1993; Van de Ven, 1989). The industrial partner for developing the framework has experienced both successes and failures in configuration projects.

2.3 Framework validation

Finally, after making the final decisions regarding the sequences of steps and proposed tools for the framework, we conducted multiple case studies to validate the framework's usability in different circumstances. Our units of analysis were the individual configuration projects. We analysed four projects in two companies. Eisenhardt (1989) recommendation to conduct the analysis in two steps was followed:

1. First, we performed the analysis within each case (project).
2. Subsequently, we searched for cross-case patterns.

Having four projects in two companies, cross-case comparisons were conducted across projects both in the same company and in different companies. The use of multiple cases in different settings and multiple sources of information for each case improved the validity of our findings. To facilitate the reading of the cases, the methodological details are reported in Section 5.

3. Literature review

This section reviews, first, the general literature on KM frameworks, second, KM challenges in configuration projects, third, KM frameworks for IT projects and fourth, the use of KM in configuration projects. With a general understanding of KM frameworks and how IT systems frame the KM process, and based on the available literature for KM in configuration projects, the paper introduces the proposed framework in Section 4.

3.1 Knowledge model and KM frameworks

To address KM in configuration projects, it is necessary to understand two fundamental KM notions, namely, knowledge models and KM frameworks. A knowledge model comprises different categories of knowledge organised in three main levels (Liebowitz and Megbolugbe, 2003). The bottom-level category is domain knowledge, which specifies domain-specific knowledge and information. The middle level is inference knowledge, which refers to the basic inference steps made on the basis of domain knowledge. The upper-level category is task knowledge, which refers to application goals and how these can be realised through decomposition into subtasks and inferences.

Knowledge has to be carefully exploited for its potential usefulness. Doing so constitutes a challenge. Heisig (2009) emphasised that addressing the challenge of knowledge handling with only one activity, like “sharing knowledge”, is insufficient. Several interconnected activities are needed for successful knowledge handling (Heisig, 2009). It is therefore necessary to have frameworks that present the activities to be performed and to properly manage knowledge and the relationships among these activities.

A KM framework represents the relation and dependency among the various KM components (processes, activities and enablers) (Liebowitz and Megbolugbe, 2003). KM frameworks support the determination and positioning of KM activities (European Committee for Standardization, 2004). During the planning and implementation of projects with KM requirements, frameworks can provide useful assistance for holistic KM solutions (Liebowitz and Megbolugbe, 2003).

Several KM frameworks have been reported in the literature. Heisig (2009) outlined the similarities and differences between 160 KM frameworks (proposed in studies such as Bose and Sugumaran, 2003; British Standards Institute [BSI], 2001; Kelleher and Levene, 2001). Heisig found that the most frequently mentioned categories of KM activities are, in decreasing order of frequency of appearance in KM frameworks, creation, application, storing and identification of knowledge. To share knowledge effectively, or use existing knowledge, tools are often necessary, although this does not always mean technical tools (European Committee for Standardization, 2004). The European CEN workshop introduced the KM framework for practitioners in terms of identification, creation, storage, sharing and usage (European Committee for Standardization, 2004), in line with Heisig (2009). Comparing the various studies makes it possible to identify a general consensus (although with some terminological differences) regarding a general KM framework that includes the following activities: identification, creation, storage, sharing and usage.

3.2 Configuration projects: a KM challenge

Academics and practitioners recognise that KM has a crucial influence on the success or failure of configuration projects (Lech, 2014). Configurators involve a great deal of knowledge that represents the complex relations among components or modules, such as configuration rules and assembly constraints (Jinsong *et al.*, 2005). The knowledge complication of configurators is because of:

- *volatility problems* – they are a dynamic subject domain;
- *scope expansion* – because configurators are successful business tools, users will ask for more; and
- the large size and information complexity of the knowledge in the systems (Barker *et al.*, 1989).

Because the mapping between functional roles and the set of components available is typically many to many, the configuration task is dynamic in nature (Sabin and Weigel, 1998). Today, companies integrate their configurators with company-wide data-modelling systems to facilitate the management of frequently changing product knowledge (Sabin and Weigel, 1998).

A simple medical device can illustrate the challenges of KM for configurators. Developing a system for configuring a hearing aid involves the following challenges:

- The configuration engineer must learn about the details to consider and model all the rules and attributes of the hearing aid, even though it is beyond his expertise.
- Because the knowledge covers millions of selections when configuring the simplest hearing aids, the project will cover all the knowledge and will become complex.
- The systems need integration with other systems, such as calculation systems, for accurate dimensioning to automate the whole process, and the scope of the project will change and expand, because the configuration engineer needs to become familiar with the other IT systems to map the systems.
- Based on recent research and developments in medical science, this product is dynamic and the configurator must be updated and aligned with all recent developments.

The tools for KM in configuration projects can be grouped, as shown in Table I, based on commonly proposed steps for KM in configuration projects in general.

These steps are summarised and explained in the following paragraphs.

Determining the scope of configurators is a KM-related challenge for industry. This step clarifies the knowledge requirements for the entire project and gives the team the opportunity to make intelligent decisions from the early phases of the project. Furthermore, in the early phases of the configuration project, the scope of the products sheds light on project goals and outputs, objectives and requirements from the stakeholders, IT architecture, etc. (Shafiee *et al.*, 2014).

Knowledge acquisition is also frequently considered a challenge (Table I). In the early phases of a configuration project, it is often difficult to identify and retrieve the right product knowledge to implement in the system (Shafiee *et al.*, 2014). Knowledge acquisition entails categorising the knowledge based on the relevant stakeholders' needs, recognising all the possible sources and resources of knowledge, collecting the knowledge and categorising it based on previous analyses of the product/process. The processes by which the products are developed usually do not create the configuration-related knowledge as a part of the development effort. Instead, this additional knowledge acquisition task is performed by persons that are not product experts, which might lead to loss of data and erroneous

Table I Literature base for the main steps in KM for configuration projects

Author (year)	*Determining the scope of the configurator*	*Knowledge acquisition*	*Modelling and knowledge validation*	*Documentation and maintenance*
Forsythe and Buchanan (1989)	✓			
Tiihonen *et al.* (1996)		✓		
Sabin and Weigel (1998)			✓	
Aldanondo *et al.* (2000)			✓	
Chao and Chen (2001)			✓	
Forza and Salvador (2002a)				✓
Ardissono *et al.* (2003)		✓		
Magro and Torasso (2003)			✓	
Tseng *et al.* (2005)			✓	
Jinsong *et al.* (2005)		✓	✓	
Forza and Salvador (2007)		✓	✓	✓
Hvam *et al.* (2008)	✓	✓	✓	
Mortensen *et al.* (2008)	✓			
Haug *et al.* (2009)			✓	✓
Yang *et al.* (2009)			✓	
Hansen *et al.* (2012)			✓	
Felfernig *et al.* (2014)	✓		✓	
Shafiee *et al.* (2014)	✓			

configuration of the knowledge being used in the configuration process (Tiihonen *et al.*, 1996).

Although gathering and representing relevant information is one of the most difficult tasks in configuration projects, modelling and validation are the challenges most frequently reported in the literature (Hvam *et al.*, 2008; Sabin and Weigel, 1998). A considerable amount of research is therefore devoted to product modelling and communicating with domain experts to validate the knowledge.

Researchers have highlighted documentation and maintenance as a critical phase of KM for configurators (Forza and Salvador, 2002a; Shafiee *et al.*, 2017). A primary motive for building a support system for product configuration is to support the transfer of up-to-date product configuration knowledge to the sales units and to enforce its proper use (Tiihonen *et al.*, 1996). Studies of companies using configurators have shown that without proper documentation, they often become unable to use the configurators and have had to abandon or rebuild them (Haug *et al.*, 2009). It is therefore important to have a reliable configuration model for the products implemented inside the configurator, i.e. one that has no technical errors and mirrors exactly the product design's updates (Forza and Salvador, 2002a).

As Table I shows, many authors have discussed different steps, but none have proposed a framework that incorporates the steps in sequence. The various steps explained in the literature on configurators can be connected to the overall KM framework presented in Section 3.1 (identify, create, store, share and use). Scoping the project means identifying the needed knowledge; knowledge acquisition is equivalent to creating knowledge; and the modelling and validation step is equivalent to the step of using and sharing; and finally, documentation is equivalent to storing.

3.3 KM framework in IT projects

Efficient creation, distribution and reuse of the up-to-date knowledge are critical success factors in IT projects, but unachievable in practice (Compton and Jansen, 1990; Komi-Sirvio *et al.*, 2002). As noted, the literature has suggested a number of frameworks for KM in IT projects (Table II). According to the level of abstraction, the frameworks range from three

Table II KM frameworks for IT projects

Authors	*Actions/phases included in KM framework*
Basili and Weiss (1984)	Establish the goals of knowledge selection, develop a list of questions of interest, establish knowledge categories, design and test knowledge collection form, collect and validate gathered knowledge and analyse the knowledge
Kucza and Komi-Sirviö (2001)	Identify need for knowledge, share existing knowledge, create new knowledge, collect and store knowledge and update knowledge
Komi-Sirvio *et al.* (2002)	Define scope and requirements for knowledge capturing, acquire knowledge and package knowledge
Rodriguez and Al-Ashaab (2005)	Identify knowledge sources and resources, identify kind of knowledge, identify knowledge flows (graphical modelling techniques) and identify faults in the knowledge flow (analyse knowledge)
Reich *et al.* (2012)	Knowledge stock (relevant domain knowledge of the IT team, the business team and the governance team), enable the environment (combination of the technological and social aspects of a project that facilitate knowledge practices), knowledge practices (actions taken to map and share knowledge within and between the IT, business and governance teams in an IT-enabled business project)
Lech (2014)	Identification (determine knowledge sources and resources), acquisition/creation, transfer/ dissemination, storage/capture and use/application
McGinnis and Huang (2007)	Socialisation (scoping and deliverables), externalisation (formalise the knowledge to be explicit), combination (knowledge clarification and team communication), internalisation (new deliverables, improved documentation, improved training and process refinements)

phases/actions to six phases/actions, and some of the frameworks focus more on acquisition (Basili and Weiss, 1984), whereas others consider the entire KM life cycle, including maintenance (Kucza and Komi-Sirviö, 2001). Some frameworks use identical terms, such as “knowledge identification” and “knowledge scoping”, whereas other frameworks use different terms, even for similar activities/phases (e.g. “knowledge stock”, “scope” and “socialisation”, all of which refer identifying the needs and goals).

Even though the frameworks use different terms for the various phases of KM in IT projects, they exhibit a number of similarities (Rubenstein-Montano *et al.*, 2001). Almost all the frameworks start by determining the scope of the project to establish the goals, requirements and deliverables of the system. After these first phases, the frameworks typically aim to collect and categorise the knowledge and ascertain the knowledge sources and resources. Subsequently, knowledge acquisition is discussed in terms of communicating, modelling and clarifying the knowledge. All authors consider the collection, validation and documentation of the knowledge as separate steps, and the majority of the frameworks end with a step for maintaining the knowledge.

However, these frameworks have a limited ability to support the KM process in configuration projects because of the differences between IT and configuration projects, which are explained in detail in the following section.

3.4 Configuration and IT projects: similarities and differences

Configurators are considered to be among the IT systems that are important for mass customisation (Blecker *et al.*, 2004; Forza and Salvador, 2007; Hvam *et al.*, 2008). However, there are several differences between IT projects and configuration projects. The first difference relates to the knowledge complexity and extensions of configurators, which make it critical to determine the scope of the project in the early phases to predict the level of the complexity and potential extensions. This is done by identifying the requirements, evaluating the time and budget and prioritising the different products and functions according to the variety and complexity of the knowledge, the required tasks and the resources for the project development (Männistö *et al.*, 2001; Shafiee *et al.*, 2014). In configuration projects, knowledge acquisition bottlenecks often occur because of the large and complex knowledge bases. In such scenarios, knowledge engineers get overwhelmed by the increasing amount, size and complexity of knowledge bases (Ulz *et al.*, 2016). There are two types of IT projects (Whitney and Daniels, 2013). The first has a well-understood, clear scope and few unknowns. The second is complex, with many unknowns; such projects often have planning and scoping issues. Therefore, IT projects can vary greatly because these also have different natures and usually require less extensive product knowledge.

The second difference relates to the details of the communication level for configuration projects as compared to IT projects. The knowledge required for configuration projects is normally very specialised product knowledge that lies beyond the configuration team's expertise (Haug and Hvam, 2008; Studer *et al.*, 1998). The consequence is that, for example, a knowledge engineer needs to learn the different domain aspects from the experts to model medical equipment. Knowledge formalisation and communication in configuration projects correspond to product modelling, which is a method of representing the structure and knowledge of the product on a relatively visual, abstract level to ensure that they are understandable to all persons concerned (Shafiee *et al.*, 2017). In IT projects, each project team declares its priorities as well as its communication and validation requirements. The team can orient itself to the amount of face-to-face communication it can manage and the extra methodology weight it should appropriately set in place (Cockburn, 2002). Because of the differences in the nature of the received knowledge, configuration projects are formalised and communicated differently than other IT projects. Consequently, the knowledge modelled in configuration projects is extensive and must be continually validated by domain experts (Basili and Weiss, 1984). Strong communication between the configuration team and domain experts in configuration projects is vital, and specific modelling techniques tend to meet this challenge in configuration projects (Forza and Salvador, 2002a). In addition, without proper validation, very minor misunderstandings in the knowledge can lead to big errors in calculations and outputs.

The third difference relates to the need for specific comprehensive documentation and maintenance of the knowledge in configuration projects (Haug and Hvam, 2007). The knowledge has to be clear and understandable to all stakeholders and expressed in non-IT language. There is a high level of integration with other IT systems, and the knowledge must be shared among participants in the supply value chain. In addition, the frequent changes in product knowledge necessitate continual updating and maintenance of the knowledge (Friedrich *et al.*, 2014; Tiihonen *et al.*, 1996). By contrast, the documentation in IT projects is normally a summarised explanation of the codes and a set of user stories that are passed on to another IT specialist (Coram and Bohner, 2005). Most IT projects are not required to work with complicated products or process knowledge, and IT specialists do not have to communicate with people outside the IT field to verify the knowledge contained in the system. Furthermore, the knowledge required for IT projects does not require constant updates (Coram and Bohner, 2005).

In summary, the knowledge, and thus the KM, for IT projects differs from that for configuration projects. Owing to the complex nature of KM in configuration projects, the frameworks designed for IT projects are unsuitable for configuration projects because these fail to incorporate sufficient steps to cover all KM needs. Table III presents a summary of this section.

4. The proposed framework

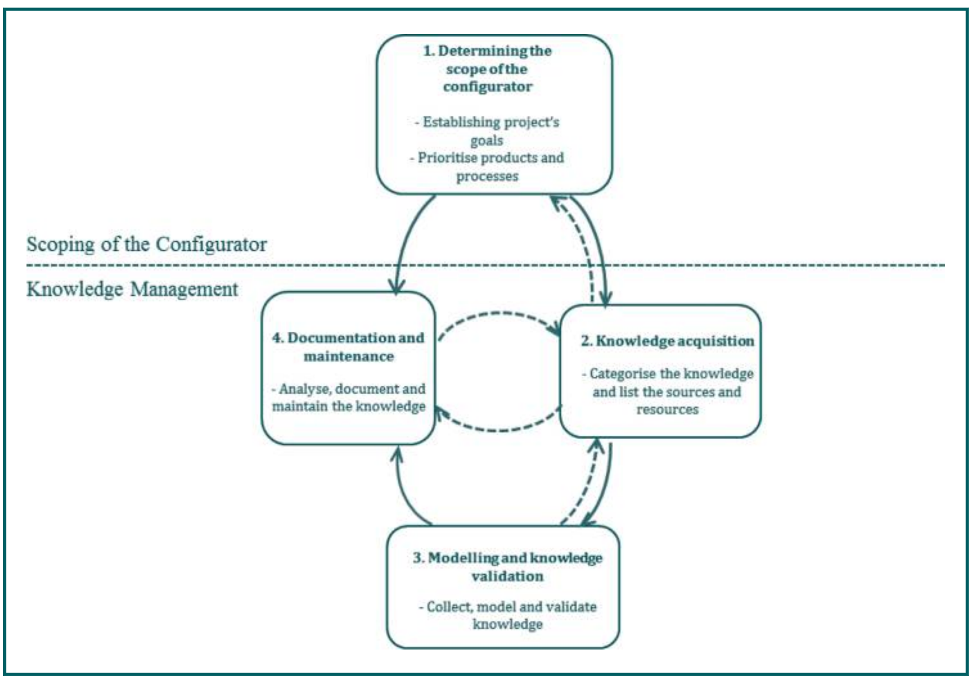
The framework proposed here is based on the literature on configurators and the literature on KM frameworks for general IT projects, integrating the main phases of their KM frameworks and including specific tools and methods. However, owing to the similarities and differences between configuration and IT systems, the framework includes the different steps available for configurator KM and incorporates experiences from the development, implementation and maintenance of existing configuration projects. The framework was

Table III Differences between IT and configuration projects			
Differences	*Knowledge complexity and project extensions*	*Level of communication*	*Documentation and maintenance of knowledge*
Configuration projects	Highly complexity and varied knowledge; continuous requests for project extensions because of updated product portfolios; further development because of usage frequency; requests for more outputs (Hvam *et al.*, 2008; Shafiee *et al.*, 2014)	Requires very strong communication that covers all stakeholders; requires continuous validation from domain experts (Basili and Weiss, 1984; Forza and Salvador, 2002a)	Documentation of different ranges of knowledge, from integrations to product knowledge, by using modelling techniques; frequent updating of the documents because of frequent changes in product portfolio (Friedrich *et al.*, 2014; Tiihonen *et al.*, 1996)
IT projects	Different levels of complexity based on the type; minor or major extensions in some of the IT projects (Whitney and Daniels, 2013)	Requires minimal communication; requires final testing for each version of the project (Cockburn, 2002)	Documentation of codes; documentation updates in the event of code updates (Coram and Bohner, 2005)

improved in an iterative process using a case company and benefited from the experiences and knowledge of practitioners and academics.

As a configurator becomes more successful and popular among users, users' expectations and requirements for the system increase (Barker *et al.*, 1989). The framework therefore needs to include the possibility of iterations in the KM. As illustrated in Figure 1, the first step involves determining the scope of the system; in the second step, knowledge acquisition is carried out; in the third step, the knowledge is structured (using special modelling

Figure 1 Proposed framework for knowledge management in configuration projects



techniques) and validated; and the final step is concerned with documentation and maintenance. Figure 1 represents the individual steps of the framework, showing the relations and iterations between the steps.

The following sections explain the four steps of the framework in greater detail and introduce the tools and the method used.

4.1 Step 1: determining the scope of the configurator

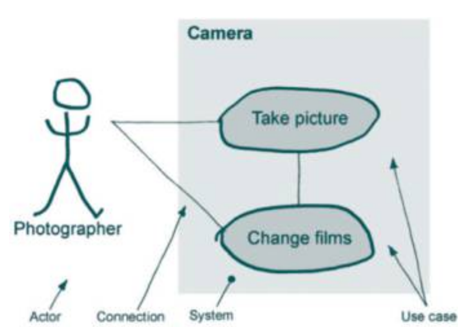
4.1.1 Establishing project goals. Project goals are determined by identifying stakeholders' functional and non-functional requirements. This step aims to improve the understanding of the project by identifying the main stakeholder requirements (Basili and Weiss, 1984). Non-functional requirements are general quality attributes that emphasise quality and compliance with requirements. A non-functional requirement describes not what the software will do but how it will work (Ebert, 1997), such as the reliability, consistency and maintainability of configurators. A functional requirement specifies each of the functions that a system must be capable of performing (Ebert, 1997), such as all the features of the user interface.

The stakeholders and their requirements can be drawn up using process flow charts based on the rational unified process (RUP) methods (Compton and Jansen, 1990) as well as the use-case diagrams. Process flow charts can be used to describe the current situation and different scenarios for future work (Hvam *et al.*, 2008), whereas the use-case diagrams (Figure 2) can illustrate the requirements and the actors involved in the project (Kruchten, 2007).

The MoSCoW rules are commonly used when prioritising stakeholder requirements. MoSCoW is derived from the first letters of the following criteria: Must have (Mo), Should have (S), Could have (Co) and Want to have (W) (Bittner, 2002). Further details of stakeholder analysis are available in the studies by Ebert (1997), Jiao and Chen (2006), Lim *et al.* (2011) and Bittner(2002) for generic IT projects, and in the studies by Forsythe and Buchanan (1989), Hvam *et al.* (2008), Nellore *et al.* (1999), Felfernig *et al.* (2014) and Mortensen *et al.* (2008) for configuration projects.

4.1.2 Prioritising products and processes to be included in the system. In this step, the products or product features and functionalities to be included in the system are prioritised. The purpose of using a component-based structure, based on RUP methods, is to break a large and complex project into smaller pieces (Briand, 2003). This makes the development process easier, especially in complicated and highly

Figure 2 Example of a use-case diagram



Source: Hvam *et al.* (2008)

engineered projects (Felfernig *et al.*, 2014). After breaking down the project, the team should start developing one of the components or products, depending on the size of the project. To make prioritisation more systematic, a supporting tool is needed.

The recommended tool for this step is a weighting table, in which each of the components is rated against several specific weighted project success criteria and a score is computed to rank the priority of the components (Wiegers, 1999). In Wiegers's(1999) approach, prioritisation is calculated on the basis of:

- the benefits and penalties of including a feature in the system (the feature could cover both functional and non-functional requirements);
- the cost of implementing the feature; and
- the time and technical issues associated with the feature.

This method seems to be applicable to prioritising products and processes in configuration projects.

4.2 Step 2: knowledge acquisition

Data clustering is a multivariate analysis technique that assigns observations (objects) of a population to clusters (groups) so that observations within the same cluster have a high degree of similarity; whereas observations from different clusters have a high degree of dissimilarity (Anzanello and Fogliatto, 2011; Kaufman and Rousseeuw, 2009; Tsai *et al.*, 2009).

Walz *et al.* (1993) observed a software design team-sharing knowledge with customers, and he recommended:

- increasing the amount of application domain knowledge;
- promoting knowledge acquisition by facilitation techniques and formally recognising these activities by allocating time to them; and
- recognising that much of the information that needs to become part of the team's memory is not captured formally, particularly in standard documentation.

According to Waltz, experienced designers recognised that customers may not understand the true nature of the requirements and the expectations from the results at the beginning of a project (Walz *et al.*, 1993).

Some knowledge acquisition tools are intended for a wide variety of contexts. For example, a card sorting tool should in theory be of value in any domain where objects, concepts or even processes can be named, shuffled about and sorted (Shadbolt *et al.*, 1999). Some knowledge acquisition tools belong to specific domains. For example, Compton and Jansen (1990) rejected the need for modelling and focused instead on the evaluation of prototypes developed on the basis of increasing numbers of test cases. The questions about knowledge are designed to reveal the expert's recommendations and hence strategies for how to deal with a variety of conditions, such as how to identify current conditions and which conditions warrant what actions (Woodward, 1990).

The process of knowledge acquisition in configuration projects includes the following activities: the knowledge engineer communicates techniques for eliciting knowledge from relevant experts, interprets this knowledge to draw conclusions about the reasoning process of the product experts and what may be the underlying knowledge and uses his conclusions to direct the construction of the product model (Byrd, 1992). However, these activities, which are common in configuration teams, can lower the quality of acquired knowledge and consume time and resources that could be devoted to validation (Shafiee *et al.*, 2017).

One method of clustering in configurators is to determine output knowledge according to stakeholder requirements and subcategorise these step by step. Table IV shows a categorisation table in which all the needed inputs and resources are determined.

Listing the sources and resources of the knowledge creates value in categorising the knowledge and helps to delegate the tasks to different resources (Tiihonen *et al.*, 1996). Organisations have two types of knowledge: explicit and tacit. Explicit knowledge is formal and systemic, whereas tacit knowledge is highly personal and difficult to formalise. Depending on the resources, the knowledge might be explicit, and come from the company's internal documentation systems, or tacit, and come from domain experts (Nonaka, 1994).

4.3 Step 3: modelling and knowledge validation

One of the steps of KM in configuration projects relates to modelling the knowledge inside the system, which normally requires validation from domain experts. Communication between IT personnel (software developers and modellers) and domain experts is an important factor for configuration projects (Stelzer and Mellis, 1998).

The knowledge modelling of configurators, known as the product (phenomenon) model structure, is one of the greatest challenges in configuration projects (Hansen *et al.*, 2012; Sabin and Weigel, 1998). Product models are also used for communicating with people outside the IT field, which is required to validate the knowledge (Duffy and Andreasen, 1995).

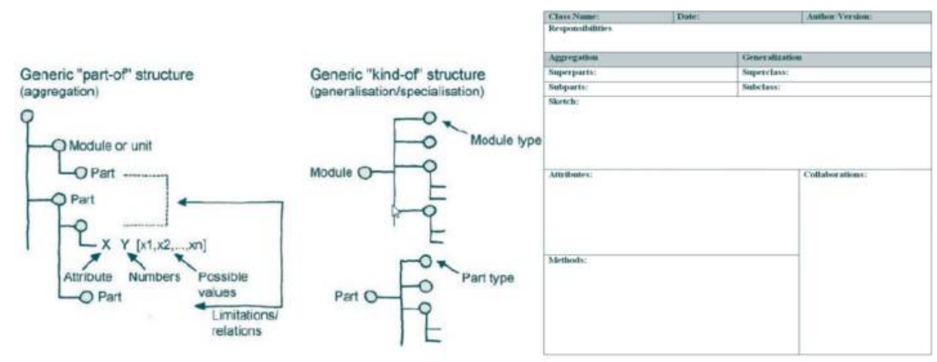
Many researchers have developed product modelling techniques to meet this challenge (Aldanondo *et al.*, 2000; Chao and Chen, 2001; Hvam, 2001; Hvam *et al.*, 2008; Jinsong *et al.*, 2005; Magro and Torasso, 2003; Tseng, *et al.*, 2005; Yang *et al.*, 2009). This paper recommends using product variant master (PVM) along with class, responsibilities and collaboration (CRC) cards, which are based on unified modelling language notation (Hvam, 2001).

4.3.1 PVM and CRC cards. The PVM presents product knowledge in a structured format from three different perspectives: the customer's view, the engineering view and the production/part view (Hvam *et al.*, 2008). The PVM comprises two structures: "part-of-structure" and "kind-of-structure", which are analogous to the structures of aggregation and specialisation within object-oriented modelling. Beck and Cunningham (1989) first proposed using the CRC cards to teach object-oriented thinking. Hvam *et al.* (2008) later presented revised versions of the CRC cards for use in configuration projects. Figure 3 shows the PVM and CRC card structure. For example, a car consists of a chassis, motor,

Table IV Example of a categorisation table

Categorised phase	*Needed input*	*Needed resources*
Configuration requirements	The product data should configure the product according to the stakeholders' requirements in the execution of the system	Stakeholders from mechanical and chemical departments, and external vendors
Calculation pre-requirements	The data need to be used for the calculations and simulations that could not be contained inside the configurator and need to be integrated with the simulations software	Stakeholders from the sales department
Document generation requirements	The data need to be used in the document generation part for the price calculation sheets, bills of materials, scope of supply, etc	Stakeholders from all related departments
Integration requirements	The data need to be used for the integration section: for calculations; and for flow diagrams	Stakeholders from the process and mechanical departments

Figure 3 Structure of PVM and CRC cards



Source: Hvam *et al.* (2008)

brake system, etc. Each module/part of the product range is marked with a circle. The individual modules/parts are also modelled with a series of attributes that describe their properties and characteristics.

4.4 Step 4: documentation and maintenance of knowledge

This step addresses how to document and maintain the knowledge to ensure that the configurator remains stable and up to date. Studies of companies using configurators have revealed that without a documentation system, companies are unable to develop and maintain their configurators (Haug *et al.*, 2009). The iterative process of testing enables feedback in the early phases of a project (Kruchten, 2007). To reach the feedbacks require a proper communication and maintenance tool. Numerous methods exist for conducting iterative project testing and validation, which eliminate unnecessary debugging processes at the end of the project (Hirsch, 2002). Modelling techniques are used as documentation tools alongside the task of communication and validation. Research supports the modelling process by adding software support and integrating these different modelling techniques (PVM and CRC) (Haug and Hvam, 2007; Shafiee *et al.*, 2017). Selic (2009) explained agile documentation by elaborating different steps for design and development. Avoidance of duplicate knowledge is critical in documenting IT systems (Selic, 2009). The automatic agile IT system, proposed by Shafiee *et al.*, involves two steps. The first concerns building the initial product model (PVM or any modelling technique), which is used for the programming of the configurators. In the second step, the product model is generated directly from the configurator and is based on the structure, attributes and constraints inside the configurators. The configuration engineer can control the models, such as showing/hiding different parts or providing users with descriptions. Therefore, the product model does not need to be maintained outside the configurators. This approach meets the demand for agile documentation and efficient communication with domain experts and uses the fewest resources possible (Shafiee *et al.*, 2017).

5. Framework validation

5.1 Method setting

Having developed the framework, we needed to assess whether and where it works. One case project was used to develop and improve the framework iteratively, and the analytical thinking and literature base used in the development of this framework should ensure that the framework works logically in different situations. However, the framework's actual practical performance can be proved only by applying it to real settings. For this reason, we decided to use our framework in case companies. However, because applying a framework requires not only a company's availability but also considerable time and resources in the organisation, we were able to apply the frameworks in only four projects at two companies. The study of a limited number of case applications allowed us to conduct a detailed assessment of how the framework works and to understand why it may present challenges in application. Case study research seeks to find logical connections among observed events, relying on knowledge of how systems, organisations and individuals work (Kaplan and Duchon, 1988; McCutcheon and Meredith, 1993). Understanding the "how" and "why" is one of the main reasons for using multiple case studies in several disciplines, such as explanatory studies in operations management and technology management (McCutcheon and Meredith, 1993; Yin, 2013).

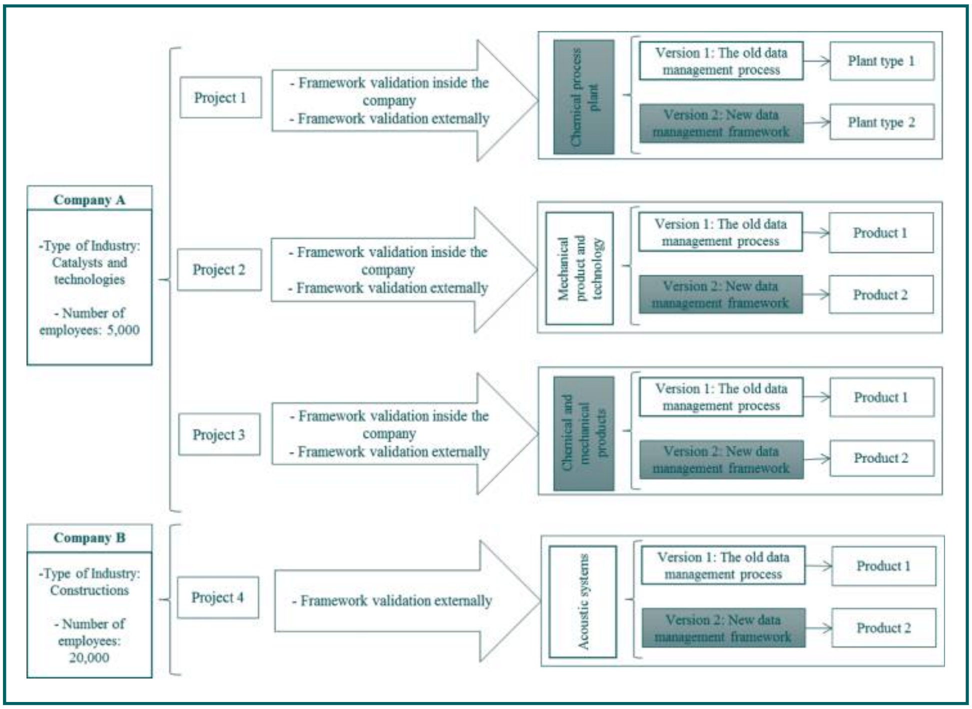
When conducting multiple case studies in this type of research, attention should be given to data triangulation as well as observer triangulation (Creswell and Clark, 2007; Johnson *et al.*, 2007; Yin, 2013). Multiple benefits can be gained from triangulation, such as complementary insights, which enhance the richness and convergence of observations, which in turn enhance confidence in the findings. For example, interviews can be conducted by two persons, with one researcher handling the interview questions and the other taking notes and recording observations (Eisenhardt, 1989). The research team observed the participants and document them during the projects by focusing on the KM process.

5.2 Selection of cases

A key concern of this study is the application of the proposed framework. Because the framework applies to different configuration projects, the unit of analysis is defined as a configuration project. Four projects at two case companies, which provide highly engineered products and were currently in the process of developing and using the configurators, were used for the case studies. Both companies were engineer-to-order (ETO) and in the development phase of a configuration project, and both understood to benefit from a better KM framework. In the selected cases, the products are physical goods with stable product architecture. A lot of configuration projects regard physical products, where the basic product architecture (or at least its core part) is stable over long periods of time, thus the configurators are also stable over years (Haug *et al.*, 2011). The survey of Haug *et al.* (2011) showed that the average life time for the configurators handling the complicated ETO products can exceed 11 years.

As Figure 4 illustrates, both companies had launched the first version of their configurators and had begun to develop the second version. Thus, we were able to compare the KM processes between the first version, where the company did not have a structured framework, and the second version, in which the company applied the proposed KM framework. The second version of a configuration project extends the project on the basis of version 1. An example of this is a plant configurator whose first version includes one plant type and whose second version introduces another plant type. The two versions are strongly related in terms of both the product or process domain and the organisation, which includes stakeholders and management principles, even though they are completely separate projects. Figure 4 shows the complexity of the projects (white boxes = less complexity and grey = more complexity), which is calculated on the basis of the configurator's parameters (number of rules and attributes) and the number of integrations required to complete the configuration task (Brown *et al.*, 2007).

Figure 4 Selection of case studies



5.3 Framework testing

A research team was formed in two industrial companies (Table V). In Company A, two researchers and two configuration engineers from the company spent 50 per cent of their time testing the framework for almost one year. In Company B, a research team comprising two researchers from the university and one employee from the company tested the framework for four months. In version 1, proper documentation was not done; however, the researchers used documents (such as Excel sheets that contained engineering calculations). For version 2, the team made documents for the undocumented knowledge (such as the knowledge elicited directly from the employees). Workshops were conducted for each project and for all the stakeholders to introduce the proposed framework and the required tools. Some of the researchers were also the practitioners at the case companies who observed the KM process for version 1 of the project. Thus, this triangulation observation leads to valuable data, related especially to the organisational challenges of implementing the new KM framework. Finally, feedback meetings were held as semi-structured interviews to collect knowledge about the team's satisfaction with the new

Table V Background information for modelling and implementing the configurators used in the four case studies

Projects	*Case 1*	*Company A* *Case 2*	*Case 3*	*Company B* *Case 4*
Time frame (months)	6	24	12	4
Complexity of the project	Medium	High	Medium/High	Medium
No. of employees involved	4	10	6	4
No. of workshops	3	6	4	3
No. of feedback meetings	4	15	4	5

framework. Each meeting lasted 30 min and included members of the configuration teams, which included project managers, developers, end users and top managers. The purpose was to obtain an assessment of the framework from all involved stakeholders. The questions aimed to elicit a general evaluation of the framework, the benefits and challenges regarding the framework's performance and the organisational and management influences on the framework's applicability.

The testing phase of this study aimed to validate the framework:

- within different projects; and
- across different companies.

To validate the framework:

- the application of the framework and different steps were clarified; and
- the organisational situation and cultural influences on the applicability of the framework were analysed.

The findings from the case studies are described in terms of the main benefits and obstacles that resulted from applying the suggested approach.

The following sections present the results of the framework tests within the different projects and across companies for each of the proposed steps. Analyses of the steps show the benefits and challenges associated with the framework testing and compare the two companies in terms of the new changes and use of the new techniques and tools. To demonstrate the individual steps, the application of the different steps is shown using examples from Case 2.

5.4 Step 1: determining the scope of the configurators

5.4.1 Establishing the project's goal.
5.4.1.1 Framework application. The recommended tools for this step include the use-case diagrams, process flow charts and MoSCoW categorisation of requirements. Use-case diagrams are used for the visualisation of requirements and goals and for communication with domain experts (Figure 5). Flow charts are also used to identify the current work processes (AS-IS) and determine the future processes (TO-BE) (Figure 6). A long list of functional and non-functional requirements for individuals is recognised and prioritised according to the MoSCoW principles (Table VI).

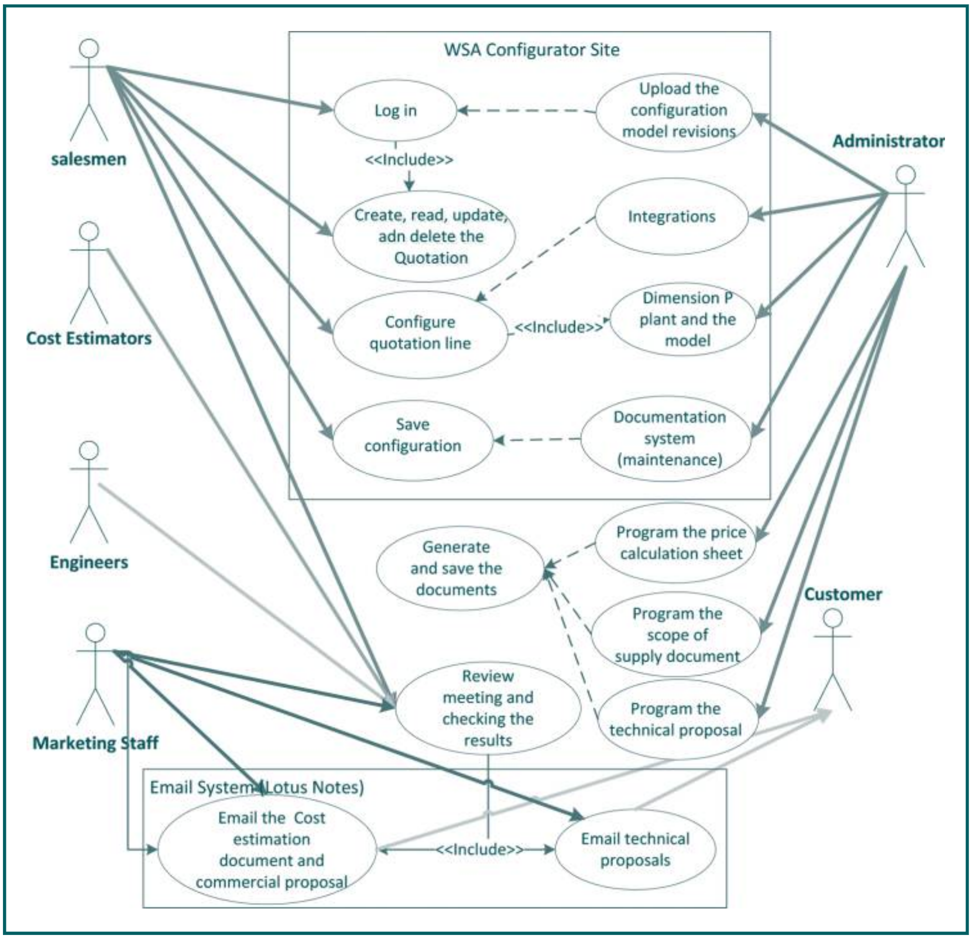
Interviews with the domain experts revealed that the goals of version 1 of the project were usually determined in unstructured meetings with the main stakeholders. However, the various requirements of stakeholders were not identified and clarified before starting the projects. Some of the requirements were ignored because of a lack of communication and tools, such as requests for outputs, user interfaces and additional IT automation. The configuration teams and domain experts at the case companies described the problems with the current situation, such as reworks in the configurator during development, late debugging, time consumed for development and excess or lack of knowledge in the development phase.

5.4.1.2 Cross-case comparison. Table VII lists the tools applied in the cases before (version 1) and after applying the framework (version 2).

Awareness of project goals and the importance of stakeholder requirements before starting the project proved to be helpful for the project team. The benefits of using the methods in version 2, as opposed to those of version 1, for the stakeholder analysis are listed below:

- improved understanding of the stakeholders' requirements for the system; visualising their needs established a common understanding;

Figure 5 Example of use-case diagram for Case 2

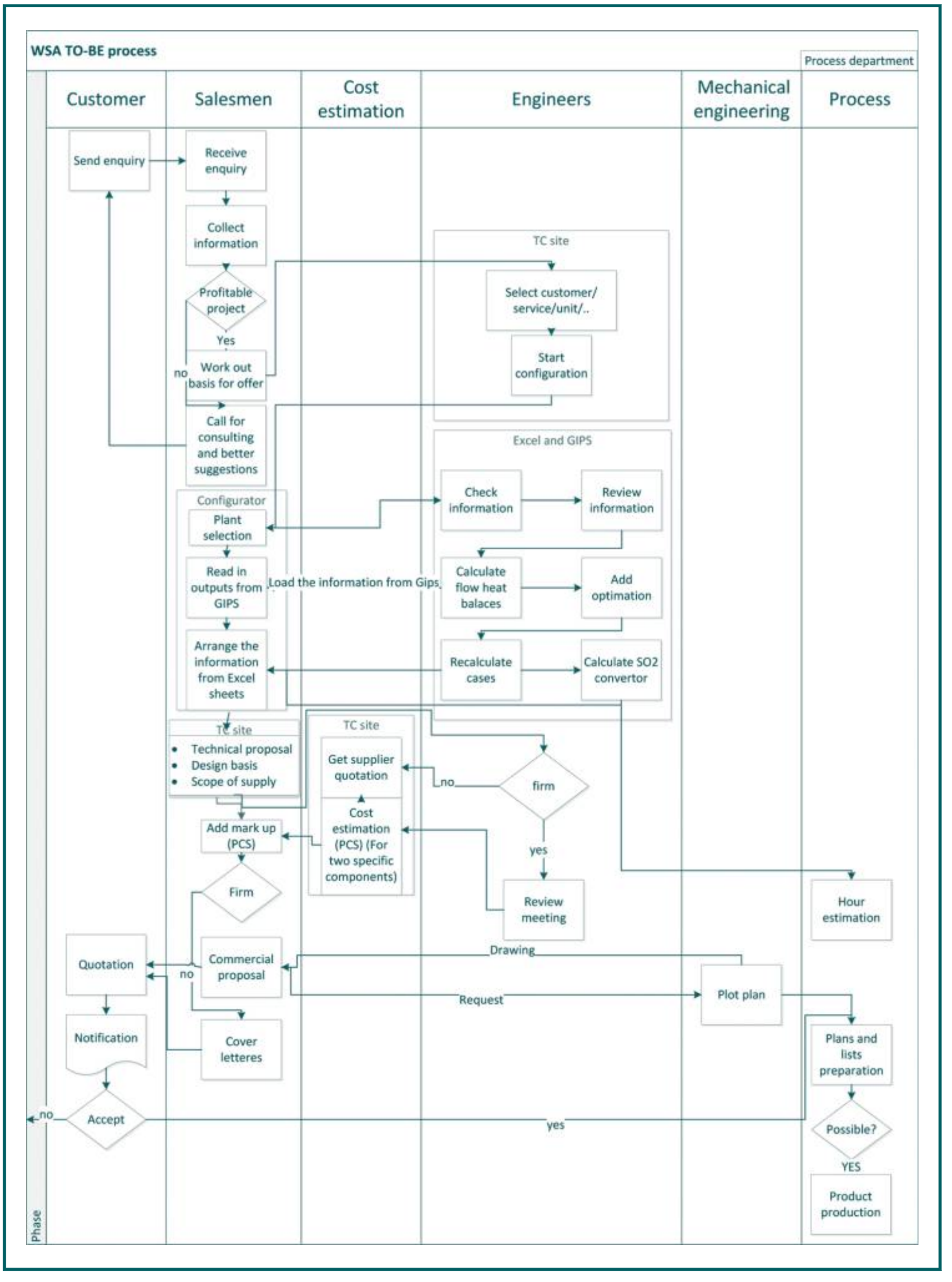


- reduced time needed for the meeting with experts as a result of clear goal setting in the first step; and
- improved communication and task delegation between the resources, which reduced the consumption of time and resources.

Obstacles involved in applying this step included unfamiliarity with the tools, amount of time needed to change the current way of working and the needed time and resources for workshop preparations. In Company A, it was difficult for the team to use and see the purpose of the use-case diagrams at first, because it is difficult to change their habits and enable them to see the value of using the illustration tools. However, the workshops proved to be helpful, because they provided step-by-step training for the configuration team and domain experts. Company B had already been using flow charts in version 1 and applying the MoSCoW principles in version 2. However, Company B refused to incorporate the use-case diagrams because the managers considered it time-consuming and preferred to use flow charts when communicating with stakeholders. The configuration team recognised the benefits as a result of discussions with different stakeholders about how to prioritise the requirements.

5.4.2 Prioritising products and processes to be included in the system.
5.4.2.1 Framework application. Weighting tables are recommended for prioritising the products and functionalities to be included in a configurator (Wiegers, 1999). In Table VIII,

Figure 6 Example of TO-BE process flow chart for Case 2



the calculations of weighting table are assessed using the explanations from Wiegers' study (1999).

On the basis of interviews with configuration teams and domain experts from the case companies, prioritising products and functionalities becomes more critical as the complexity of the project increases. However, the significance of this step varies greatly across the cases. In Company A's version 1 projects, the products and functionalities were prioritised according to interviews with the domain experts; however, the participation of only a few domain experts meant they could ignore the important parts of the process

Table VI Examples of stakeholder requirement prioritisation for Case 2

List of requests	*Must have*	*Should have*	*Could have*	*Want to have*
Combining document snippets into full technical or commercial proposals (salespeople and cost estimators)		✓		
Loading data from the configurator into tables in the technical and commercial (sales, cost estimators and marketing group)			✓	
Price calculation, bills of material and scope of supply (all stakeholders)	✓			
Having colours for different components in user interface				✓

Table VII Cross-case comparison of the configuration project goals

		Company A		*Company B*
Projects	*Case 1*	*Case 2*	*Case 3*	*Case 4*
Version 1 (work procedure before applying the framework)	Informal stakeholder identification using the project organisation Chart, but no requirement prioritisation	No formal stakeholder identification and requirement prioritisation	The department manager identified the main stakeholders beforehand but no prioritisation	Flow charts to map the current processes and design the future processes, but no requirement prioritisation
Version 2 (methods used in the testing period of the framework)	Use-case diagrams, flow charts and MoSCoW principles			Flow charts and MoSCoW principles

Table VIII Example of a priority table (Case 2)

Feature	*Relative benefit*	*Relative penalty*	*Total value*	*Value %*	*Relative cost*	*Cost %*	*Relative risk*	*Risk %*	*Priority*
Product 1	5	5	15	21.1	2	12.5	5	31.3	0.116
Product 2	9	9	27	38.0	5	31.3	2	12.5	0.209
Product 3	5	2	12	17.0	3	18.7	3	18.7	0.151
Product 4	4	1	9	12.6	4	25	5	31.3	0.049
Product 5	2	4	8	11.3	2	12.5	1	6.25	0.361
Totals	25	21	71	100	16	100	16	100	–

because it did not directly touch on their daily work. In version 1, Company B broke down the overall design processes for complex construction into smaller subprojects, which are mostly prioritised on the basis of coincidences. However, the configuration engineers in both case companies pointed out problems that arose because important features and functionalities were not recognised in the early phases of the project in version 1, and the configuration model had to be restructured.

5.4.2.2 Cross-case comparison. Table IX lists the tools used for product and process prioritisation in different cases before (version 1) and after development of the framework (version 2).

The initial resistance to adding a new tool to current work routines stemmed from the requirements for managers' time and energy. Using weighting tables and formulas to calculate the priorities of the components and functionalities required some training, and debates arose with regard to setting the values and deciding which parts and functions should be included. However, when the weighting tables were applied, a difference was noticed in the domain experts' prioritisations of products. In Case 2, this was especially important because of the complexity of the overall project.

Table IX Cross-case comparison of the methods used for prioritising of products and functionalities to be included in the configurator

	Company A			Company B
Projects	*Case 1*	*Case 2*	*Case 3*	*Case 4*
Version 1 (work procedure before applying the framework)	Interviews with 1-2 domain experts	Interviews with the resources listed in the organisational chart	Interviews with department manager and one domain expert	Prioritisation based on coincidences on high level of abstraction
Version 2 (methods used in the testing period of the framework)	Weighting tables (different modules and functionalities)			Weighting tables (overall configurator concept)

5.5 Step 2: knowledge acquisition

5.5.1 Framework application. This stage of the project was concerned with categorising the required knowledge and identifying knowledge sources and resources. Because neither of the companies had a structured way to identify knowledge sources and resources, they were typically identified during project development, as needed; the result was many meetings and much wasted time. However, the new framework required the companies to apply categorisation tables in version 2 based on the needed configurator outputs. The categorisation table significantly increased the speed of knowledge collection because the source of the knowledge and the person responsible for delivering the knowledge to the configuration team was identified. In addition, the management of the knowledge was improved in both companies such that various actors involved in the project could access the shared knowledge.

5.5.2 Cross-case comparison. Table X lists the work procedures applied in all cases before (version 1) and after the implementation of the new framework (version 2).

The categorisation tables were easily generated from the stakeholder requirements, based on the expected configurator outputs. The tables were used for categorising the required knowledge and sources and defining the resources.

Table X Cross-case comparison of knowledge categorising and knowledge sources

	Company A			Company B
Projects	*Case 1*	*Case 2*	*Case 3*	*Case 4*
Version 1 (work procedure before applying the framework)	Difficulties identifying knowledge sources and resources. Experienced employees asked to provide required knowledge. Lack of knowledge led to delays	Configuration team was responsible for identifying experts who could provide knowledge. Lack of responsibility and access was reported	Access to knowledge was challenging because resources were not identified beforehand	Categorisation for some of the required knowledge was unstructured. Lack of KM
Version 2 (methods used in the testing period of the framework)	Categorisation tables. Knowledge sources, such as ERP system, regular meetings and shared folders	Categorisation tables. KM systems, such as ERP. Drawings and explanatory documents for this product were stored in the documentation system	Categorisation tables. Knowledge sources such as ERP system, regular meetings and shared folders	Categorisation tables. Knowledge managed in shared folders

In version 1, a misunderstanding that could be traced to insufficient categorisation led to unnecessary meetings. Conversely, in version 2, all the required knowledge was determined before starting the project, and resources were aware of their tasks.

5.6 Step 3: modelling and knowledge validation

5.6.1 Framework application. In this step, the knowledge was modelled and validated by domain experts to improve the system's quality and accuracy. The suggested modelling method was PVM along with the CRC cards (Figure 3). Figure 7 presents an example of the PVM structure. In this step, the following achievements were fundamental for the project success:

- *Logical consistency*. The attributes, variables and constraints should be consistent when entered into the configurator.
- *Validation of the model with domain experts*. An efficient communication method was established between the configuration group and domain experts so the domain experts could validate the critical knowledge modelled in the configurator.

Because the tree structure, hierarchy, rules and attributes of the configurator model, which are written in an IT language, are not easily understandable for people outside the IT field, other methods were required for communicating with domain experts. The PVM–CRC method was used for documentation and maintenance and for communication with domain experts. However, in Case 4, manually updating and maintaining all the product models proved to be a significant task.

5.6.2 Cross-case comparison. Table XI shows the methods used for this step before (version 1) and after applying the framework (version 2).

A comparison of the two versions reveals a significant difference in system quality that resulted from the validation by domain experts because of the visual representation. In version 1, quality was reported as an issue, errors resulted in infeasible configurations and the configuration team faced difficulties finding the source of the errors. This highlights the importance of incorporating knowledge validation into different steps of configuration projects. In Company A, an agile system was developed to structure the knowledge included in the configurator and generate a PVM structure, which allowed domain experts to validate the knowledge. Two main benefits were gained from this phase:

1. This validation phase saved time and resources for future testing to find possible minor and major errors.
2. The quality and reliability of and confidence in the system improved as stakeholders took control of knowledge validation.

5.7 Step 4: documentation and maintenance of the knowledge

5.7.1 Framework application. This step involved the documentation and maintenance of the knowledge to ensure that the configurator was up to date and could be maintained. Both companies neglected documentation because of heavy workloads. In Company B, documents representing the knowledge contained in the system were spread across the firm. Company A implemented PVM in all cases and used the CRC cards in Case 2. CRC cards were used only in Case 2 because of the complexity of the project. Even though Company A used a formal modelling technique, it is difficult to know whether the PVM and CRC cards were up to date and aligned with the knowledge inside the configurator and with product changes, because updates were neglected. As noted, Company A developed an agile documentation system in version 2 to represent the

Figure 7 Example of initial PVM structure (Case 2)

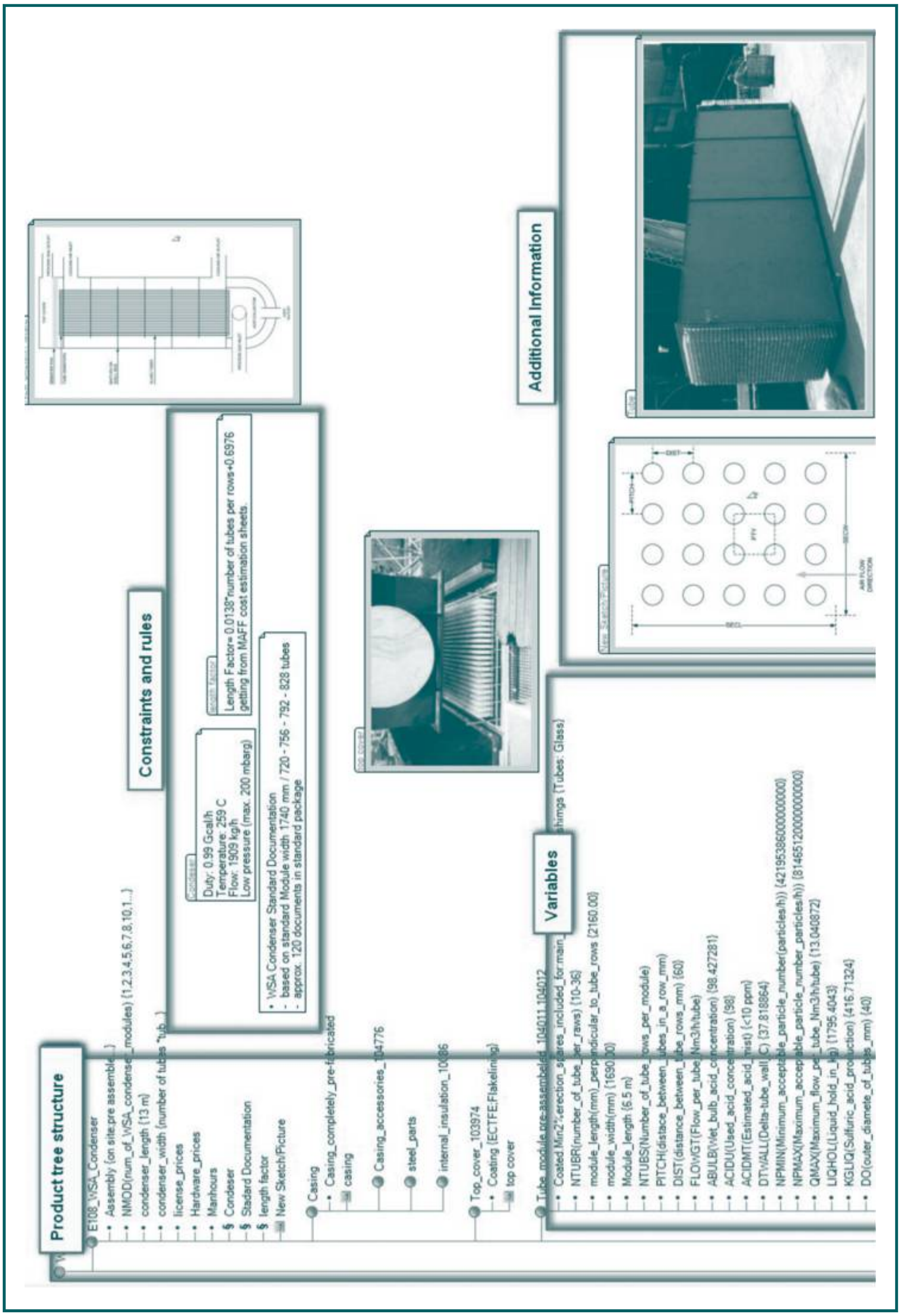


Table XI Cross-case comparison of modelling and knowledge validation

Projects	Company A Case 1	Case 2	Case 3	Company B Case 4
Version 1 (work procedure before applying the framework)	PVMs the only modelling tool; challenges regarding knowledge validation because the PVM did not include all the knowledge	PVM–CRC method used but not updated; therefore, validation was performed by testing the system and using Excel spreadsheets	PVMs the only modelling tool; challenges regarding knowledge validation because the PVM did not include all the knowledge	No standard modelling technique; knowledge stored in various Excel spreadsheets; validation was performed by testing and using the system
Version 2 (methods used in the testing period of the framework)	PVM and CRC cards, additional tables and an agile and efficient documentation system	Agile documentation system automatically generated PVM and CRC and allowed domain experts to validate the knowledge		PVM for system validation and communication with stakeholders

knowledge inside the configurator in the form of a PVM and class diagrams, as shown in Figure 8 (Shafiee *et al.*, 2017). Conversely, Company B delegated the responsibility for performing updates to the different classes of the PVM.

5.7.2 Cross-case comparison. Table XII lists the work procedures applied to the cases before (version 1) and after using the new framework (version 2).

A comparison of the cases using automatic documentation with those using completely manual processes highlights the importance of using an automatic documentation system. Company B began to benefit even from manual documentation, because in version 1, their configurator was out of use because they were not updating and maintaining knowledge inside the configurator.

5.8 Summary of the cross-case analysis

The cross-case comparisons show that the framework affects the companies differently. Company A took the risk of experimenting with new tools and techniques, and the employees reported that many benefits and challenges resulted from using those. Company B's management board achieved efficiency by keeping up with routine work while making minor changes. In comparison, Company A's management board aimed to improve the current work flow by accepting the changes and modifications recommended by researchers.

The differences in the way the framework has effected Companies A and B may derive from the different cultures of Companies A and B. Studies have found that results- and job-oriented company cultures have positive effects on employee decisions during the KM process, whereas a tightly controlled culture has negative effects (Chang and Lin, 2015). Although every organisation has its own identity and language, the aim is to find a common basis and help companies define their own KM framework with minor changes (European Committee for Standardization, 2004). KM is a difficult task because knowledge sharing and transfer, and the consequent realisation of the full value of the organisation's knowledge resources, require changes in the organisational culture (Firestone and McElroy, 2003). The perception of the involved people about the KM process in the configuration projects changed as the project-related information was precisely communicated, they were trained and they experimented the benefits of the new approach. Thus, the application of the framework could have initiated a small change in the organisational culture. The companies considered this framework as the efficient KM process for the future projects and decided to continue to use it. However, we do not know whether organisational culture has changed enough to continue to keep the new approach.

Figure 8 Automatic generation of PVM and CRC structure in the developed documentation system

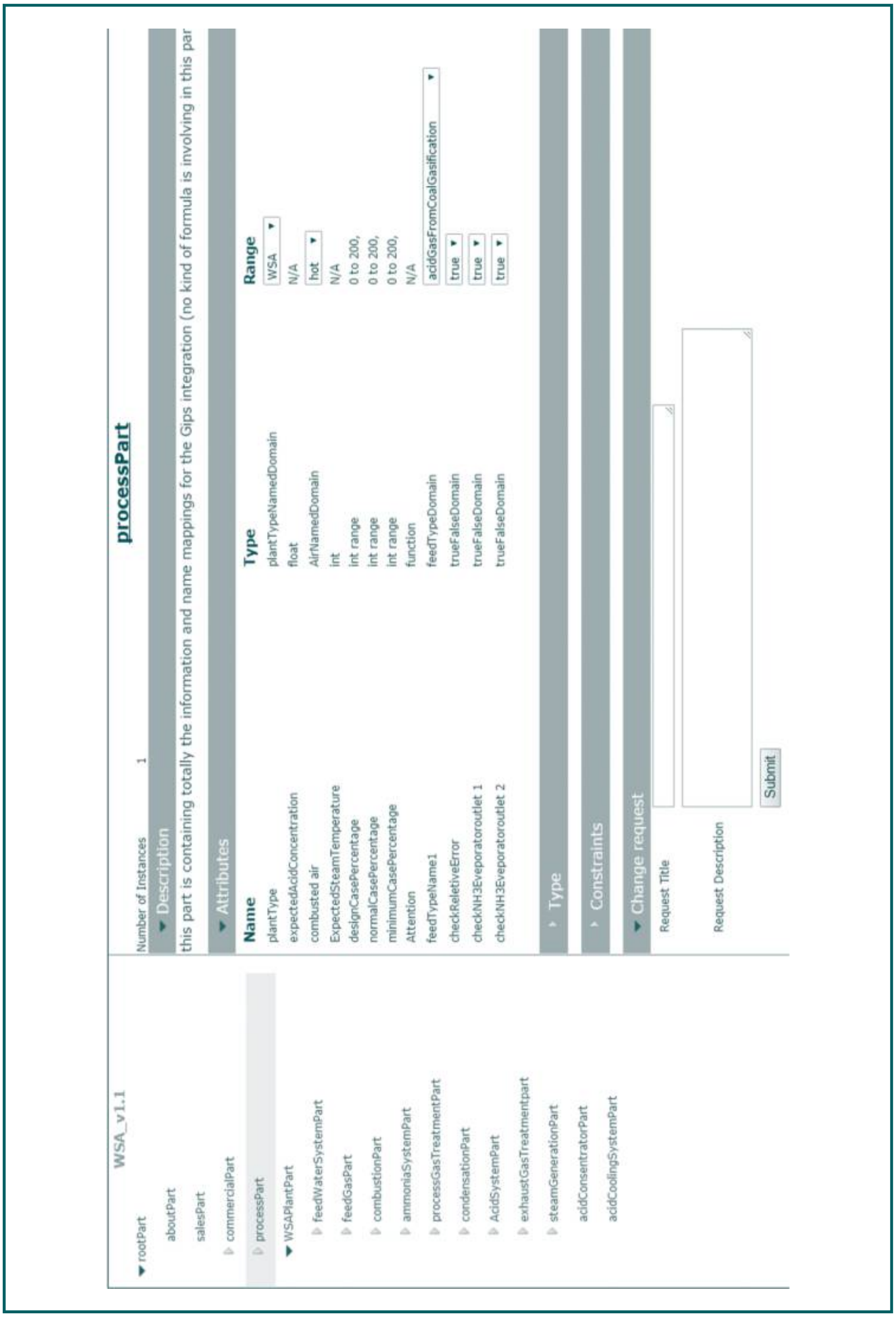


Table XII Cross-case comparison of knowledge documentation and maintenance

Projects	*Company A* *Case 1*	*Case 2*	*Case 3*	*Company B* *Case 4*
Version 1 (work procedure before applying the framework)	PVM, spreadsheet documents gathered from stakeholders	PVM, spreadsheet documents, documentation in internal team sites	PVM, spreadsheet documents, documentation in team sites	Spreadsheet documents
Version 2 (methods used in the testing period of the framework)	An agile documentation system, updated automatically based on the configuration model			PVMs and CRC cards, a manual but structured system for updates

6. Discussion

In the first part of the discussion section, we discuss the framework development, which was based on the literature and experiences in one case company. In the second part, we discuss the framework validation, which took place in the two case companies.

6.1 Integration of the proposed framework with the existing literature

By analysing the extant literature, our study has shown that implementing the KM process in configuration projects is challenging because of the amount and complexity of the knowledge involved (Jinsong *et al.*, 2005). The available frameworks for KM in IT projects do not meet the KM challenges for configuration projects because the knowledge in configuration projects is even more complex and vast and often lies outside the configuration team's expertise (Basili and Weiss, 1984). There is also a strong need for communication between domain experts and the configuration team to validate the knowledge in configuration projects (Shafiee *et al.*, 2017). In addition, the KM tools and techniques needed for managing the knowledge in configuration projects are specific to configurators (Hvam *et al.*, 2008). Without a clear KM framework, configurators become complicated and unstructured (Forza and Salvador, 2007).

There is a paucity of research on developing a comprehensive KM framework for configuration projects even while many of the recognised critical challenges in configuration projects are related to KM (Jinsong *et al.*, 2005; Lech, 2014; Sabin and Weigel, 1998). Moreover, we maintain that modern configurators are IT-based and that some IT-oriented KM frameworks can inspire KM frameworks tailored to configuration projects (Basili and Weiss, 1984; Reich *et al.*, 2012; Rodriguez and Al-Ashaab, 2005). The research on configurators has investigated the KM steps during different phases of configurator development and the specific tools and methods (Forza and Salvador, 2002b; Haug, 2010; Hvam *et al.*, 2008). The present study therefore took the opportunity to exploit these potentially useful integrations of different, though closely related, research streams.

The framework proposed here integrates the literature on configurators with the literature on general KM frameworks and the literature on KM frameworks for IT projects. The suggested framework not only contains the same main phases as suggested in literature on general and IT projects KM frameworks but also adds specific tools and methods needed for KM in configuration projects, such as the critical need for modelling of the products knowledge. In building this bridge, the research on configurators takes advantage of what scholars have discovered about KM in general and the IT-oriented KM in particular. On the other hand, the literature on KM has a new case to address, namely, KM in projects aimed at implementing configurators. This case is particularly intriguing because it suffers from serious problems of knowledge validation resulting from issues related to communication and the complexity, specificity and vastness of the knowledge involved.

The proposed framework includes four KM steps for configurator projects based on KM frameworks presented in the extant literature on IT projects (Lech, 2014) and on KM steps outlined in the literature on configuration projects (Forza and Salvador, 2007). The first step involves determining the scope of the project while suggesting tools for analysing stakeholders and prioritising different products and processes (Basili and Weiss, 1984; Shafiee *et al.*, 2014). The knowledge acquisition step discusses how to manage all the sources and resources to categorise inputs and outputs (Nonaka, 2008; Tiihonen *et al.*, 1996). The third step analyses different product modelling techniques for better communication across the supply chain and for knowledge validation (Aldanondo *et al.*, 2000; Chao and Chen, 2001; Hvam, 2001; Hvam *et al.*, 2008; Jinsong *et al.*, 2005; Magro and Torasso, 2003; Tseng *et al.*, 2005; Yang *et al.*, 2009). The last step considers documentation and maintenance, which help configurators remain stable and up to date (Haug and Hvam, 2007; Shafiee *et al.*, 2017). Departing from the existing literature on configurators, the proposed framework integrates the proposed steps into a specific sequence to fulfil the need for a standard process in managing knowledge. It also makes knowledge validation possible by establishing communication between domain experts and the configuration team.

6.2 Applicability of the framework

The suggested framework was tested on four configuration projects in two industrial ETO companies. The configuration projects were engineering projects in which vast, complicated knowledge had to be managed. The proposed framework helped the companies address the main challenges of KM in configuration projects. The scope of the projects was kept limited (whereas before they were continuously expanded); this limitation supported collaboration with domain experts, thus reducing the difficulties associated with accessing their knowledge. Continuous validation of the knowledge was enabled by modelling the knowledge. Consequently, the companies witnessed a reduction of the time and resources needed for scoping, developing, implementing and documenting their configuration projects. The proposed KM framework aligned all members of the configuration project team, from the IT team to domain experts, thus leading to a better configurator. In the end, the framework standardised the knowledge acquisition process, using simple tools to align the entire configuration team.

The configuration teams involved in the development and testing of the framework expressed a willingness to use the framework in future projects to save both time and resources. Domain experts at the company also appreciated their involvement in knowledge verification. These results indicate both the effectiveness of the framework and its positive involvement effects on the people engaged in the configuration project.

The main obstacle for the configuration team's use of the framework was their lack of familiarity with the suggested tools. An introduction of the tools in workshops significantly reduced their resistance to the framework. Using the framework and suggested tools did not introduce additional burdens or costs, and the training for configuration engineers and domain experts was carried out in a short time (two weeks maximum).

7. Conclusion

The challenges of KM and the ability of the organisations to handle knowledge have been thoroughly considered in both research and practice. The present study proposes a KM framework for projects aimed at the implementation of configurators. The framework includes four steps:

1. determining the scope of the project;
2. acquiring knowledge;
3. modelling and validating knowledge; and
4. documenting and maintaining the system.

The execution of each step is supported with relevant tools. The proposed framework was tested on multiple projects and companies. These tests demonstrate both its applicability in different industrial settings and its potential to enhance the quality and speed of the implementation of configurators.

This paper contributes to the existing literature by proposing a KM framework for configuration projects, developed on the basis of the literature on general KM frameworks (European Committee for Standardization, 2004; Liebowitz and Megbolugbe, 2003), KM frameworks in IT projects (Lech, 2014; McGinnis and Huang, 2007) and available KM tools and steps for configuration projects (Forza and Salvador, 2007; Tiihonen *et al.*, 2014; Yang *et al.*, 2009). The steps and tools are drawn from the general KM frameworks and the frameworks for IT projects as well as the proposed solutions for configuration projects. The results fill the research gap by connecting and sequencing these available tools and methods in the proposed framework and validating the framework in multiple case studies.

The proposed framework is a powerful tool for reducing the scope and complexity of configuration projects, making the KM in such projects more manageable. In this way, managers can more easily collaborate with the people involved, reducing the time and resources required. Configuration projects can be less risky and the small deliverables have a shorter payback time.

To validate the framework, versions 1 and 2 of the same project were compared to eliminate the threat of uncontrolled influencing factors. The companies used the proposed framework in version 2 of the project and compared the results with version 1, when no KM framework was available. However, some threats remained while the configurator experts gained knowledge about the product in version 1 and while the product experts became familiar with the configurator. Because the framework compared two versions of the same project, the team was familiar with the stakeholders and with the product and process in general, and the team was aware of all the available sources and resources. Although such familiarity could be considered a risk in testing the framework by clarifying parts of the KM process, it was still beneficial for the researchers to compare the same situations and observe the benefits. Further assessment of the framework with a low level of initial knowledge by the configurator team and domain experts could therefore strengthen our confidence in the framework's capabilities that limit the threat of uncontrolled influencing factors.

The use of cases allowed us to assess – in depth, in detail and in real-world contexts – the proposed framework's effectiveness. However, we were able to apply the framework only in a limited number of projects and companies, and this limits the generalisability of our results. Furthermore, we have studied configuration projects in companies making physical products with stable product architecture. The study does not include KM on configurators for non-physical products or services. The study also does not consider KM on configurators for the new physical products, where the product architecture is not stable. Moreover, one of the limitations in testing the framework is to compare two versions of the same project, which was decided to control all the dependent factors in terms of both the product or process domain and the organisation, even though they are completely separate projects. Another limitation of the test is that the observation did not continue for long time to check the continued utilisation of the framework in the future. Even though the companies announced that they will continue to use the framework, only a longitudinal observation could inform us about the role of organisational culture in absorbing the proposed KM framework in configuration projects. The further testing is needed to verify the successful changes in the organisational culture. Therefore, the successful implementation of the framework during the present research does not mean full adaptation and change at the companies. The ability of the framework to cope with highly engineered, complex products in ETO companies indicates that it could also be used in configuration projects of less complexity. However, the necessity of applying such a structured framework in smaller projects is questionable and needs further testing. Future research should test the framework in various industrial settings and identify more efficient and simpler tools and techniques for use in each step of the framework.

Notes

1. The experts who provide domain knowledge of the process of performing the task and the data content, as well as quality assurance and verification support (Barker *et al.*, 1989).
2. The team working on configuration projects include knowledge engineers, modellers, developers and project managers (Hvam *et al.*, 2008).
3. By building a configurator, engineers design the engineering model and the rules to construct the product and define the methods of work (a so-called product model). Hence, the knowledge can be expressed explicitly and incorporated into a configurator, which can subsequently be used by the company's sales staff to configure a product in collaboration with the customer (Hvam *et al.*, 2008).
4. Knowledge engineers interpret and organise knowledge from domain experts. The expert system technologist performs the knowledge acquisition, knowledge representation and knowledge base development and testing tasks (Barker *et al.*, 1989).

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APPENDIX I

Proceedings of 18th International Configuration Workshop, September 2016, Toulouse

Improved Performance and Quality of Configurators by Receiving Real-Time Information from Suppliers

Katrin Kristjansdottir, Sara Shafiee, Martin Bonev, Lars Hvam[1], Morten H. Bennick and Christian S. Andersen

Abstract. Companies providing customized products are increasingly applying configurators in order to support the sales and design activities. Yet, especially for engineer-to-order (ETO) companies, such activities are often divided across different organizations, where throughout the configuration process product specifications have to be retrieved across the supply chains. Therefore, it is required that relevant information from suppliers is included in the configuration process, either as sub-models or by integrating configurators across the supply chains. This study investigates the challenges associated with including suppliers' product specifications as sub-models and how these can be addressed by integrating configurators across supply chains to receive real-time information from suppliers. Based on the established literature on the illustrated technical integration of configurators across the supply chains, this paper contributes with empirical evidence on the overall impact of its implementation. The results presented are based on a case study in an ETO company where it is supported that the complexity of the configuration models can be significantly reduced as well as the time devoted for the modelling and maintaining the systems. Furthermore, with the ability to receive accurate and up-to-date information from suppliers, the quality of the specifications can be improved, which leads to reduced cost of the overall design.

1 INTRODUCTION

The ability to provide customized products has become more important across a wide range of industries [1]. To effectively guide communication with the customers and increase the quality of the product specifications, configurators are being applied to a greater extent when defining product variants within the chosen scope of variety [2]. Such systems utilize formally expressed product architectures, i.e. knowledge bases, consisting of a set of components, their relationships, and constraints to prevent infeasible designs [3].

In engineer-to-order companies (ETO) the supply chains can be characterized by being tailored and complex [4], where manufacturing tends to be vertically integrated, including both internal manufacturing processes and outsourced supply [5]. Furthermore, the dynamic and segregated character of the early sales and engineering processes limits the availability of design information and increases the uncertainty of project's profitability [6]. As a result of this, there is a high dependency of receiving information across the supply chains in the early sales design phases.

To address the complexity and the vertically integrated supply chains in ETO companies, the configurator's knowledge base needs to cover up to date product information related to the companies' own designs and of outsourced components/modules from suppliers. By including the suppliers' information as sub-models in the configurators, there are some limitations, as the information is often confidential and sensitive for sharing outside the companies. Therefore, critical design detail and cost structures, which are often considered as confidential information, are not shared from the suppliers' side. This can result in an insufficient level of detailed information being provided that can affect the overall quality of the configuration. Furthermore, rapidly changing components and modules supplied internally or externally drastically increase the effort for maintaining the configurator's knowledge base. This increases the risk of operating with outdated prices and variant designs and thereby decreasing the overall quality of the systems and the generated output. This underlines that centralized knowledge base is not desired, which emphasise the need of having distributed configurators across the supply chains [7].

The recent advancement of cyber-physical systems has enabled a closer integration of supply chains relationships [8], allowing for efficient ways of information management across multiple organizations. However, to make such an e-business environment possible, the established knowledge base needs to account for the high degree of tailoring and dependency from suppliers [9]. Academia has proposed a technical approach that enables real-time information sharing across the supply chain by integrating configurators [7]. However, it's successful implementation, and the actual impact from receiving the information directly from suppliers in the configuration processes has not been addressed in previous literature.

This paper aims to capture that research opportunity by analysing the overall impact of establishing the supplier integration to retrieve more accurate and up-to-date information across the supply chains in ETO companies. This includes a description of the gained benefits; the challenges companies are faced with the process and directions for further improvements. Aligned with the focus of the research, the following propositions have been developed.

> **Propositions 1:** By integrating configurators across supply chains, the complexity in terms of business rules, tables, parts and values of the configurator model, and consequently the modelling and development effort can be reduced.

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Propositions 2: By integrating configurators across the supply chains, the quality of the product specifications in terms of increased accuracy, more detailed and up-to-date, can be improved.

Propositions 3: The more detailed specifications from the supplier make it possible to improve the overall designs, which lead to cost optimization both for the component in focus and for other related components.

Aiming to investigate the impact of integrating configurators across the supply chains, a case study is introduced in an ETO company, which has established this integration with one of their suppliers. The company operates globally and provides their customers with highly engineered and complex products and is thought to be a good representative of other ETO companies. The results of the case study are based on the in-depth interviews with the configuration engineers and managers at the case company as well as the related supplier.

The paper is organized as follows. First, relevant literature is reviewed to identify the key constructs of the research model. In the next section, the results in connection with the propositions and the managerial implications are presented. Finally, the main findings are discussed and concluded, and directions for further studies are elaborated.

2 LITERATURE REVIEW

In this section, the related literature is explored. The theoretical foundation for this article consists of configurators' main benefits and challenges and integrative information technologies in supply chains.

2.1 Configurators benefits and challenges

Configurators are used to support design activities throughout the customization process, where a set of components along with their connections are pre-defined and where constraints are used to prevent infeasible configurations [3]. The main technical component of the configurator is the knowledge base, which includes a database where the different components and their instances are stored along with the configuration logic representing constrains how different components can be combined [10].

Configurators have been considered as one of the key success factors in order to achieve the benefits from the mass customization approach [11], [12]. The main benefits of using configurators can be listed in terms of reduced lead-time, improved quality of product specifications, preservation of knowledge, use of fewer resources, optimization of product designs, less routine work, improved certainty of delivery, reduced time for training new employees and increased customer satisfaction [13]–[15].

Even though configurators have proven to be beneficial and provide various benefits, there are some challenges concerned with utilizing such a system. The main challenges can be described in terms of supporting the customer in the customization process where the configuration process should be simple and short [10]. As a result of insufficient tools and methods, it can be difficult to guarantee consistency, completeness and formal documentation of the models and the long-term management of interfaces and data can as well be a challenge [16]. Structuring and modelling product information [17], product characteristics, customer relations and long time span of the projects, and product complexity are also considered as one of the main challenges especially in ETO companies [18]. Lack of documentation which can lead to confusion about the variation possibilities [16], [19] and finally acceptance of the systems and change management as employees might see the implementation of the configurators as a threat to their job security [20] has also been named in relations to the challenges related to configurators.

2.2 Integrated information technologies across supply chains

Supply chain management involves the activities concerned with flow information and the transformation of raw materials to the end users [21]. In order to develop an integrated supply chain, a detailed top-down approach is important. However, successful achievement of the integrated supply chain is more likely to happen through bottom-up approach through a number of stages as shown in Figure 1 [22].

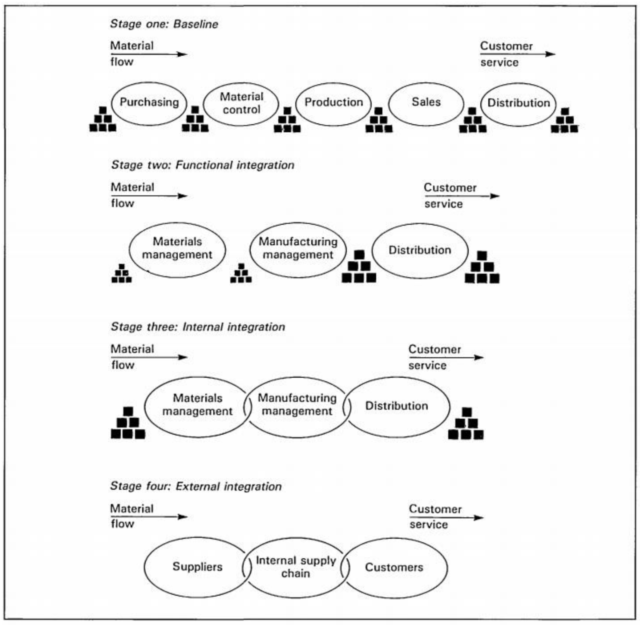

Figure 1. Achieve integrated supply chain [22]

There are a number of research that has explored the hypothesis "the higher the degree of integration across the supply chain, the better a firm performs" [22]–[27]. Ragatz et al. [28] identify the linked information systems applicability as a key success factor for integrating suppliers into the new product, process or service development process. Tallon et al. [29] point out that any positive impact of IT comes from its ability to coordinate value-adding activities. A linkage between integrative IT and supply chain is a key aspect of supply chain integration. Stroeken [30] examines the link between IT and supply chain innovation in six industry sectors in order to show the importance of IT to develop the process-oriented structure of the supply chain needed for the integration [30].

Mukhopadhyay and Kekre [31] quantify both strategical and operational impacts for Electronic Integration which leads to efficient procurement processes. The strategic benefits concerning the supplier and the operational benefits are in respect to both parties, or the suppliers and the customers. It should though be noted that the operational benefits are generated by Electronic Data Interchange (EDI) through re-engineering of the internal processes of an organization, unlike strategic benefits, which result from changes in the buyer-supplier trading relationship [31]. A supply chain strategy recognizes that integrated business processes create value for the companies' customers if these processes reach beyond the boundaries of the firm by drawing suppliers and customers into the value creation process [22], [32]. Vickery at al. [33] explain this linkage as the relationship between where one value activity is performed, and the cost or performance of another is then introduced as the core purpose of supply chain integration as optimizing linkages amongst value activities.

IT development can lead to process innovation, or more broadly, supply chain integration, followed by cheaper, more diverse and customer-specific products. By considering organizations and markets, information processes makes the economic role of computers clearer [34]. To be successful, firms need to be able to adapt to computers as part of a system or cluster for reinforcing organizational changes [35]. Additionally, the extent clients achieve real time, or direct access to information maintained by service providers constitutes a goal of customization efforts efficiently and economically attainable through newly developed Internet-based technologies [36]. Suppliers utilize information specific to client requirements for global optimization of plans and adaptive execution of processes and these clients integrating logistics applications, enable suppliers to plan capacities for peak periods and exhibit requisite scalability of operations [9].

Configurators have been proven to be useful in distributed supply chains, where information from sub-suppliers is retrieved in the configuration processes. Ardissono et al. [7] express the development of configuration services which offers personalized user interactions and distributed configuration and services in the supply chain. In Figure 2, the architecture for configurators setup integrated to the suppliers is demonstrated. The approach suggested is thought to support further cooperation, where the exchange of orders, publishing of product catalogues and the billing processes is supported in the supply chain [7].

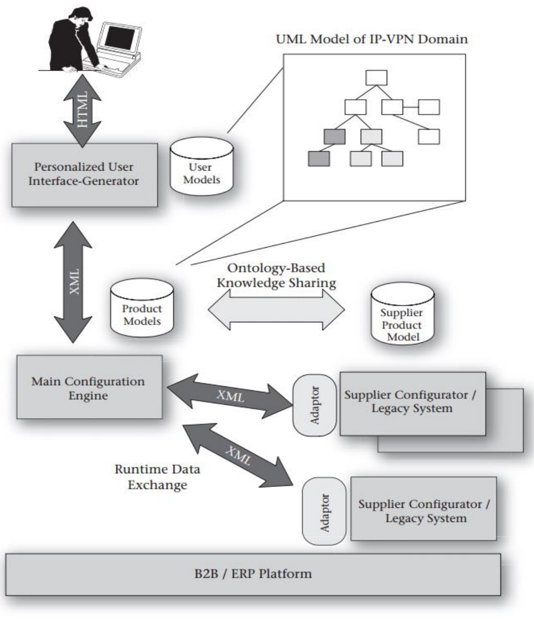

Figure 2. Architecture overview [7]

2.3 Summary of the literature

Based on the current literature in the field, the research highlights the importance of achieving greater integrations across the supply chains where IT plays a key role. Furthermore, for companies providing customized products, there is a need for having up-to-date information across the supply chains. Therefore, by integrating configurators across the supply chains, it allows companies to integrate the flow of information further and at the same time solve some of the main challenges concerned with mass customization and configurators. However, the impact from increased integration across the supply chains by enabling interactions of configurators across the supply chains has not been addressed previously in the literature.

3 CASE STUDY

3.1 Background information

The case company introduced in the study has a world-leading position in providing cement plants and equipment for the minerals and cement industry. The company has utilized configurators since 1999 and has currently 136 operational configurators[2], which support the specification processes in the sales and the engineering at the company. The configuration setup at the case company has been addressed in previous researches where Hvam [37] describes the benefits and Orsvarn and Bennick [38] provide an explanation of the overall configurations set up, integrations, output and the benefits. Even though, the company has been very successful in applying configurators to support their specification processes in the past, receiving up-to-date and accurate information from suppliers to use in the overall configuration process has proven to be a challenge.

The case company has a great number of suppliers providing the compnay with customized products to be used in the overall design. Therefore, there is a close dependency of receiving relevant product information and prices from suppliers in the configuration process. In many cases products are sourced from several suppliers, and it has to be considered which supplier is the most suitable one for a particular project. The initial strategy for past years was to include high-level product specifications from each supplier in the form of sub-models, modelled and maintained directly in the configuration system. This additional responsibility requires a regular follow up activity with the suppliers to ensure the correctness and validity of the product specifications. There are several challenges reported using this approach, as the knowledge is not available in-house it can be difficult to access and validate it. Furthermore, with no mechanism in place for the required supplier updates to be communicated, the company has to compromise on the overall configuration quality and generated specification outputs.

In order to overcome these challenges, the company has made an integration to one of their gear supplier's configurator via API web services as suggested by [7]. Through this integration, information can be retrieved directly during the configuration process, thereby leaving the modelling and maintenance task to their suppliers. Through that, the suppliers can obtain the

[2] A configurator is defined as model based expert system with it is own knowledge base and inference engine.

confidentiality of sensitive product data while increasing the level of details and optimization and ensuring up-to-date provided specifications.

In this chapter, first, the procedure to include the suppliers' information before the supplier integration and the main limitations of those procedures will be elaborated. Secondly, the technical setup and the protocols will be explained in order to give more understanding of the overall technical setup for this specific case. Thirdly, the impact of integrating the configurators across the supply chains will be explained in relation to the propositions. Finally, the suppliers' incentives for providing the integrations and the main organizational challenges with establishing the setup will be addressed.

3.2 The prior documentation of the suppliers' information

To include the suppliers' information in the internal configurators used at the case company, three different methods have been used over the years. The method selected to document the supplier's information each time depends on the product complexity and the availability of the product information. Following is a brief description of those methods.

- The first method includes making a list of all possible configuration of the supplied product. In cases where a highly complex product with great numbers of possible configurations, it will become impossible to map down all different configurations. Therefore, a limited number of possible combinations of the products and pre-calculated ranges of values are included in the configurator for the product.
- The second method includes building a configuration model based on the supplier's documentation, which allows covering all different configurations even for complex products. However, the main limitations can be traced to the knowledge not being available for the programmers, which makes it difficult to access and validate the models. Furthermore, changes over the time are not always communicated, which can result in invalid or inaccurate configurations of obsolete supplier designs.
- Finally, the third method is to integrate with .DLL[3] files provided by the supplier. The .DDL files can contain both codes and data, which enables that the program division into separate modules. Therefore, the .DDL files from the suppliers can be incorporated into the configuration system as separate components of the program. In these cases, where .DDL files are used, it has to be assured that in case of any changes, the supplier will send an updated file to the company. Furthermore, the suppliers are in most cases not willing to share company critical information. Therefore, these files are often missing product-related information concerning the sensitive aspect of the design and the overall cost structure.

Even though these approaches have been used at the company to include the suppliers' information, they are not without limitations. The main limitation is the insufficient level of detail of the included product specification and its availability in an up-to-date form. In order to overcome these limitations, the suppliers could be contacted every time an input or a proposal from them is required. However, that would delay the overall process, as the lead-time for receiving input or proposal can take weeks. Furthermore, this requires resources being available both at the company and the supplier to request and send the information. This scenario is therefore regarded being unfeasible or impractical. With the current technological progress, an alternative approach to receive up-to-date and accurate products' information from suppliers is to establish integration that allows data exchange in an automatic and efficient way. Here, the case company has decided to connect its internal configurator via API web services to the supplier's configurator. During the configuration process input parameters configured in prior steps are sent to the supplier's configurator, which calculates possible solutions within the given criteria in 0,1 - 0,2 seconds and send back the requested product specifications. This setup enables the company to use the correct and up-to-date designs. Besides, suppliers have the ability to optimize the design for the particular customer requirements with a greater level of detail, instead of using a fixed range of pre-calculated calculations. The technical setup used in this case study is further described in next section.

3.3 The technical setup and the protocols of the case company

The case company and the supplier both had operational configurators used for the internal operation to support the sales and engineering processes. The technical setup allows the configurators at both companies to interact (business-to-business communication) in order to retrieve real-time and accurate product configuration from the supplier. In Figure 3, the setup of the supplier integration in the case company is demonstrated. The company has currently established integration with one of their suppliers but has planned to expand the numbers of suppliers in close future as is shown in the figure below. By expanding the number of suppliers, it both allows expansion of the parts that can be configured via the integration and also by including a number of suppliers providing the same product the most desirable supplier can be found each time in an automatic way, which is done manually today.

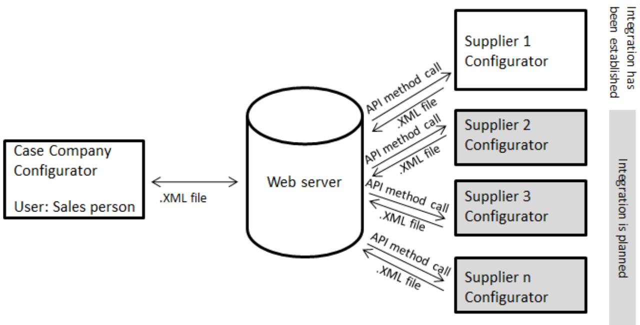

Figure 3. The technical setup at the case company: the supplier integration via API web services

[3] Dynamic link library (DDL)

3.3.1 The setup for transferring data from one system to another system

Confidential data are transferred across the companies, and therefore special security methods are required. In this specific case, the confidential part is limited to the pricing logic as different product designs are already accessible for customers in product catalogues. Therefore, by establishing the integration, the supplier does not have to revile the logic behind the pricing as only the final price for the specific configurations are reviled. In order to reduce the risk from the supplier's site of sharing confidential information, several methods have been established. Those methods are not only limited to the prices but to the overall access of the information that can be gathered from the supplier's configurator.

In order to prevent spying collection, data tracking and men in the middle attack, a third party is not used for transferring the data, and the data communication is directly established between the two companies. The case company has special access rights to the supplier's server, which can be used without identification after login. The initial login therefore only enables persons having access to the configurators at the case company to access the supplier's configurator as the server is not accessible without the login. In addition at the case company, the access rights are not shared with the whole company as it is only available for the employees, which needs to work with the specific configuration/product model. These security methods should, therefore, protect the supplier from misusages of the integration both from the case company and from other external threats.

3.3.2 Input and output parameters

The data exchange between the case company and the supplier is done via .XML files. The case company sends 20 design parameters (such as min/max torque, what the reduction should be in the gearbox, gear factors), which are defined in the previous steps of the configuration process. The request is to find a design within these parameters, where the supplier's configurator, based on their logic and business rules, find all possible design solutions, which can be around 100 and the prices for the different designs. It is highly unlikely that the supplier's configurator will not be able to find a feasible solution. However, if that situation comes up either parameters have to be changed in the configuration at the case company, or the supplier has to be contacted. The design solutions are sorted according to prices (from lowest to highest) and sent back on an .XML format via the web API web services. For this specific product, the prices are most important and therefore the cheapest solution is automatically selected by the case company's configurator. It should though be noted that other parameters can be used to sort after, such as in terms of quality, lead-time etc. The information retrieved from the supplier is then used in the further steps of the configuration as the dimensioning of the product, will affect the overall design under configuration at the case company.

3.4 The impact of integrating configurators across the supply chains

3.4.1 Reduced complexity of the configuration model

The configurator models operated at the case company contain a number of sub-models that in turn include parts and modules bought from suppliers (as described in section 3.2). Outsourcing these sub-models, the complexity of the configuration model has been reduced. By reducing the complexity, in terms of business rules, tables, parts and values, of the configurators' models, the development and maintenance effort can simultaneously be reduced as the supplier's configurator is accessed in the configuration process. The supplier, therefore, becomes responsible for developing and maintaining his own products' information. In Table 1, it is summarized how the supplier integration affects the complexity of one of the configurator's model operated at the case company and the impact it is having on the development time.

Table 1 Summary of reduction of complexity in the configuration at the case company

Characteristics of the configurator	Before the supplier's integration	After the supplier's integration
Business rules	86	0
Tables	13	0
Parts	17	1
Values	18.836	20
Development time of the system	8+ days	2 days
Specialist time spent in the development	8+ days	0 days

3.4.2 Improved quality of the specifications in terms of updated and more detailed product information

An important aspect of the proposed approach is improved quality of the products' specification as they are based on the real-time, optimized and more detailed information. This secures a valid solution, right dimensioning of the product under question and exact and up-to-date prices are used in the overall configuration process.

For the product provided by the supplier addressed in this case study that is gears, the numbers of possible configurations for a product are 25-26 million. When having so many possible combinations, it is not feasible to include them all by using Excel sheets or preliminary databases as it will take too long time to look up and affect the time it takes to start up the configurators. Therefore, for the product in question in this case study only 20 different configurations were included (out of 25-26 million) in the configurators before the integration. As a result of this, the company was not using the most optimal design of the supplier's product (as the feasible solution is selected based on a limited number of configurations). The solution that was chosen was always scaled up to the predefined range, which means that surrounding systems also needed to be scaled up. As if one part of the design is over-dimensioned other parts have to be adjusted accordingly, which will cause a snowball effects in the overall design. In Figure 4 this is demonstrated where the blue line represents the predefined configuration that would have been selected prior to the supplier integration and the red line represent the exact configuration, which can be selected as a result to more detailed information retrieved after the supplier integration was established. The product' dimensions for this specific product are determined based on required kilowatts (kW).

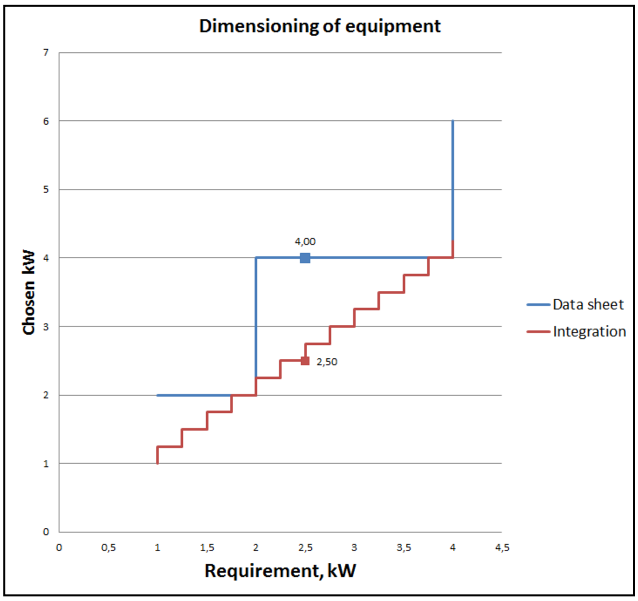

Figure 4 Dimensioning intervals of the equipment before and after the supplier integration

Having the precise dimensions of the supplier's product in the configuration process has proven to improve the accuracy of the generated specifications and reduce over-dimensioned surrounding systems. Therefore, the company has achieved both immediate and indirect cost savings as a result of more detailed product information. The immediate cost saving, for example, presented in Figure 4, is the difference between the 4,00 kW and 2,50 kW gear while the in-direct cost savings represent the related systems or the frame as the gear is positioned on and again the platform area, weight of supporting building and etc. It is estimated that the company saves up to 20% in material cost in the overall design by having more detail information in the design phase.

3.5 Supplier incentive for providing integration

From a supplier perspective, this approach provides additional benefits as it allows the supplier to protect sensitive product information, as these are considered as a secure black box in the configuration process. The supplier also saves resources for generating and sending proposals to their clients and thereby drastically reducing lead-times across the supply chains. Finally, the supplier hopes to increase their business share in long-term with the case company as when this integration has been established it can easily be expanded to include additional products provided by the supplier.

3.6 Challenges with the approach

The main challenges can be related to legal barriers from both parties and to identifying suppliers that have the capabilities for the suggested collaboration with respect to operating with configurators.

For the companies addressed in this case study, this is the new way of doing business, which needs the management and power to be able to execute it in a bigger scope so both parties can get some substantial gains from it. The main challenges can, therefore, be described in terms of organizational and not in terms of technical challenges. From the technical aspect, the whole programming was done in 2 days for the first time, and afterwards, for other integrations, it was even less than 1 day, which highlights that the integration can be established without great effort.

4 DISCUSSIONS

The supplier integration used in the customization process where configurators are connected via API web services has proven to improve the overall process and provide substitutional benefits both for the case company and their supplier. This can be traced to the accuracy of the suppliers' data, where more detailed and optimize information are provided, which are constantly up-to-date. This has enabled the case company to save up to 20% of the overall material cost in the overall design. Furthermore, the complexity of the configuration models can be reduced, and the time-consuming task of modelling and maintenance are delegated to the supplier. Finally, with this setup, the supplier does not have to revile the actual logic behind the designs and the pricing strategy as the supplier's configurator is treated as a black box in the configuration process.

As the application of the configurators is constantly increasing, this integration to supplier's configurators becomes more realistic. That is the requirement for making the integration is limited to the suppliers having operational configurators or willing to develop a configurator, which is capable of covering the required configurations. In addition to the integration that has been established at the case company four other suppliers have been identified that fulfil these requirements and have approved to participate in the project.

Further work at the case company with this approach will, therefore, include establishing the integration to a greater number of suppliers, where comparisons capabilities of the configurator are used to identify the most suitable supplier. As for each product bought at the company, there are several suppliers able to provide the product. For plant equipment, the aim is to have 2-3 suppliers for each of the products and the most favourable supplier each time will get the quote. The criterion for selecting the most desirable supplier has to be selected in the system for different products. In many cases, the cheapest supplier would get the quote, but it could also be lead-time, quality etc. The configurations retrieved from the suppliers are then sorted based on the selected criteria, and the best one is selected by the system. This will automate the processes of comparing different suppliers' offers, which is done manually in the company today. For configurations on plant level there are preferred suppliers, and therefore this cannot be applied in these cases. However, the comparison capabilities can be used to analyse the impact of changing the preferred suppliers to see the effect it has on prices, delivery-time etc.

The company has also made plans to increase the number of documents retrieved from the suppliers in the configuration process. Therefore, further work will include making it possible to retrieve documents such as 3D models and technical specifications as now only prices and dimensions of the product are received. Furthermore, currently, the integration is only used to receive data as input in the configuration process, where the procurement will then contact the supplier to make the actual order purchase. In close future, it is anticipated to automate that as well so that the product can be requested from the supplier via the integration.

5 CONCLUSION

The present paper analyses the impact of having integrated configurators in the supply chains in an ETO company. The approach suggests the involvement of configurators that retrieve accurate sub-product information in real-time from suppliers during the customization process. The results indicate an improved quality of the product specifications and reduced complexity of the configurator model. Three propositions were developed to analyse the impact from integrating configurator across the supply chains to retrieve more accurate, detailed information and optimized in the configuration processes.

The first proposition investigates if by applying this approach the complexity of the configurator model can be reduced. The modelling and development effort proved to be reduced at the case company as they are not responsible for modelling the supplier's product information. Thereby the modelling and maintenance effort is moved to the supplier. The findings support this proposition as the complexity, which is defined in numbers of business rules, tables, parts and values are reduced to almost zero. This also affects the development time of the system which is reduced from 8+ days to 2 and the specialist time spent on the development has been reduced from 8+ to 0.

The second proposition questions if by integrating configurators across the supply chains, the quality of the specifications generated by the configurators will increase. The quality of the configurators model in this article is defined in terms of improved accuracy as the information retrieved via the supplier integration is optimized, more detailed and up-to-date. The findings support this as over-dimensioning of different parts is not required as a result of improved quality of the products' specifications.

Finally, the third proposition is concerned with the improved quality of the specifications will lead to cost savings at the company. The result indicates that the company can save up to 20% of material cost as a result of immediate and in-direct savings gained from over-dimensioning both the supplier's product and the surrounding systems. The results based on this study indicate that significant benefits can be gained from increased supply chains integrations in ETO companies where integrated configurators are distributed across companies.

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APPENDIX J

International Journal of Industrial Engineering and Management (IJIEM), Vol. 8 No 3, 2017, pp. 167-176
Available online at www.iim.ftn.uns.ac.rs/ijiem_journal.php
ISSN 2217-2661

UDK 658.5:005

Automatic Identification of Similarities Across Products to Improve the Configuration Process in ETO Companies

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Received (10.03.2017.); Revised (12.05.2017.); Accepted (05.07.2017.)

Abstract

Engineer-To-Order (ETO) companies making complex products face the challenge of delivering highly customised products with high quality, affordable price and a short delivery time. To respond to these challenges, ETO companies strive to increase the commonality between different projects and to reuse product-related information. Therfore, ETO companies need to retrieve data about previously designed products and identify parts of the design that can be reused to improve the configuration process. This allows companies to reduce complexity in the product portfolio, decrease engineering hours and improve the accuracy of the product specifications. This article proposes a framework to identify and compare products' similarities. The framework (1) identifies the most important product variables available in the Product Configuration System (PCS), (2) retrieves data of previously designed products in an Enterprise Resource Planning (ERP) system, (3) identifies a method to compare products based on the main products variables and (4) sets up an IT system (database) with data of the previously designed products to integrate with the PCS. The proposed approach (the framework and the IT system) is tested in an ETO company to evaluate the application of the framework and the IT system. We retrieved the needed data from the ERP system at the case company and developed the IT system in Microsoft Excel, which is integrated with the PCS.

Key words: *Clustering, Framework, Integration, IT system, Product Configuration System (PCS), Similarities*

1. INTRODUCTION

A product configuration system (PCS) supports users to specify different variables* of a product by defining how predefined entities (physical or non-physical) and their properties (fixed or variable) can be combined [1]. PCS offers a good opportunity to enhance a company's resale and production processes starting from the improvement of the quotation process [2]. Several benefits can be gained from utilising a PCS, such as a shorter lead-time for generating quotations, fewer errors, an increased ability to meet customers' requirements with regards to the functionality and quality of the products, and increased customer satisfaction [3–6]. To realise the advantage that can be gained from utilising a PCS, the organisations and the support systems need to change in the order acquisition and fulfilment processes [7,8].

In Engineer-To-Order (ETO) companies producing complex and highly engineered products, a significant problem arises when calculating the prices in the presale and sale processes, especially when domain experts cannot determine accurate price curves, or when vendors fail to provide sufficient information to model within the PCS. Therefore, estimates are often used and mark-up factors are added. Alternatively, ETO companies use prices and other data based on previously made products as a base for the new design. However, this method affects the accuracy of calculations because previous projects are not easily accessible and significant work is required in manual comparison of new products with previous products to find the relevant information [1].

* A variable is a value that can change, depending on conditions or on information passed to the program.

Hvam et al. [1] presented a solution to the discussed problem, based on a real case. The authors described an ETO company that strives to reuse information from previously made products to calculate the price based on weight and capacity [1]. Price and weight curves are drawn up by inserting the capacity, price and weight based on information from three to five previously produced machines [1]. A curve is then drawn through the points to identify the prices and weights for machines that have not previously been produced, as shown in Figure 1.

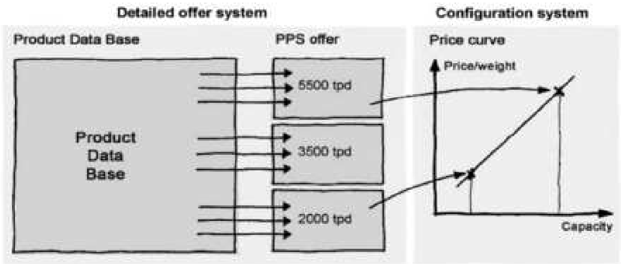


Figure 1. Price and weight curve for the main machines in FLSmidth [1]

However, with regard to highly complex products, the price curves may not be the most accurate because there are several dependent variables and a large number of neighbours on the curve. Another important drawback of the price curves is that the user is only provided by access to some of the previously made projects, and thus the most similar previous projects might be missed.

To identify the similarities of previously designed products and new products, an automated IT system† can be beneficial, which makes it possible to produce the customised products while using the least possible amount of time and resources.

Previous research has described how modules across different products [9, 10] can be used to compare different products. Kristianto et al. [11] claimed that platform-based designs can result in economies of scale by mass-producing the same modules and lowering design costs from not having to redesign similar products. Standardisation or system level configuration strategies can be applied in the ETO context [11]. Thus, if an existing product has standardised and decoupled interfaces, the design of the next product can borrow heavily from the modules of the previous product [12].

Thevenot and Simpson discussed a framework that uses commonality indices for redesigning the product families to align with cost reductions in the product development process. They argued that standardising and modularising the product structure incorporated into the PCS can make it easier to select the relevant variables or add them to the PCS [13]. Mäkipää et al. [14] presented the solution of design-configurators for ETO companies. However, they concluded that there are certain limitations of design-configurators, such as handling calculations and adjusting the design accordingly [14].

Inakoshi et al. [15] proposed a framework to support the PCS, which frames the integration of a constraint satisfaction problem with case-based reasoning (CBR), where the framework is applied to an online PCS. In ETO companies, the integration of existing PCS technologies with recommended approaches is crucial for supporting end-users in their configuration processes [16, 17]. Felfernig et al. [16] discussed different recommendation systems, divided into Collaborative Filtering (CF), content-based filtering (CBF) and knowledge-based recommendations (KBR). The available recommendation technologies in e-commerce are potentially useful in helping *customers* to choose the products' variables. Comparing the new project with previous ones could also result in developing a recommendation system in the companies.

Existing literature do not respond to the need of a structured automatic solution for retrieving the data of previously designed products to reuse in the configuration process.

In this paper, we aim to use a PCS to make a connection between previously designed products and the new products being configured. When generating quotations in the PCS, it is valuable if we can compare the configured products with the previously designed products by comparing the main products variables. This means that, if there is a high percentage of similarity between the new product and a previous made product, the previous documentations and specifications designs can be reused for the new product. Thus, the costs and resources required to generate the product specification can be significantly reduced (i.e. costs in the sales, engineering and production phases).

To achieve this, we develop a framework, as a supporting structure for ETO companies. The framework aims to identify previously designed products that are most similar to the one that a customer is asking for in the configuration process. The framework considers different steps, which guide the company to fulfil this gap. Based on the proposed approach, a framework and an IT system can be generated, where clustering methods are coded to compare the similarities of the products variables.

The remainder of the paper is organised as follows. Section 2 elaborates on the research method. Section 3 details the framework development and discusses each of the proposed steps. Section 4 presents the results of the case study and Section 5 discusses the limitations and presents the conclusions of the research.

2. RESEARCH METHOD

This research was conducted in two phases. The first phase developed the framework for identifying the similarities from previously designed products and new products. The second phase validated the framework.

† An IT system is a group of components that interact to produce information [18].

2.1 **Phase 1: Framework development for identifying similarities between products**

The main purpose of the framework is to define the similarities between previously designed products and new products. To provide a foundation for the proposed framework, we evaluated existing literature focusing on identifying and retrieving the most important product variables, retrieving data of previously designed products and clustering methods to compare products based on the main variables. The literature provides the sequences of steps and methods by which to identify the product similarities. Next, we study the integration of PCS with another IT system in the previous literature [15, 16].

The framework is developed and improved in an iterative testing process, which is described in detail in the subsection 2.2. The next step assesses the framework validation by developing and testing an IT system to automate the process based on the framework.

2.2 **Phase 2: Framework assessment through case application**

After clarifying the available literature on clustering methods, retrieving the product data and finding the sequences of steps, we developed an IT system to use in a pilot project at a case company that produces highly engineered complex products. The project team formed at the case company included four researchers from the Technical University of Denmark and three experts from the company. The experts from the company included a specialist from the configuration team, a manager and an IT engineer in the IT department.

Based on the proposed framework, we specified the product variables in the PCS and ERP systems at the case company. We identified the product variables from the PCS and managed to collect, treat and structure data from the ERP (SAP) system using MS Excel. We decided to run the pilot project to avoid additional costs by integrating the PCS and ERP and by only coding the clustering constraints in MS Excel. In this step, we selected the clustering methods based on the literature, tested them in the case company and compared the results of the tests.

We prepared the IT system by storing the data from the previously designed products in MS Excel and coding the selected clustering method. However, the success criteria had to indicate what kind of data should be retrieved from previously designed products and how the clustering should be done for the purpose of comparison. Thus, the acceptance criteria for the IT system in the case company were determined as follows:

1. The MS Excel developed IT system should demonstrate its capability to store and retrieve the relevant product variables need to search for similar products.

2. The selected clustering method for comparing the similarities with previously designed products in the configuration process have to be programmed in MS Excel.

3. The IT system (MS Excel) should be integrated into the PCS.

3. FRAMEWORK DEVELOPMENT

Section 1 provided the theoretical bases for developing the framework by covering subjects as: identifying product variables, clustering the data for the comparison purpose, creating an IT system and integrating it with the PCS [9, 10, 12, 14–16, 18–22] The framework aims to fill a gap in the literature, which fails to discuss how the clustering methods can be used to identify similar previously designed products or develop an IT system that can be integrated to the PCS. The proposed framework consists of the following four steps:

1. *Identify the most important product variables available in the PCS*
   The first step of the framework involves defining clear objectives to guide the development and the implementation processes. This includes describing the nature and characteristics of the product and listing the main variables of the products that have to be included.

2. *Retrieve data of previously designed products in the ERP system*
   The second step involves retrieving the data from the identified product variables from the ERP system or any other available database storing the product information.

3. *Identify a method to compare products based on the main variables*
   The third step involves defining a method for clustering the main variables to find the similarities between the products.

4. *Set up the database with data of the previously designed products to integrate with the PCS.*
   The *last step* involves setting up an IT system using the following steps [23]:
   (a) Requirement analysis.
   (b) Conceptual database design.
   (c) Logical database design.

The following subsections explain the individual steps in more detail. In Section 4, the IT system is implemented in the case company and the framework is assessed. Section 4 provides a visual representation and elaboration of the individual steps in the case company.

3.1 **Identify the most important product variables available in the PCS**

Different techniques can be used to demonstrate, identify and communicate product structure and variables, such as Product Variant Master (PVM) [1] and Product Family Master Plan [24]. A company's product range is often large, with a vast number of variants. To obtain an overall view of the products, the product range is drawn up in a PVM (Figure 2).

In this paper, the PVM is used to break down the components of the product into a tree structure and identify the main product variables. The product structure, variables and rules in the PCS are illustrated using PVM to identify the different variables.

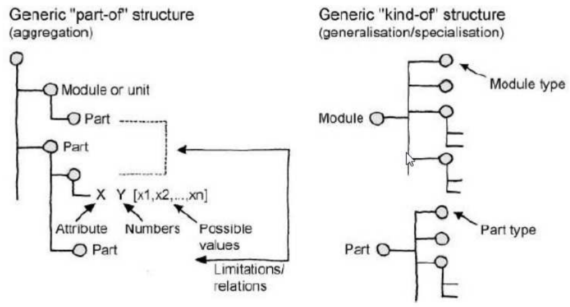


Figure 2. Principles of the PVM [1]

3.2 Retrieve data of previously designed products in the ERP system

The current generation of database systems is designed mainly to support business applications, and most of these systems offer discovery variables using tree inducers, neural nets and rule discovery algorithms [25]. One of the fundamental problems of information extraction from ERP systems is that the format of the available data sources are often incompatible, requiring extensive conversion efforts [26]. Knowledge discovery (KD) in databases represents the process of transforming available data into strategic information, which is characterised by issues related to the nature of the data and the desired features [27, 28]. Brachman et al. [29] broke the KD process into three steps:

1. Task discovery, data discovery, data cleansing and data segmentation;
2. Model selection, parameter selection, model specification and model fitting; and
3. Model evaluation, model refinement and output evaluation.

KD includes the derivation of useful information from a database, such as "which products are needed for the specific amount of engineering hours for installation?" [30]. In this article, the specific steps of KD are followed to retrieve the data from the ERP system.
Most companies use the traditional technique called "British classification" when naming different components according to the product variants. However, as products become more complicated, this technique becomes more impractical. When using this technique, as shown in Figure 3, a "surname" of five digits represents the general class of an item and a "Christian name" of three digits provides a particular item with an exact identity [31].

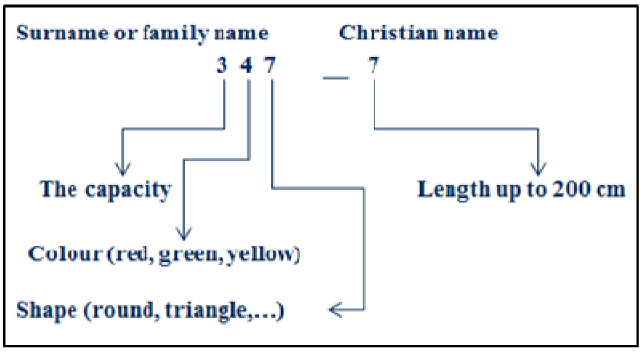


Figure 3. Expansion of a major class [31]

The British classification can be used to assess the products similarities with a high level of abstraction. Thus, we used this technique to decode the high level data from the ERP system.

3.3 Identify a method to compare products based on the main variables

Clustering techniques are required for identifying and clustering relevant products variables. Burbidge [31] described how to cluster the product components and code them by introducing the Group Technology (GT) method. Martinez et al. [32] provided an example of using the GT technique in a manufacturing plant to minimise unnecessary diversity by making designers aware of existing components.
The aim of clustering and coding is to provide an efficient method of retrieving information and improving the decision-making. Leukel et al. [33] discussed the design and components of product clustering systems in business to business (B2B) e-commerce and suggested a data model based on XML. Fairchild [34] discussed the application of clustering systems and their requirements. Simpson [35] used GT for adding, removing, or substituting one or more modules to a product platform that should improve the design of the product platform and the customisations. Fairchild et al. [34] suggested an automated clustering system for the specialisation of life cycle assessment. Ho [28] introduced a system, called OSHAM, generated in a hierarchical graphical browser, which competes with C4.5. Software Product Line Engineering (SPLE) was introduced to represent the combinations of features that distinguish the system variants using feature models [36].
A popular non-hierarchical clustering method is the k-means clustering algorithm, which is recognised for its efficiency [37]. This method aims to minimise the k-means algorithm considering the squared differences between the observational data vectors and the cluster centroids overall observations and k-clusters [37]. A method proposed by Anzanello and Fogliatto [38] is based on six steps: (1) Obtain experts' variables, (2) Model the variables, (3) Define bounds, (4), Select the variables, (5) Check whether the upper bound is selected, and (6) Identify the best variables and clusters. Euclidean distances are typically used to calculate the distance between observations because a Silhouette Graph can be generated for displaying the

performance of a clustering procedure [39]. The method provides, for each observation j, the SIj, which can vary from –1 to +1. The closer SIj is to one, the less is the distance within a cluster, meaning that it is properly assigned to the correct cluster [40]. SIj is estimated as follows:

$$\mathrm{SI(j)} = \frac{b(j) - a(j)}{\max(\mathrm{a(j)}, \mathrm{b(j)})} \quad (1)$$

3.4 **Set up the database with data of the previously designed products to integrate with the PCS**

Ramakrishnan et al. [23] provided an overview of database design based on the following three steps:

1. Requirement analysis: Understand what data are to be stored in the database, what applications must be built on top of it and what operations are most frequent and subject to performance requirements.
2. Conceptual database design: The information gathered in the requirements analysis step is used to develop a high-level description of the
3. data along with the constraints to be stored in the database.
4. Logical database design: The Database Management System (DBMS) has to be chosen to implement the database design, and the conceptual database design must be converted into a database schema in the data model of the chosen DBMS.

In this paper, we used the database design instruction proposed by Ramakrishnan et al. [23]. First, we performed the requirement analysis, which is discussed and elaborated in step 1 of the proposed framework. Next, the conceptual database design is built based on the analysis from step 1 and the retrieved data in step 2. Finally, the logical design of the database is followed by choosing MS Excel, and the logics are built upon the selected clustering method.

4. CASE STUDY

The proposed framework was tested in an ETO company by developing the IT system. Figure 4 illustrates the process of fulfilling the framework steps to deliver the IT system to the case company over four months. The stakeholders of this pilot project are the sales engineers, sales managers and technical designers from the relevant department. The main potential benefits from using this IT system in the case study were discussed by the stakeholders and listed as the following project aims:

Recommendation system: The decision was made to design the system and its user interface to be replaceable by a recommendation system in the sales process.

Price estimation: It would be beneficial if the IT system could be used to analyse the relationship between costs and variables in the cluster analysis. Thus, the calculated estimated costs from the PCS could be verified or corrected accurately after configuring the product by comparing them with the previously designed products.

Statistical analysis: It would be preferable if a more detailed overview of the product complexity, the most sold products and the products never sold was provided. This would help the company to reduce the complexity in product ranges based on market requests, clean up the product range and replace it with new product variables based on the knowledge from the market.

4.1 **Step 1: Identify the most important product variables available in the PCS**

The first step involves selecting the main product variables to be compared across new and previously made products. The PVM is used as the tool to identify the main product variables [1]. The tree structure of the PVS is then used to structure the entire product and to break the main overall product structure down into small enough issues to analyse. Using the PVM, we determined the main product variables of the chosen products.

4.2 **Step 2: Retrieve data of previously designed products in ERP system**

In the second step, all the main product variables and data were retrieved from the ERP system using KD [29]. The main customised variables were determined as the main variables of the selected products (e.g. weight and cost). Based on these customised product variables, one specific component with different variables was selected, and the IT department helped to retrieve the cost documents from the ERP system into MS Excel. The retrieved data were then divided into subparts (based on the specific variables from the PCS) and the project numbers were decoded to make the deliverables more generic.

4.3 **Step 3: Identify a method to compare products based on the main variables**

After testing multiple clustering methods, this paper uses k-means and Euclidean distance measurement methods. The first objective in this step was to select the most suitable set of clustering variables leading to an optimised product grouping. Therefore, the k-means procedure was run for every combination of the variables. Each one belonged to a different Excel sheets. In this case, there were four sheets for each cluster: x-y, x-z, y-z and x-y-z. We assess which sheet would lead to the optimal clustering, where the average Silhouette Index (SI) for all the analyses was stored. A higher SI means more accurate clustering. The next step was to calculate the distance between the previously designed and the new product based on the Euclidean distance. This distance was calculated for all combinations of the variables—three variables (x, y, z) and six possibilities (xyz, xy, xz, yz, x, y, z). A small distance between the new product and the previously designed product indicated a high similarity. The formula shown in Figure 5 is based on a Euclidean distance measurement. The final step of the

comparison platform is to list the products based on similarity. This was done by ranking the distance measurements. As shown in Figure 6, the distance rank a6 has the shortest distance to the new product, a4 has the second closest product and a7 is the third closest to the new product among the previously made products.
The cluster was initially placed and based on the k-means algorithm, and a final position for the cluster's centroids was found. The algorithm continued with the second iteration, where the same procedure was applied. As a result of the further iteration, the cluster centres moved according to their belongings, which resulted in an increase in the average SI. A higher SI means a more accurate clustering. The algorithm continued until the cluster centres stopped moving. Figure 7 illustrates the situation resulting from several iterations.

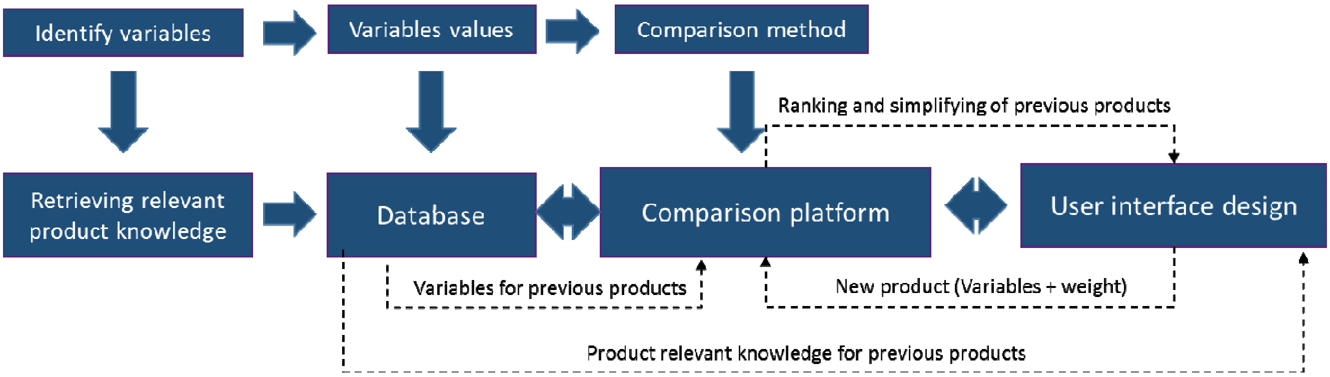
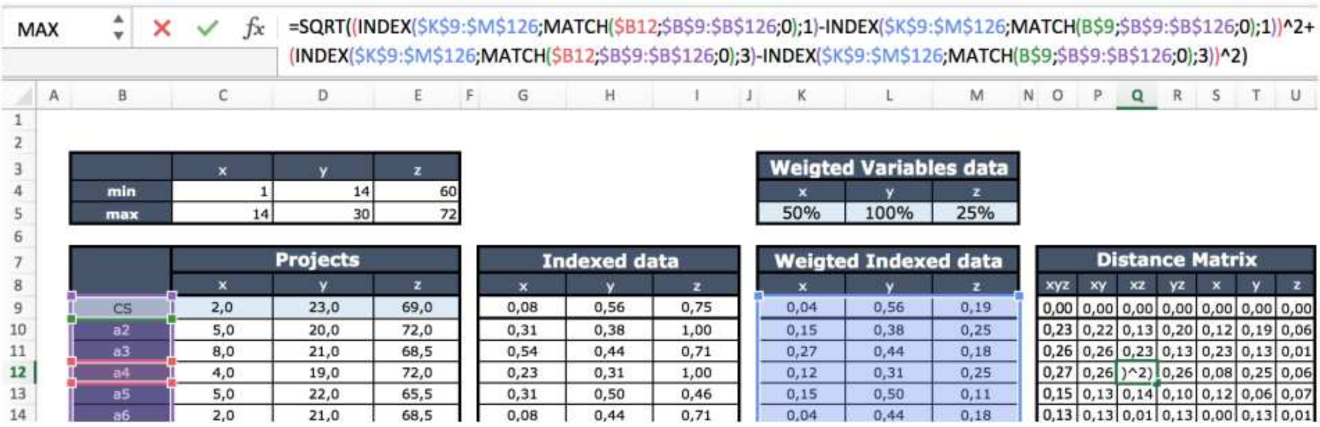


Figure 4. Structure and information flow of the IT system in the case company



MAX =SQRT((INDEX($K$9:$M$126;MATCH($B12;$B$9:$B$126;0);1)-INDEX($K$9:$M$126;MATCH(B$9;$B$9:$B$126;0);1))^2+(INDEX($K$9:$M$126;MATCH($B12;$B$9:$B$126;0);3)-INDEX($K$9:$M$126;MATCH(B$9;$B$9:$B$126;0);3))^2)

	x	y	z
min	1	14	60
max	14	30	72

Weigted Variables data		
x	y	z
50%	100%	25%

	Projects			Indexed data			Weigted Indexed data			Distance Matrix						
	x	y	z	x	y	z	x	y	z	xyz	xy	xz	yz	x	y	z
CS	2,0	23,0	69,0	0,08	0,56	0,75	0,04	0,56	0,19	0,00	0,00	0,00	0,00	0,00	0,00	0,00
a2	5,0	20,0	72,0	0,31	0,38	1,00	0,15	0,38	0,25	0,23	0,22	0,13	0,20	0,12	0,19	0,06
a3	8,0	21,0	68,5	0,54	0,44	0,71	0,27	0,44	0,18	0,26	0,26	0,23	0,13	0,23	0,13	0,01
a4	4,0	19,0	72,0	0,23	0,31	1,00	0,12	0,31	0,25	0,27	0,26	)^2)	0,26	0,08	0,25	0,06
a5	5,0	22,0	65,5	0,31	0,50	0,46	0,15	0,50	0,11	0,15	0,13	0,14	0,10	0,12	0,06	0,07
a6	2,0	21,0	68,5	0,08	0,44	0,71	0,04	0,44	0,18	0,13	0,13	0,01	0,13	0,00	0,13	0,01

Figure 5. Distance matrix

	Distance Rank							Project Rank						
	xyz	xy	xz	yz	x	y	z	xyz	xy	xz	yz	x	y	z
CS														
a2	95	95	95	13	95	13	95	a6	a6	a6	a87	a6	a87	a96
a3	94	94	94	68	94	68	94	a4	a4	a4	a64	a4	a64	a95
a4	2	2	2	10	2	10	93	a5	a5	a8	a47	a8	a47	a94
a5	3	3	4	9	4	9	92	a8	a8	a5	a45	a5	a45	a93
a6	1	1	1	8	1	8	91	a14	a14	a14	a37	a14	a37	a92
a7	8	8	8	73	8	73	90	a12	a12	a10	a29	a10	a29	a91
a8	4	4	3	67	3	67	89	a10	a10	a9	a12	a9	a12	a90
a9	15	15	7	81	7	81	88	a7	a7	a7	a6	a7	a6	a89

Figure 6. Ranking the distances and projects

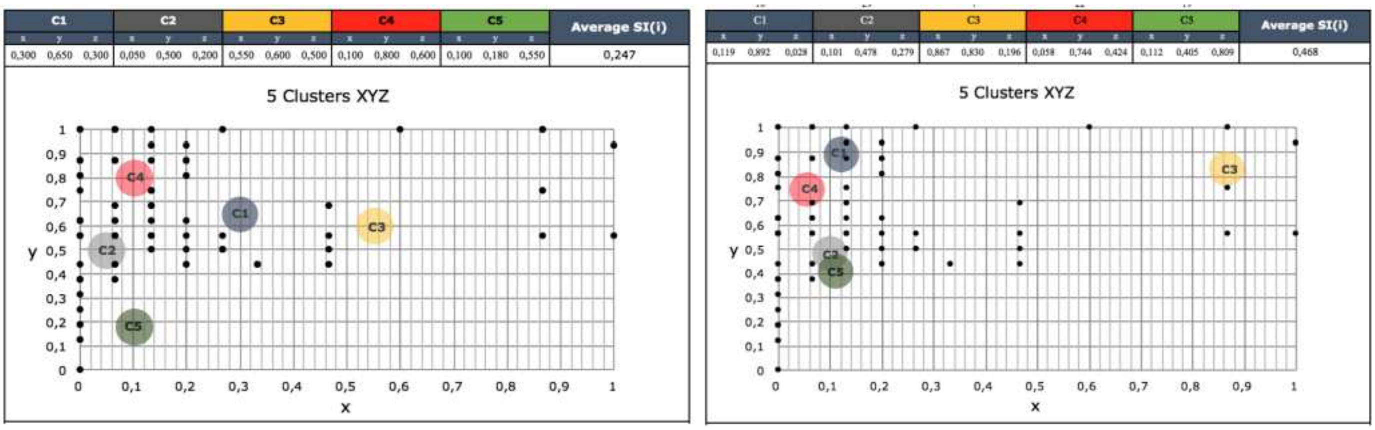


Figure 7. Movement of the clusters and average SI, at the beginning (left) and at the end of the k-means algorithm (right)

4.4 **Step 4: Set up the database with data of the previously designed products to integrate with the PCS**

The PCS at the case company is based on a commercial platform, where the integration with MS Excel forms part of the standard system. The aim of the user interface is to return similar previously made products when the user configures a new project. Based on this, the user can use product-relevant information from previous projects.

The IT system, which was developed based on the proposed framework, was tested in the case company with one of the current PCS. Figure 8 shows the simple user interface after the Excel sheet is generated from the PCS, where the main product variables are exported to MS Excel. Furthermore, MS Excel is integrated with and receives the relevant input from the PCS.The inputs were received from the PCS and added to the MS Excel. However, there is an input area in the Excel spreadsheet in case the PCS is not used.

The input part is covered by the three upper-left boxes in the user interface, which can be seen in Figure 9. The white fields are where the user can enter inputs. Therefore, the use of the Excel sheet is not only limited to the PCS.

Users can exclude products variables if they are not relevant. If a variable is taken out of the interface, it will be taken out of the distance calculation and other products will be recommended. The “elimination feature” is also integrated into the PCS. Figure 10 shows how the user can eliminate variables by clicking “YES” or “NO” and indicates how this impacts the output.

To visualise the output, a bar graph was added to the user interface. Data for the graph are based on the relevant product information chosen as first priority in the input field. Thus, it is possible for the user to change the data subsequently. In addition, the graph was programmed so that it would fit the number of recommended products (Figure 11).

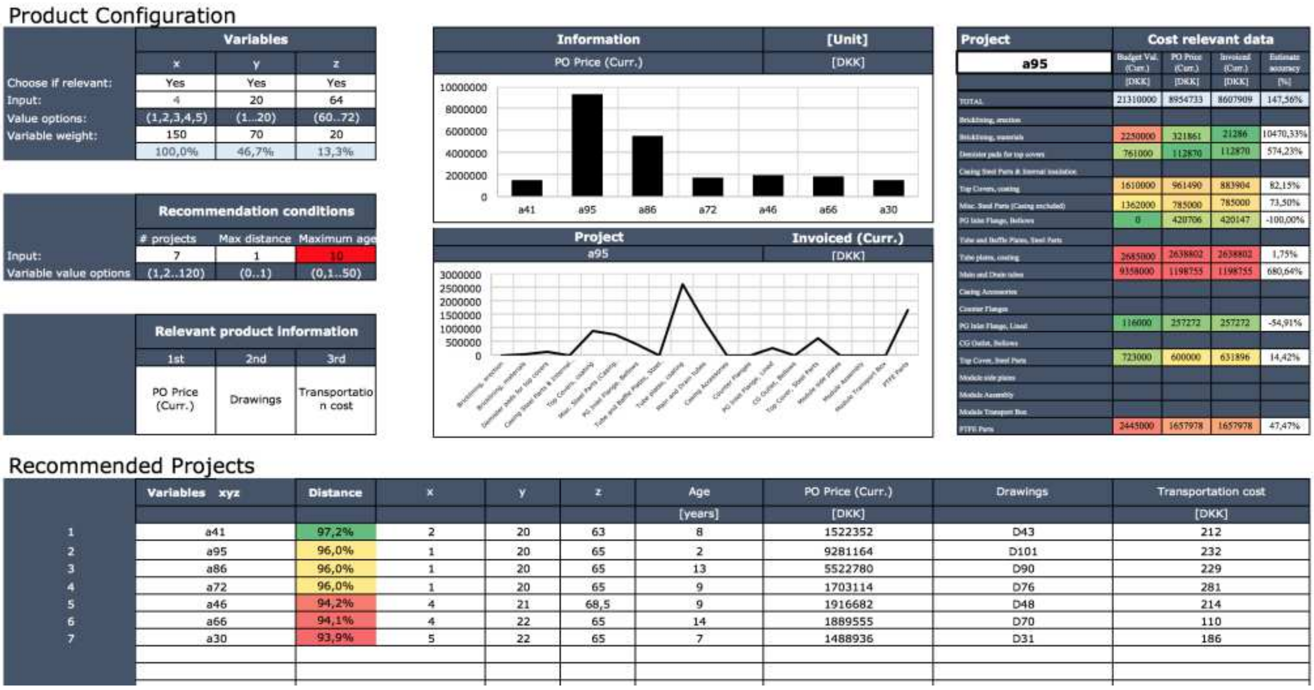


Figure 8. Final user interface of the IT system

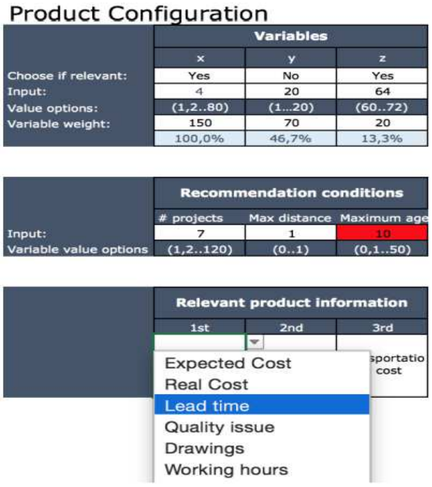


Figure 9. Choice of product-relevant information

Figure 10. Exclusion of variables

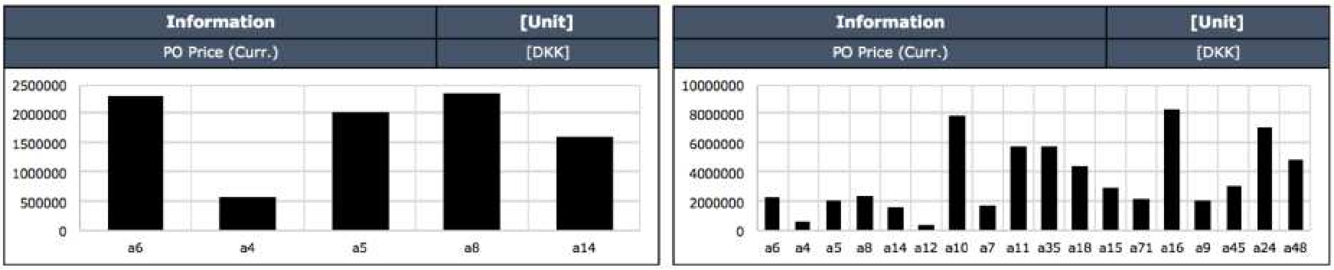


Figure 11. Graphs for recommended products

5. DISCUSSION AND CONCLUSION

As products become increasingly complex, it becomes more difficult to generate precise product specifications from the PCS, especially for complex products. Integration of existing configuration technologies with recommended approaches is crucial to support end users in the configuration processes [16, 17]. Researchers have proposed various support measures to help to integrate PCSs with other IT systems [15], and existing literature provides examples of clustering methods [37–40]. However, there is no automatic solution for retrieving and reusing product information in the configuration process. This solution proposed in this paper thus builds on the available literature on clustering and integration. Based on the literature and experiences working with PCSs, the users of PCSs check and compare some of the old projects they are capable of remembering before sending out new order proposals. In this way, they might be able to find similar products and thus reduce the necessary time and resources, improve the quality, increase the accuracy of their calculations and eliminate the engineering processes or even offer customers the same product at a lower price. However, even when there are similar products, it can be difficult to find them in the ERP system, and this process of finding similar products can become even more challenging once the proposal phase is accepted and the engineering phase has started. The engineers sometimes waste time repeating the same processes without realising that another similar project was completed earlier, and they could simply reuse the data.

In this paper, we propose a framework for creating an IT system of previously completed products and compare against new projects. This approach allows efficient comparisons to be made while using the available methods and tools. An IT system was coded in a separate MS Excel file as the pilot project using the minimum resources at the case company. The IT system showed the ability to cluster and compare the product data and thus proved the feasibility of the concept. Moreover, we tested the proposed approach in a case ETO company to determine whether the framework and IT solution are practical in a real-life situation.

As discussed in Section 2, we need to determine some criteria at the case company for accomplishing the project. The criteria and deliverables fulfilled during the case company project are as follows: (1) We retrieved and stored the relevant product variables for the product in MS Excel, (2) we coded the selected clustering method for comparing the similarities from previously designed products in the configuration process in MS Excel, and (3) we integrated the Excel database into the PCS used at the case company.

The users of the system at the case company saved time and resources by using this IT system. Previously, they faced a number of problems estimating costs and engineering and workshop hours, which led them to check the previous projects manually.

The IT system, that was developed based on the proposed framework in this paper, helped the users of the PCS to manage the high number of previously designed products and the high level of customisation. The users of IT system did not have to overcome any challenges related to training or system changes because the engineers were familiar with the setup of Excel and it had a friendly user interface. They also mentioned that this clustering method and IT system not only saved around 50% of their time when making sales quotations but also reduced errors and increased the accuracy of their proposals. This paper is limited to a single-case study containing limited data. Limited numbers of clustering methods were tested. The coded IT system might not be efficient when the number of variables increases. This IT system needs to be continually maintained because it has to be aligned with the ERP system; otherwise, it will become outdated and forgotten after a number of projects have been sold. Therefore, in the future it might be more beneficial to integrate the PCS directly to the ERP system. As mentioned, the framework and IT system are eveloped in an iterative process in an ETO case company. However, the case study type allows the research group to face the complicated types of products and repeat the in-depth testing of the developed framework and IT system. Meanwhile, the study of one case company allowed the team to have hands-on practice and make IT developments to assess the research in a real situation long-term.

Further research should be conducted to enable generalisability of this approach and to test the proposed approach in more and different case companies with different products. Future research can focus on clustering and integrating the IT systems with the ERP system to update the knowledge automatically. The goal is to use the ERP as the main database and automatically retrieve the stored and updated data from the ERP system.

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Unapređenje procesa konfiguracije kroz automatsku identifikaciju sličnosti proizvoda u kompanijama koje projektuju po narudžbini

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Primljen (10.03.2017.); Recenziran (12.05.2017.); Prihvaćen (05.07.2017.)

Apstrakt

Kompanije koje projektuju i proizvode složene proizvode po narudžbini (engineering-to-order) se susreću sa izazovom isporuke kastomizovanih poizvoda visokog kvaliteta, u kratkom roku i po prihvatljivoj ceni. Kako bi odgovorile na ove izazove, kompanije koje projektuju po narudžbini teže da povećaju sličnost između različitih projekata i na taj način u više slučajeva iskoriste informacije vezane za proizvode. U tom smislu, kompanije koje projektuju po narudžbini treba da prikupe podatke o prethodno projektovanim proizvodima i identifikuju one delove koji su mogu ponovo koristiti kako bi se unapredio proces konfiguracije. To omogućava kompanijama da smanje složenost portfolia proizvoda i vremena za inženjering, kao i da unaprede preciznost specifikacije proizvoda. Ovaj rad predlaže okvir za identifikovanje i poređenje sličnosti proizvoda. Ovaj okvir (1) identifikuje najvažnije elemente proizvoda dostupne u sistemu konfiguracije proizvoda (SKP), (2) prikuplja podatke o prethodno projektovanim proizvodima u ERP sistemu, (3) identifikuje metod da uporedi proizvode na osnovu najvažnijih elemenata proizvoda i (4) postavlja IT sistem (bazu podataka) sa podacima o prethodno projektovanim proizvodima kako bi ih integrisao sa SKP-om. Predloženi pristup (okvir i IT sistem) je testiran u kompaniji koja projektuje po porudžbini kako bi se ocenila primena okvira i IT sistema. Prikupljeni su neophodni podaci iz ERP sistema kompanije i razvijen je IT sistem u excel-u, koji je integrisan sa SKP-om.

Ključne reči: *grupisanje, okvir, integracija, IT sistem, sistem konfiguracije proizvoda (SKP), sličnosti*

APPENDIX K

Complexity of Configurators Relative to Integrations and Field of Application

Katrin Kristjansdottir[1] and **Sara Shafiee** and **Lars Hvam** and **Loris Battistello** and **Cipriano Forza**

Abstract. Configurators are applied widely to automate the specification processes at companies. The literature describes the industrial application of configurators supporting both sales and engineering processes, where configurators supporting the engineering processes are described more challenging. Moreover, configurators are commonly integrated to various IT systems within companies. The complexity of configurators is an important factor when it comes to performance, development and maintenance of the systems. A direct comparison of the complexity based on the different application and IT integrations is not addressed to a great extent in the literature. Thus, this paper aims to analyse the relationship of the complexity of the configurators, which is based on parameters (rules and attributes), in terms of first different applications of configurators (sales and engineering), and second integrations to other IT systems. The research method adopted in the paper is based on a survey followed with interviews where the unit of analysis is based on operating configurators within a company.

1 INTRODUCTION

In today's business environment customers are increasingly demanding high quality customised products, with short delivery time, and at competitive prices [1]. To respond to those increasing demands, mass customisation strategies have received increasing attention from both practitioners and researchers. Mass customisation refers to the ability to make customised products and services that fit all customers' needs through flexibility and integration at similar costs to mass-produced products [2]. Configurators are used to support design activities throughout the customisation process in which a set of components and connections are pre-defined, and constraints are used to prevent infeasible configurations [3].

Configurators can be used to support different specification process at companies, which can include sales, design/engineering and/or production. Configurators can bring substantial benefits, such as shorter lead times for generating quotations, fewer errors, increased the ability to meet customers' requirements regarding product functionality, use of fewer resources, optimised product designs, less routine work and improved on-time delivery [4–8].

Configurators used to support the engineering processes are considered more complex [1,9]. However, a direct comparison of configurators to support the different applications within the same company has not been conducted. Furthermore, in configuration projects, there is usually the need for integration to IT systems, such as ERP, CAD, PLM and PIM systems. However, the literature does not address what influences it will have on the configurators complexity when integrations to other system are made.

In this paper, the complexity of configurators is determined based on parameters, or a number of rules and attributes, included in the configurators. By analysing the complexity in terms of application, configurators supporting sales and engineering processes, and in relation to different integrations, it will give more understanding of what factors influence the complexity of the configurators. The complexity of configurators is a relevant topic as it influences the performance of the system and affects the effort needed in terms of development and maintenance. Nevertheless, complexity can be both good and bad depending on whether it is value adding or not. This paper, therefore, aims to provide more understanding of factors influencing the complexity of configurators by providing answers to the following research questions (RQs):

> ***RQ 1*****:** What are the differences in terms of complexity between sales and engineering configurators?
>
> ***RQ 2*****:** What are the differences in terms of complexity when configurators are integrated to other IT systems?

To answers to the RQs, a survey followed with interviews is conducted. The results presented in this paper are preliminary as this is an ongoing study. This includes analysis based on one company where the unit of analysis is based on operating configurators within the company.

The structure of the paper is as follows. Chapter 2 discusses the literature background for the study, and Chapter 3 explains the research method. Chapter 4 presents the results of the research, and Chapter 5 discusses the results in relation to the RQs and presents the conclusion.

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2 Literature Review

This section aims to provide the background for the study. Section 2.1 discusses configurators and integrated system and provides a definition of configurators' complexity. Section 2.2 discusses the difference between configurators supporting sales and engineering processes.

2.1 Configurators and Integrated Systems

The underlying IT structure of a configurator consists of configuration knowledge representation and reasoning, conflict detection and explanation, and finally a user interface [10]. Configurators can be applied as standalone software, as well as data-integrative and application-integrative systems [11]. Data-integrative configurators can be used to avoid data redundancies, and application-integrative configurators allow for communication across different applications (e.g. CAD drawings can be generated from the output of the configurator) [11]. In terms of data integration for configurators, common sources for master data can be found in Enterprise resource planning (ERP) systems that often define a production-relevant view of the material. This is required for the assembly process, product data management (PDM) and product lifecycle management (PLM) systems, which are used to maintain production relevant data. Finally, product information management (PIM) systems are used to maintain sales-relevant data [12]. Different configurators can be integrated into terms of, for example, sales and engineering configurators [13]. Finally, configurators can be integrated into suppliers systems to retrieve the required data from the configuration processes [14].

To measure the complexity of configurators, Brown et al. [15] categorize them into three major components; (1) execution complexity, (2) parameter complexity, and (3) memory complexity. Execution complexity covers the complexity involved in performing the configuration actions that make up the configuration procedure, and the memory complexity refers to the number of parameters that system manager must remember. In this paper, the parameter complexity is considered the most important, as it measures the complexity of providing configuration data to the computer system during a configuration procedure [15]. Therefore, the article focuses on parameters complexity to determine the complexity of the configurators. The parameter complexity is determined based attributes and rules included in the configurators.

2.2 Sales and Engineering Configurators

Configurators are used to support the product configuration process, which consists of a set of activities that involve gathering information from customers and generating the required product specifications [13,16]. The product configuration process can be divided into sales and technical configuration processes [17]. The sales configuration process is concerned with identifying products that fulfil customers' needs and determining the main characteristics of the products [17]. The technical configuration process, on the other hand, is concerned with generating documentation for the product based on the input gathered during the sales phase [17]. In this article, the technical configurations are referred to as the configurators supporting the engineering processes. Another dimension of the configuration process is production configuration [18].

The challenges of configurators used to support the engineering companies are described in terms product characteristics, customer relations, and long time span of projects [19]. Further, the sales process in engineering companies can be categorized where a high-level design is made in the sales phase, and the actual design processes do not start before the sale is confirmed. Thus, sales configurators in engineering companies are often modelled on a high level of abstraction where the engineering configurators that are concerned with the actual design of the product have to include more detailed information [4]. This usually leads to higher complexity of the configurators supporting the engineering than the sales processes.

3 RESEARCH METHOD

The chosen research method for this article is survey followed with interviews. As this is still ongoing study, only one company is analyzed. However, by only including one company, it was possible to get an in-depth knowledge of the configuration setup and compare the complexity of the configurators within the same settings. The unit of analysis is based on operational configurators at the company, where a configurator is defined as a system that has its own knowledge base or product model and user interface. The company uses commercial configuration software for all of their configurations. Meaning that the same modelling paradigms are used in the company for all the configurators, which is a requirement to compare the complexity of the different configurators.

The case company introduced in the study has a world-leading position in providing process plants and related equipment for industrial use. The company has utilized configurators since 1999 and has currently 159 operational configurators, which support the product specification processes both in sales and the engineering. The company, therefore, has an extensive experience from working with configurators.

To analyse the complexity of the configurators first, a questioner was developed and reviewed several times by the research team in order to check consistency and understandability. Secondly, the questionnaire was emailed to the company, and an interview was set up. Based on the first interview it was decided that the data gathering would be conducted in collaboration with one of the project manager from the configuration team for two days. The data was gathered from internals systems and evaluated by the project manager to check accuracy and consistency.

The data was then analyzed in Microsoft Excel in relation to the RQs. First, the configurators were grouped according to processes they supported, or into sales, sales and engineering, engineering and few configurators where grouped under others. A limitation of the data is that the majority of the configurators are used to support the engineering processes (75%), and sales and engineering processes (19%) while there are few configurators used to support only sales processes (3%) and finally configurators used to support other processes are (2%). Nevertheless, the results presented are thought to provide valuable insight into the parameters complexity of configurators, while further data gathering is planned to support the findings. Secondly, the data related to the configurators integrated IT systems were grouped. In cases where there is more than one integration to the configurators they were listed under a combination of integrations, which included the following combinations: (1) CAD and ERP, (2) CAD, ERP and calculation systems, and finally (3) ERP and calculation system. This is required as the focus of the study is to analyze integrations to what IT systems result in the most complexity and therefore including combinations of integrations would give biased results.

4 RESULTS

In this chapter, the main result of the survey are presented aligned with the two RQs introduce in the paper.

Section 4.1 elaborates on the complexity of the configurators used in the sales, both in sales and engineering processes and finally only in the engineering processes (RQ 1). Section 4.2 elaborates and the complexity of the configurators in relation to integrations to IT systems (RQ 2). The integrations include ERP, CAD, calculation systems, integrations to other systems or combination of systems and finally few configurators that have no integrations. The results presented are based on data from 159 configurators that are used within on company as explained in Section 3.

4.1 Complexity in Relation to Engineering and Sales Configurators

This section provides the results in relation to the complexity based on sales and engineering configurators. Figure 1 shows the percentages of configurators used to support the (1) sales, (2) sales and engineering, (3) engineering, and finally (4) other activities.

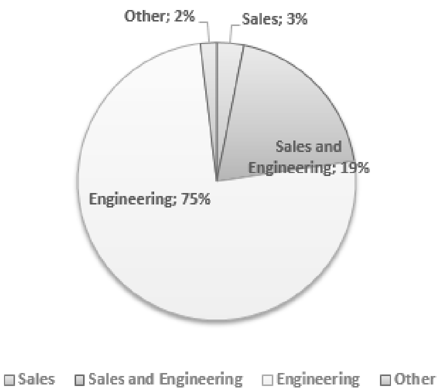
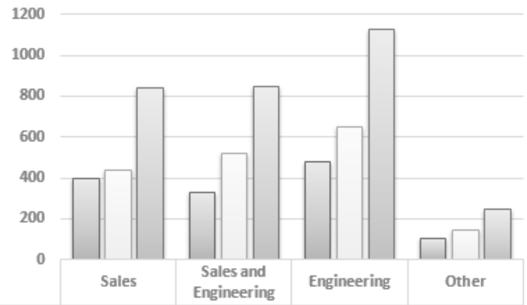


Figure 1. Percentages of configurators used to support different activities at the company.

As can be seen in Figure 1 only 5% of the total configurators support the sales processes, while 19% of the configurators are used to support both sales and engineering, 75% of the configurators are used to support only engineering, and 2% support other activities.

The complexity of the configurators used for the different activities is shown in Figure 2 in terms of average numbers of rules and attributes and total where the numbers of rules and attributes are summarized.



	Sales	Sales and Engineering	Engineering	Other
Avg. no. rules	397	329	477	102
Avg. no. attributes	440	518	652	146
Total	837	847	1129	248

Figure 2. The complexity of the configurators used to support the different activities at the company.

Figure 2 shows that in terms of rules configurators used by engineering have on average 477, while sales have 397 and configurators used by sales and engineering have on average 329. In terms of attributes, configurators used by engineering have on average the most attributes or 652, while configurators used by sales and engineering have on average 518 and sales have 440. Finally, as previously defined, the complexity of the configurators is determined based on parameters or the sum of attributes and rules. Thus, configurators supporting only engineering activities have the highest total score of complexity or 1129 while if we look at the configurators only supporting sales or sales and engineering the total score is 837 and 847 respectively. Other configurators supporting simpler tasks at the company have the lowest rate of complexity or only 248.

4.2 Complexity of Configurators in Relation to Integrations

In the company used for this study, the application of the configurators was divided according to the integrations. The integrations included the following IT systems (1) ERP, (2) CAD, (3) calculation systems, (4) combination of the above-mentioned systems, and in few case (5) other systems. Only 4% of the configurators did not have any integration, while 70% of the configurators were integrated into one of the above-mentioned systems and 26% were integrated to one or more of the systems. Figure 3 shows the percentages of integrations the different configurators have.

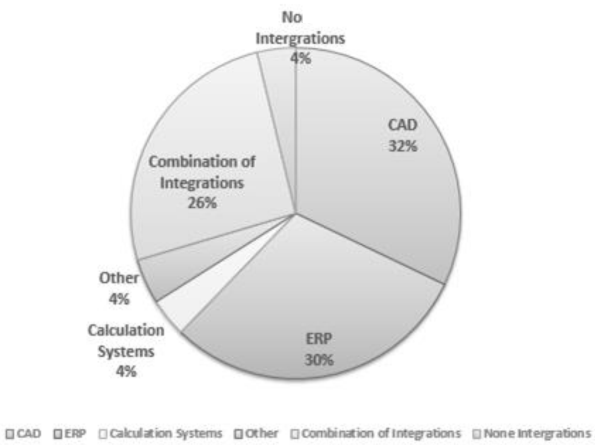
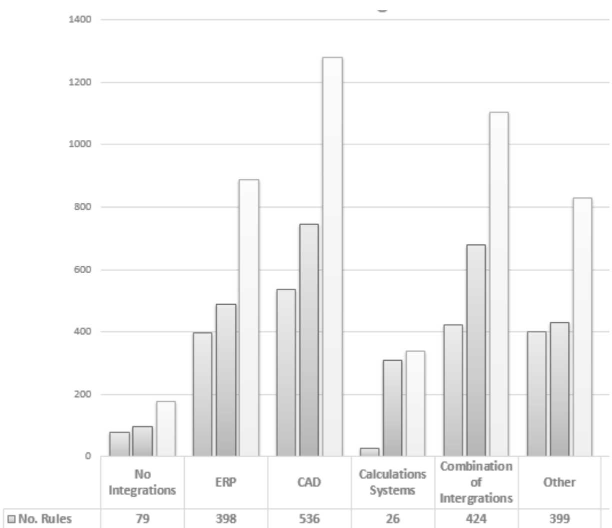


Figure 3. Percentages of integrations and combinations of integrations to different IT systems used at the company.

As can be seen in Figure 3 the majority of the configurators are intergraded to the CAD and the ERP system used at the company or 32% and 30% respectively while only 4% are integrated only to calculation systems or other IT systems used at the company. Finally, 26% of the configurators are integrated to more than one of the above mentioned IT systems.

The complexity of the configurators integrated to the different IT systems is shown in Figure 4 in terms of average numbers of rules, attributes and then the sum of the average rules and attributes.



	No Integrations	ERP	CAD	Calculations Systems	Combination of Intergrations	Other
No. Rules	79	398	536	26	424	399
No. Attributes	98	489	744	310	679	430
Total	177	887	1280	337	1103	829

Figure 4. The main characteristics of the configurators integrated to different IT systems at the company.

From Figure 4 it can be seen that in terms of both attributes and rules the configurators integrated to CAD system score the highest in terms of complexity. Configurators that have combinations of integrations, or more than one integration, have the second highest score. That can be explained by the fact that in most cases that also includes integration to a CAD system. By looking into configurators that have integrations to calculation systems it can be seen that they have the fewest rules, may be due to the calculations being performed within another system. Finally, it can be seen that configurators with no integration have the lowest complexity factor.

5 DISCUSSIONS AND CONCLUSIONS

This study provides insights into the complexity of the configurator where the complexity is analysed based on parameters, which consists of numbers of attributes and rules. The complexity is analysed first based on the field of application (sales and engineering) and then based on integrations to different IT systems. The results provided in the present article aim to contribute to the field of configurators' complexity and the factors influencing them. This is an important topic not only for the research community but also for practitioners. The results show that a difference can be found in relation to the complexity by analysing the field of application and different kind of integrations.

The first research question in this study aims to identify if there is any relationship between the complexity of the configurators and the field of applications. Our analysis shows that the configurators that are only aimed at supporting the engineering processes have the highest parameters complexity. However, there was only a slight difference between the complexity factor of the configurators only used to support sales and the configurators used to support both sales and engineering.

The second research question aims to analyse the relationship between integrations and complexity of the configurators. In the literature, it is discussed how configurators are integrated to different IT systems, e.g., [11–14,18]. However, the literature does not explain to what extent the integrations to different IT system will influence the complexity level of the configurators. In this paper integration to CAD, ERP and calculation systems are analyzed. The result shows out of the above mention IT systems the complexity of the configurators integrated to CAD systems is the highest. This can be supported by the fact that in order to generate CAD files from the configurators, they have to be able to support the detail design including all the product dimensions, which will increase the complexity. Thus, configurators integrated to CAD systems can be defined as product design configurators, which support the engineering processes where the complexity can be anticipated to be higher even though not integrated into a CAD system. Configurators integrated to ERP systems scored as the second highest while configurators integrated to calculation systems scored the lowest out of those systems. When configurators are integrated to calculation a system, the reason is usually that the calculations being too complex or specialized to handle within the configurator. This supports the fact that configurators integrated to calculations systems have very low number of rules and thereby they also have low parameters complexity.

The result presented in the paper is based on answers and interviews from one company. This is thought to provide valuable insight as by studying one company an in-depth knowledge about the configuration setup could be accessed. Furthermore, it allows comparison of the complexity as all the configurators are developed based on the same commercial configuration platform. More companies will be contacted in the future, to enable cross-functional comparison.

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