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Transitioning towards a modular setup through architectural focus

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MODULAR PRODUCT AND MANUFACTURING SYSTEM PORTFOLIOS

TRANSITIONING TOWARDS A MODULAR SETUP
THROUGH ARCHITECTURAL FOCUS

BY
MORTEN SKOGSTAD NIELSEN

DISSERTATION SUBMITTED 2022

AALBORG UNIVERSITY
DENMARK

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Transitioning towards a modular setup through architectural focus

by

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Dissertation submitted

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CV

Morten Skogstad Nielsen was born in Randers, Denmark. With a background as a military police officer in the Danish armed forced, he started his academic career in 2014 with a B.Sc. in Global Business Engineering from Aalborg University. Thereafter, he received a M.Sc. in Operations and Supply Chain Management, also from Aalborg University. Upon the finalization of his M.Sc. degree in 2019, Morten became a part of both the Mass Customization research group from Aalborg University and the case company in which this PhD project is made. During his PhD project, he made a research collaboration with University Ecole Des Mines de Saint-Etienne in France, which he visited on multiple occasions.

ENGLISH SUMMARY

This thesis presents the results of a three-year long research project which has been conducted in a collaboration between the department of Materials and Production at Aalborg University and an industrial partner. This project takes its outset in the overall practical problem: how to select what to modularized when looking across: market, product and manufacturing. This problem is highly relevant as the industrial partner for some time has experienced an increased demand for more customized products with shorter lead times at a cost close to mass produced products. This has led the industrial partner to embark on a journey of creating modular products and manufacturing systems. There is a large knowledge-base on: modular product development, product and production platforms, reconfigurable manufacturing systems, and co-development. However, this knowledge is limited to the development of specific systems and is not concerned with the pre-development-phase where development projects are selected from a list of potential projects in a portfolio management process. To address these challenges with selecting which development project to conduct, this research project utilizes a framework for conducting design science research in information system. Design science research is chosen as it combines design science and behavioral science and has therefore been found effective when conducting research in operations management. By taking an outset in design science research, this project has improved some of the decision-making processes by designing multiple novel artifacts using case-studies, literature review, and axiomatic quantitative modelling. The contributions of this research project are documented in six appended papers which has been summarized in this thesis. Through a multi-case study and a literature review it was found that information management was a critical challenge both in the selection of projects and in the development projects them self. Firstly, this leads to the development of a decision support system that is extracting near-real-time data from multiple IT systems, which was used as the foundation for the remainder of this research project. Secondly a method for visualizing the complexity of a portfolio of products through the number of existing different system elements and combinational opportunities between these was created. This is followed by method to utilize the decision support system to quantitatively link specific system element of a product architecture to a specific product feature. Finally, a method for modelling various master data that allows for the creation of different scenarios to be created in the product domain and presenting the expected result in manufacturing is presented.

DANSK RESUME

Denne PhD afhandling er resultatet af et tre årigt forskningsprojekt som er lavet i et samarbejde mellem Institut for Materialer og Produktion på Aalborg Universitet og en industriel samarbejdspartner. Dette projekt udspringer fra et overordnet praktisk problem: Hvordan vælger man hvad der skal gøres modulært når man kigger på tværs af: markedet, produktet, og produktionen. Denne problemstilling er yderst relevant for den industrielle partner der gennem noget tid har oplevet en større efterspørgsel på mere kundetilpassede produkter som leveres hurtigere og til en pris der matcher produkter der er masseproduceret. Denne efterspørgsel har sendt virksomheden på en rejse mod at udvikle modulære produkter og produktionssystemer. Der findes meget viden og information omkring: udvikling af modulære produkter, produkt og produktions platforme, rekonfigurerbar produktions systemer, og co-development. Men denne viden er begrænset til udviklingen af enkelte of specifikke produkter eller produktions systemer og omhandler ikke de forud gående beslutninger omkring udvælgelsen af hvilke udviklingsprojekter der skal prioriteres frem for andre gennem en portefølje sætnings proces. For at håndtere dette problem med at prioritere hvilke udviklingsprojekter der skal i gangsættets bruger dette forskningsprojekt design science research som er udviklet til at forskning i informationssystemer. Design science research er en kombination af design science og behavioral science og er derfor også brugbar inden for forskning i operations management. Ved at tage udgangspunkt i design science research og brugt metoder som: casestudier, litteratursøgninger, og kvantitativ modellering har dette forskningsprojekt udviklet flere værktøjer til at understøtte disse beslutningsprocesser. De videnskabelige bidrag genereret på baggrund af dette projekt er dokumenteret i seks videnskabelige artikler som er vedhæfter og opsummeret i denne afhandling. Gennem casestudier, og litteratursøgninger er blev det identificeret at vidensdeling og generering af viden er en kritisk problemstilling, både i udvælgelsen og i udførslen udviklingsprojekter. Dette førte til udviklingen af et decision support system som automatisk opdaterer i near-real-time fra forskellige IT systemer og som blev brugt som fundament for det resterende forsknings projekt. Herefter blev en metode til at visualisere kompleksiteten i en portefølje af produkter udviklet. Dette værktøj visualiserer kompleksiteten ved at identificere antallet af unikke komponent varianter og antallet kombinationsmuligheder imellem dem for en given produktportefølje. Herefter blev en metode til kvantitativt at identificere hvilke produktkomponenter der påvirker specifikke produkt funktioner præsenteret. Til sidst blev en metode præsenteret som modellerer forskellige stamdata der tillader genereringen af forskellige scenarier i produktporteføljen og som viser den forventede effekt på produktionen.

ACKNOWLEDGEMENTS

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I would further like to extend my deepest gratitude to my company supervisor Bjørn Langeland for the continuous support, guidance, and difficult questions I have received throughout the entire three years of this research project. Furthermore, I would like to say thank you to my managers Director Kjeld Schmidt and Director Jakob Vernersen for opening doors within the case company and allowing me to go where the research directed me. In general, I would like to thank the case company for allowing me this opportunity and for the openness and willingness they have shown throughout the entire organization when engaging in this PhD project.

Most importantly, I would like to thank my girlfriend and life-partner Camilla Kjær Skovgaard. I could not have completed the tremendous task of this PhD project without your support, love, and least of all patience. Thank you for listening with curiosity when new things were learned and thank you for the encouraging words when these were needed.

Thank you.

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C. Skogstad, M., Andersen, A., Brunoe, T. D., Nielsen, K., (2022). Data Driven Decision Making When Transitioning Towards a Modular Setup. SysInt 2022. Springer proceedings (Accepted)

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F. Nielsen, M. S., Brunoe, T. D., Andersen, A., & Nielsen, K. (2022). Scenario-based Portfolio Management: Modelling Future Cost and Effect on Manufacturing. Procedia CIRP, 107, 1509-151

CHAPTER 1. INTRODUCTION

Doing business, at its core means generating profit by serving customers with either services or products. Looking closely at businesses, there are as many different ways of doing business as there are businesses. There are however similarities in the overall approach to doing business. These overall approaches to doing business change like paradigms over time depending on the customer requirements and the competitive landscape of other business serving the same group of customers. For manufacturing companies, these shifts in< paradigm as described by Koren (2010) and ElMaraghy et al. (2013) in figure 1 have forced manufacturing companies to undergo vast changes in their approach to doing business. With these changes, manufacturing companies are facing new challenges that require them to seek new solutions.

> “If one is truly to succeed in leading a person to a specific place, one must first and foremost take care to find him where he is and begin there”

So said the famous Danish philosopher Søren Kirkegaard. He might not have thought about business, product, or manufacturing system portfolios when he spoke those words, but they are just as true in such a context. Therefore, transitioning from one paradigm into another requires a deep understanding of the current situation.

1.1. MOTIVATION

One of the earliest and most famous examples of shift in paradigm was the introduction of mass production when Henry Ford introduced the Model-T which was produced in high volume with minimal variety (Batchelor, 1994). This change in paradigm allowed Henry Ford to change his business model to one with focus on offering customers what have since become the well-known benefits of mass production; lower cost, shorter delivery times, and improved quality. By 1914 the transition to mass production had reduced the production time of one car from 12,5 hours to 93 minutes while using less manpower and having reduced the cost to one fifth. What is noteworthy in this case is the size of the Ford company before the transition and thereby the amount of carryover into the new paradigm. In this context carryover means both existing products, existing manufacturing equipment but also the organizational setup and company culture. When companies today decide to change their business and transition into a new manufacturing paradigm like mass customization or modularization the complexity is immense (Andersen, R. et al., 2019; Perona & Miragliotta, 2004). It is however a necessary change for many companies as the proliferation of product variants required by customers can be observed in nearly every market as a result of the move from a one-size-fit-all paradigm to a market-size-one paradigm (Koren, 2010; Pine, B. J., 1993).

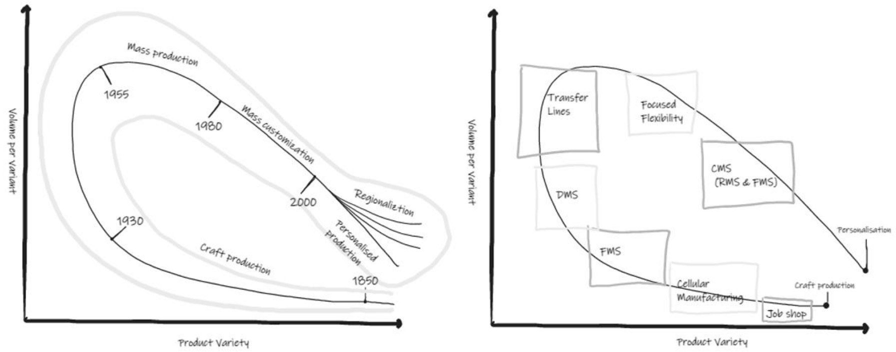

Figure 1.1: Left: Depiction of the evolution of the manufacturing paradigm as illustrated by Korens (2010). Right: Depiction of the manufacturing system evolution as illustrated by ElMaraghy et al. (2013).

Achieving a business setup where individual customers are served with unique solutions require manufacturing companies to master both the development of modular product architectures and manufacturing system architectures which is still a challenge for many today. Furthermore, most companies are not only offering one type of product meaning that one modular product architecture with its corresponding manufacturing setup is often only part of a portfolio og products and manufacturing systems. When manufacturing companies are faced with the challenge of modularizing across multiple product and manufacturing architectures other problems such as information sharing, planning, and organizational problems further complicates things (Bruch & Bellgran, 2014). These challenges only increase when existing products and manufacturing systems that are not developed with reconfigurability in mind are brought into the equation. The following sections introduce the manufacturing company in which this project is made in collaboration with. They furthermore provide a background for subjects related to this project and finally a state-of-the-art is presented.

1.2. INDUSTRIAL PARTNER

This industrial PhD project is made in collaboration between Aalborg university and an industrial partner with a long history of working on research topics related to this project. This long focus on research in topics related to this project makes it a suitable collaboration partner for this project. The industrial partner is a large-scale manufacturing company who is world leading within its field partly because of its long history of having focus on quality and innovation.

The company is operating on both business-to-business and business-to-consumer markets. On the business-to-business markets it is mainly engineer-to-order (ETO) products for global OEM customers being produced in high volumes over a longer period of time. On the business-to-consumer markets it is mainly produce-to-stock where products are sold globally through wholesalers to the end customer. The company´s product portfolio consists of several hundred thousand variants spread out over more than 25 product families. The company is however, as displayed in figure 1.2 experiencing challenges with an increasing internal complexity that has grown dramatically for the last decade. This internal complexity is the result of multiple factors. Some of them being long lifetime on products, frequent launches of new products, and product variants with no governance for reusing: components, designs, or technologies across time and product families.

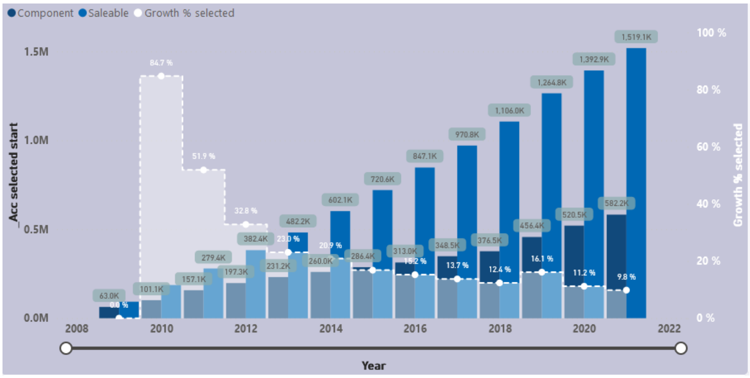

Figure 1.2: Annual growth in components and sellable products within the case company over a fourteen year period.

Inspired by the successful implementation of a modular or platform-based approach to product and manufacturing system development in other industries the company have made a strategic initiative to transition from a mainly mass production setup into one with more individual products in certain areas of the portfolio. This is done while still improving the reuse of components, design, and technologies across the entire portfolio where this is possible and does not decrease the quality and value delivered to the customers. In doing so, the company expect to eventually gain the benefits similar to those reported by other manufacturing companies that has transformed into a modular or platform-based approach, such as reduced internal complexity, reduced product cost, reduced time-to-market, and more innovation. This research project is initiated to support this transition within the case company with novel tools and methods to tackle the complex challenges.

1.3. BACKGROUND

As a response to the complex dilemma of producing an ever-increasing amount of product variants while still maintaining cost similar to mass production, different concepts emerged during the late 80´s. Two of these concepts is known as mass customization, introduced by Davis (1989), and modularization which has a broader definition within academia (Gershenson et al., 2003). As these concepts lay the foundation for many modern-day initiatives in both industry and academia, these must first be explained.

MASS CUSTOMIZATION AND MODULARIZATION AS CONCEPTS

The concepts of mass customization and modularization are two similar ideas of how manufacturing companies can approach the challenge of meeting individual customer requirements while gaining the benefits of mass production. There are numerous definitions of both mass customization and modularization which are variations covering and overarching approach to doing business. Silveira et. al. (2001) suggest that mass customization can be defined either broadly or narrowly. The broad initial concept of mass customization was first introduced by Davis (1989) as the ability to deliver customer specific products and services through high process agility, flexibility and integration (Eastwood, 1996; Hart, Christopher WL, 1995; Pine, I. I. et al., 1993). Other authors define mass customization as a system that delivers a wide range of products and services that meet specific needs of the individual customer at a cost near to that of mass products by utilizing information technology, flexible processes and organizational structures (Kay, 1993; Kotha, 1995; Ross, 1996). Similar to mass customization, there are numerous definitions of modularization between different authors, industry, applications, and research field (Gershenson et al., 2003). Gershenson et al. (2003) made an extensive literature review on product modularity where authors defined modularity differently depending on specific context but with some consensus. Therefore Gershenson et al. (2003) summarized modularity as having three fundamental elements: “The independence of a module’s components from external components, the similarity of components in a module with respect to their life-cycle processes, and the absence of similarities to external components”. In a literature review on modularization Nielsen et. al. (2021) found that most research on modularization presents specific design methodologies that take an offset in product modularization and it´s relation to the market and manufacturing domains. In the mass customization literature it is commonly acknowledged that the three organizational capabilities: 1) “Solution space development”, where the focus is on developing product variety that is in alignment with customer requirement, 2) “robust process design” where the focus is on maintaining and developing the capability of delivering a constantly changing variety of products at low costs through the reuse of manufacturing solutions, and 3) “choice navigation” where the focus is on the ability to support customers in choosing or configuring the specific product that are fulfilling their requirements (Salvador et al., 2009). Within the case company, the concept of modularization is the most commonly used. This is thought to be for historical reasons as engineers and developers have been trained within the field of System Engineering where the general term modularization is used. Therefore, to minimize the chances of conceptual misunderstandings and ensure the best possible collaboration and research contribution this research project builds upon the concept of modularization.

WHAT IS A PLATFORM

Product and manufacturing system platforms are frequently mentioned together with mass customization and modularization when discussing how to handle product variety. The term platform is however not new as it has been used in a product and production context as far back as the 16th century with the meaning “a design, and idea, or a pattern or model” (Baldwin & Woodard, 2009). A large number of definitions that differentiate on levels of abstraction and specificity exist today (Michaelis, M. et al., 2010). The level of abstraction is spanning from wide descriptions including some parts of a company´s activities to focused descriptions focusing on the physical products and parts. In the product domain Robertson and Ulrich (1998) uses a wide definition by defining a product platform as “A Collection of assets that are shared by a set of products, including components, processes, knowledge, as well as people and relationships”. Whereas Meyer and Lehnerd (1997) uses a more focused definition by defining a product platform as “a set of subsystems and interfaces developed to form a common structure from which a stream of derived products can be efficiently developed and produced”. Likewise, Ulrich & Eppinger (2011) describes a platform as “a collection of assets, including component designs, which are shared by the products of a product family”. On the level of specificity Michaelis et al. (2010) argues that “a platform can penetrate all system levels and domains without imposing layers in a system hierarchy of products, manufacturing systems and manufacturing processes”. In the manufacturing domain Meyer and Lehnerd (1997) expand their definition of a platform to include commonality in processes and production. Sanchez (2004) continues to argue that from a manufacturing perspective, a platform also includes all supporting processes such as manufacturing and supply chain activities. Within the case company and throughout this research project a platform is defined as:

“A platform is the agreed and documented foundation used to design, produce and procure solutions. This includes e.g., product and production architectures, production equipment, product and production modules, design guides, tools templates and instructions.”

Much literature exists on the topic of product platform and modular architecture development. Gershenson et al. (2004) defines four categories of design methodologies: step-by-step measure and redesign methods, checklist methods, design rules, and matrix manipulation methods. The checklist and design rule methods are usually simplistic, proactive, and easily applied but inefficient and lack the ability to create specific or complete design results. The matrix manipulation methods are information intensive but allow for guided component/module manipulation resulting in more specific outputs. The step-by-step measure and redesign methods are often part of the matrix manipulations methods as these require the component/module manipulations is done one at the time based upon a modularity measure. Within the case company a modular architecture is defined as:

"A modular architecture includes one or more modules, allowing substitution of the modules without making compensating changes to other elements or interfaces."

And continues to define a module as:

"A module is a system element appointed based on module drivers. A module has a specified and stable interface enabling reuse or substitution without affecting the remaining system."

PORTFOLIO MANAGEMENT

Portfolio management is traditionally referred to as a dynamic decision-making process where a list of active and potential product development projects is updated and revised based on the resources available (Cooper, Robert G. et al., 1997). To mitigate risk and improve overall performance, it is important that this selection process accomplishes a balance of projects that could be a potential breakthrough and turn into a strategic competitive advantaged with project with high likelihood of success but only less reward (Cooper et al., 1997). Portfolio decisions are critical to a company´s overall performance. If projects that are not in line with the company´s strategy is selected or if to many projects are conducted simultaneously with reluctancy to kill projects the consequences for a company can be immense (Chao & Kavadias, 2008; Cooper, Robert et al., 2001). To ensure the strategic alignment and a long-term perspective the development projects cannot be evaluated based on individual characteristics but must be evaluated in context of the existing product and production portfolio and strategic goals (Kester et al., 2009).

1.4. STATE-OF-THE-ART

From the introduction and description of the industrial partner it is evident that the challenges addressed in this thesis revolves around the development of an integrated portfolio of modular product and manufacturing system architectures. Because this project is conducted in collaboration with an industrial partner with existing portfolios the focus will be on utilizing existing data and information when transitioning from a more traditional setup towards a setup with modular product and manufacturing systems. Therefore the state of the art section will investigate the current knowledge base for quantitative tools and methods used within the general concepts of product and manufacturing system development, integrated portfolio management and product data modelling.

PRODUCT AND MANUFACTURING PLATFORM DEVELOPMENT

Much literature exists on the topic of product platforms and product family development (Jiao et al., 2007). Gershenson et al. (2004) defines four categories of design methodologies: step-by-step measure and redesign methods, checklist methods, design rules, and matrix manipulation methods. The checklist and design rule methods are usually simplistic, proactive and easy applied but inefficient and lack the ability to create specific or complete design results. The matrix manipulation methods are information intensive, but allows for guided component/module manipulation resulting in more specific outputs. The step-by-step measure and redesign methods are often part of the matrix manipulations methods as these require the component/module manipulations is done one at the time based upon a modularity measure. Within the matrix manipulation and step-by-step categories different quantitative methods exist, such as: fuzzy goal, mixed integer, and linear programming is used with the overall objective of designing a near optimal product platform. Here Tyagi et al. (2012) propose a method where fuzzy goal programming is used to identify one or more platforms. Similarly Ben-Arieh et al. (2009) propose a method for utilizing linear programming to identify multiple platforms across product families. Other mathematical methods utilizing similarity indices are presented by Anggraeni et al. (2013) and Galiza et al. (2019). Galizia et al. (2019) introduce a decision support system for product platform selection and design in high variety manufacturing and Anggraeni et al. (2013) use similarity indices for architecture comparison in the early conceptualization phase when developing new product variants. Qu et al. (2011) propose an embryonic product platform method where graph-theory and a generic algorithm is used for platform identification. Zhang et al. present the generic bill of functions, materials and operations method where information from all three domains are combined to assist the achievement of product customization from a holistic view. Within the same category of matrix manipulations and step-by-step methods are some more qualitative methods. Here Thumm and Goelich (2015a) present a method for utilizing product architecture drivers to develop standardized modules in a brownfield environment. Ulonska et al. (2016) present a method using product and variant maps to structure and analyze product variant information to create future configure-to-order strategies.

Manufacturing platform development is often done in collaboration with product platform development thereby conducting co-platform development. Most of the literature within the domain of platform-based co-development can be categorized as checklist and design rules methods as described by Gershenson et al., (2004). This means that they are typically simplistic and lack the ability to create specific or complete results. Here Michaelis & Johannesson (2011) argue that the manufacturing paradigm of a manufacturing company should affect the co-platforming setup a company should use. Four different setups are described and discussed based on two examples. Gedell et al. (2011) present an integrated class model which focuses collecting and combining information on interfaces and interactions between product and manufacturing. It is argued that this should help the interdepartmental development in co-development projects. ElMaraghy & Abbas (2015a) defines co-platforming as “the synthesis of manufacturing and assembly systems by mapping of products platform feature” and presents a method where product features and manufacturing capabilities are described with vectors in a design matrix like formulation. Michaelis, Marcel T. & Johannesson (2011) identified two types of approaches for integrated development of product and production platforms: 1) the first type is connecting the manufacturing process to the product structure which focuses on manufacturing processes. 2) The second type is focusing on their common characteristics and looks at products and manufacturing as co-equal systems and elaborate on the interactions between products and manufacturing systems. Bossen et al. (2015) argue that models and visualization techniques is an important aspect of both platform-based production development and platform-based co-development. Such a model is introduced by ElMaraghy et al. (2015b) that uses vectors to model the relationship between an automotive cylinder block and the required manufacturing equipment. This example fits well with what Andersen A. et al. (2015) concluded based on an extensive literature review that the majority of the methods for designing reconfigurable manufacturing systems found in literature focuses on the lower levels of the manufacturing hierarchy. Andersen et al. (2019) continue to conclude that coordination between product and manufacturing should be uplifted to joint design due to tasks being highly dependent between design domains. Brunoe et al. (2020) presents a method for establishing a model that could link a portfolio of products or components to a portfolio of processes and equipment. This could potentially automate the matching of components to equipment and thereby creating a more detailed picture to be used in future development projects. This however would require a database with the right company specific ontology to developed and implemented. Hanafy & ElMaraghy (2017) propose a mathematical model co-planning the development product platforms and their assembly systems. Levandowski et al. (2015) presents a two stages model that enables design reuse in an Engineer-to-order setup by creating a two-layer model (architectural and scalable) in order to cope with changing parameter values. Finally, Michaelis & Johannesson (2011) characterize two different paths from dedicated to platform-based co-development. This is done by analyzing two manufacturing setups and discussing how these interacts with the products being produced in these.

INTEGRATED PORTFOLIO MANAGEMENT

As much literate exist on product platform development, manufacturing platform development, or co-development, as scarce is the literature on developing portfolios of these. This could be seen as counter intuitive as the development of any product platform or manufacturing platform must be described in a business case and selected from a list of other potential development projects in a portfolio management process before being initiated as a development project. Bruch and Bellgran (2014) identified some critical challenges in performing integrated portfolio management. Some of the main challenges is the introduction of a production system portfolio and the previous focus on comparing R&D to manufacturing operations and not the manufacturing development. They continue to propose a conceptual model of integrated portfolio planning of product and production systems. Andersen, A. et al. (2016) concluded that by introducing the concept of reconfigurable manufacturing systems companies are forced to deal with several of the challenges identified by (Bruch & Bellgran, 2014) to perform integrated product and production system portfolio management. Janne Mämmelä et al. (2022) analyzed the difference between the technical aspects of product family development and the business aspects of product portfolio management and suggest how a combination of best practice of both aspects can prove superior. Nieuwmeijer & Lutters (2022) presents a framework for product portfolio development where the current as-is portfolio is mapped to create a to-be portfolio from a technical perspective. Even though Mämmelä et al., (2022) and Nieuwmeijer & Lutters (2022) are not considering the link to manufacturing, these are relevant as Nieuwmeijer & Lutters (2022) framework for mapping the technical solutions of the current product portfolio could be combined with the findings of Andersen, A. et al. (2016). Having mapped the current technical product and manufacturing systems solutions then must be linked to the portfolio setting process as described by Mämmelä et al. (2022).

CHAPTER 2. RESEARCH OBJECTIVES

Based on the introduction and state-of-the-art it is evident that manufacturing companies could potentially benefit from transitioning into developing a portfolio of modular and platform-based products and manufacturing systems to cope with the trend of growth in product variety and complexity. As the background and state-of-the-art found, much of the existing knowledge on modular and platform-based product and manufacturing system development revolves around tools and methods used in specific development projects. No existing knowledge was found on the process of selecting specific development projects from a list of potential development projects being defined as portfolio management. All changes to a portfolio (both product and manufacturing) are made through development projects, hence, if manufacturing companies which to transition into developing modular and platform-based portfolios, this change takes its offset in the portfolio management process. However, because the current knowledge-base on this subject is limited, tools and methods to support an portfolio management process selecting the correct development projects in order to efficient transition from traditional product and manufacturing system architectures into modular and platform based architectures is needed.

Therefore, an important element of the research presented in thesis is to generate new knowledge through relevant research contributions as well as supporting the use of practical applications. This research is therefore based on the hypothesis: A competitive portfolio of products and manufacturing systems can be obtained by modeling and managing customer requirements, modular products and manufacturing architectures in an integrated long-term perspective.

Based on this hypothesis the objective of this thesis is:

`Develop concepts and methods for developing and managing a portfolio of products and manufacturing system architectures based on a long-term and full-cost perspective, to accommodate future requirements for product variety and shorter product life cycles´.

This thesis addresses the research objectives by answering a series of research questions. These research question set the frame for this research and support the individual research activities within this PhD project.

RQ1. What challenges emerge when manufacturing companies transition from a traditional to a modular and platform based product and manufacturing development setup?

This RQ is related to the objectives by seeking to clarify which challenges the case company is experiencing during the design and development of new products and resulting manufacturing setup. The case company is conducting co-development of products and manufacturing systems and it is therefore possible to investigate some of the challenges in a real-life case to create empirical data on the subject.

This RQ has been answered through paper A which is based on case research and through paper B which is a systematic literature review. For paper A, the case research method was chosen because it is a well proven method for building theory in an industrial context and because the phenomenon can be studied in its natural settings. Furthermore, the case research method allows the much more meaningful questions of *why,* rather than just *what* and *how* (Benbasat et al., 1987; Voss, Tsikriktsis et al., 2002). For paper B a systematic literature review was chosen because it is widely acknowledged as a method of expanding the knowledge of a specific research field (Hart, Chris, 1998; LEVY & ELLIS, 2017; Snyder, 2019). These methods were chosen to answer RQ 1 because of their exploratory nature which was found important in the early descriptive stages of this research project.

RQ2. How is it possible to quantitatively model the relations between current market requirements and the existing product and manufacturing system architectures in terms of cost and performance?

This RQ is related to the objectives in two ways. Firstly, it must be identified what data is required to provide sufficient information within each of the three domains: market, product, and manufacturing to quantitatively describe these individually. Secondly, it must be described how can these data be modelled in order to describe the interrelations between the three domains.

This RQ have been answered through papers: B, C, D, and E. Firstly, paper B is based on a systematic literature review which was chosen for its ability to identify existing methods and expand the existing knowledge within the research field (Hart, 1998; LEVY & ELLIS, 2017; Snyder, 2019). Secondly, paper C utilize action research and data management methods to identify and model the required data to describe the: market, product, and manufacturing domains individually. Action research was chosen because of the possibilities in the interaction between the researcher and environment in which this research project was made. Finally, paper D and E uses quantitative data modelling methods to develop the novel artefact as an to answer research question 2.

RQ3. How can the model developed in RQ 2 be used to create and validate different portfolio scenarios in terms of expected cost and performance?

This RQ is related to the objectives by investigating how all the previously identified and transformed data can be used to support the development of modular products and manufacturing architectures by creating and testing different scenarios.

This RQ have been answered through paper F which is based on design science and quantitative data modelling. Design science was chosen because of its focus on developing novel artifacts to solve problems or improve existing process within the application domain (Hevner & Chatterjee, 2010). Quantitative modelling was used within the design cycle with continuous evaluation within the design team and through the relevance cycle between the design science and the environment.

CHAPTER 3. RESEARCH DESIGN

A central aspect of this PhD project is the creation of new knowledge about integrated product and manufacturing system portfolios with both theoretical and practical implications. With the limited amount of existing research on the subject and the continuous difficulties for manufacturing companies in implementing integrated portfolios new concepts, tools, methods, models, and theories extending the state-of-the-art are needed. In particular, the tools and models required for mapping the existing product and manufacturing portfolios as found a necessity in the state-of-the-art. Creswell & Creswell (2017) refer to research design as an overall plan and involves the intersection of three components: philosophy, strategy, and specific methods. This chapter will therefore describe these three components in detail and how they are reflected in this research.

3.1. SCIENTIFIC PARADIGM

Researchers will adopt different philosophical worldviews, which will constitute how they make decisions regarding the design of their research (Creswell & Creswell, 2017). A researcher's worldview is shaped by their general orientation about the world, in which discipline they have studied, and past research experience. The worldview of the researcher will often lead to preferring either qualitative, quantitative, or mixed methods in their research (Creswell & Creswell, 2017). Four philosophical worldviews are presented: postpositivism, constructivism, advocacy/participatory, and pragmatism.

This research project is grounded in a pragmatic worldview as it is described as arising out of situations, actions and consequences. This is suitable because this research project is an industrial PhD which is grounded in real situations in the industrial partner, and it is very much in line with the personality of the researcher. Furthermore, a researcher with a pragmatic worldview is not committed to any one specific philosophy and therefore instead of focusing on methods, emphasize the research problem and utilize all available approaches to understand the problem. This way of focusing on the problem at hand and utilizing all available means to understanding it is imbedded within the researcher based on his previous career and the problem-based learning methodology utilized at the university in which he obtained his bachelor and master's degree. As most research grounded in pragmatism this research will also be a mixed method as both quantitative and qualitative method are used to generate new knowledge within the problem domain identified.

3.2. RESEARCH METHODOLOGY

Based on the overall objectives of this research project, which are to develop new knowledge within the research field while still creating tools and methods which can be used to solve actual problems in the case company, the design science research methodology is used (Hevner, Alan & Chatterjee, 2010b). Hevner & Chatterjee (2010) define design science research as follows:

"Design science research is a research paradigm in which a designer answers questions related to human problems via the creation of innovative artifacts, thereby contributing new knowledge to the body of scientific evidence. The design artifacts are both useful and fundamental in understanding the problem."

Based on this general description of design science combined with context and scope of this PhD project, design science research is found to be a suitable research framework in which to structure the activities within this project.

It is imperative that research conducted using design science is only relevant and justified when the result is usable and affecting the organization in which is intended. Having traditionally been used in research within information system, design science have also been found successful for doing research within operations management (Dresch et al., 2019). Organizations and their management are studied through behavioral science and therefore Hevner & Chatterjee (2010) argues that the two complementary but distinct paradigms (behavioral and design science) are both involved when acquiring new knowledge through design science research. To improve the connection between the two paradigms and the usability of the artifact created through design science research, Hevner & Chatterjee (2010) present seven guidelines outlined in the table below.

Table 1: Seven guidelines presented by Hevner & Chatterjee (2010) and their implications on this project.

Guideline	Project implication
Design as an Artifact	Design science must product a viable artifact. Several artifacts have been produced and presented in papers C, D, E, and F.
Problem relevance	The objective is to develop solutions to relevant problems. This has been ensured through case research and literature reviews, identifying important problems.

Design evaluation	The design of an artifact must be rigorously evaluated. This has been done through workshops, continuous collaboration with stakeholders, and data management methods.
Research contributions	Effective design science must provide clear and verifiable contribution. These contributions have been made through papers and conference presentations.
Research rigor	Design science relies on the application of rigorous methods. This has been assured through literature reviews before designing and evaluating the presented artifacts.
Design as a search process	The design of an artifact required the use of all available means. This has been assured through searching the existing knowledge base and close collaboration with the case company and external research environments.
Communications of research	Design must be presented effectively. This has been ensured through scientific papers, conferences, workshops, and presentations within the case company.

When using design science as framework for conducting science, there is no specific process to follow, however three design science research cycles as presented in figure 3 exists (Hevner, 2007) Firstly, the relevance cycle connects the contextual environment of the project with the design activities. Secondly, the rigor cycle bridges the design activities with the existing scientific knowledge base within the research domain. And finally, the central design cycle iterates between the core activities of creating and evaluating the artifacts and processes of the research project.

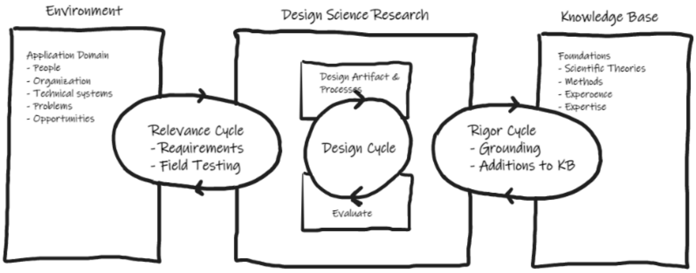

Figure 3: The three cycles of design science research (Hevner, 2007)

Environment: Because this research is made in close collaboration with a case company as an industrial PhD, the integration with the application domain has come naturally. This is because the researcher has been an integral part of the case company, allowing interaction with: people, organization, and technical systems without limitations or restrictions. This interaction has been realized by allowing the researcher to participate in all relevant projects conducted within the case company during the period of the research project. Furthermore, the researcher has been given an unprecedented level of access to IT system and data across the full organization. By having the interaction with multiple projects while having unprecedented level of access to data and information, the identification of highly relevant problems and opportunities has been made possible (Hevner & Chatterjee, 2010).

Design cycle: The design aspect of design science research consists of two core activities, developing and evaluating. The design methods have been similar, but not identical, for the four artifacts presented in this thesis. The design methodology used for the artifact presented in paper C was done by first reengineering the data structure of the IT systems within the case company and rebuilding this in an external relational database. This was consistently evaluated by recreating transactions from the IT system from which the data originated in the external database and comparing result. The design methodology for the artifacts presented in papers: D, E, and F was done by an iterative process where various designs were tested and evaluated in small cycles internally in the design team before being evaluated with subject matter experts (Hevner & Chatterjee, 2010).

Relevance cycle: Design science research is motivated by solving problems or improving process in a specific application domain. Thus, the relevance cycle provides the requirements and the acceptance criteria for the research. The requirements and acceptance criteria for this research was identified through action research as the researcher was included in multiple projects in the case company. In this project the output from the design science was returned into the environment for field testing and evaluation with domain experts (Hevner & Chatterjee, 2010).

Rigor cycle: Maintaining rigorous advances in the design process is what separates research from trivial design projects. The type of rigor used in design science varies from rigor in traditional research in the way that they should not always be grounded in behavioral or mathematical theories as they may not be feasible or appropriate for creating cutting-edge design artifacts. The design methodologies used for this research originates from other research areas but have been found useful in the design cycle in this project. The results of the design cycle in this research have then been added to the existing scientific knowledge base through scientific papers and presentations at scientific conference while the existing knowledge within the case company has been expanded through the development process and the presentation and implementation of the artifact (Hevner & Chatterjee, 2010).

Knowledge base: The knowledge base contains the known scientific theories and engineering methods upon which the design cycle is made. As important, the knowledge base also contains the experience and expertise within the application domain, in this project the case company, and the existing artifacts and processes. Through this project the knowledge base has been approached through literature review, case research, interviews, and action research to identify state-of-the-art in scientific methods and knowledge in the application domain (Hevner & Chatterjee, 2010).

3.3. RESEARCH METHODS

When research is conducted with a pragmatic worldview, utilizing design science to answer questions trough the creation of novel artifacts, there is an indication that not one single theoretical perspective is enough to sufficiently justify the knowledge creation. One single scientific research method cannot cover all the aspects of design science inquiry into integrated portfolio management. Therefore, a combination of research methods has been selected. The following subsections elaborate on the motivation for selecting specific scientific methods.

Case study is a well proven method for building theory in an industrial context (Voss, Nikos Tsikriktsis et al., 2002). Benbasat et al. (1987) identified three core strengths of doing case studies: (1) the phenomenon can be studied in its natural settings and meaningful, relevant theory generated from the understanding gained through observing actual practice, (2) the case method allows the much more meaningful questions of *why*, rather than just *what* and *how*, to be answered with a relatively full understanding of the nature and complexity of the complete phenomenon, and (3) the case method lends itself to early, exploratory investigations where the variables are still unknown and the phenomenon not at all understood. Therefore, this method was used in the early phases of this research projects as a multi-case study where three development projects were analyzed through quantitative data analyses and structured interviews.

Literature reviews is a widely acknowledge method for effectively advancing the knowledge of a specific research topic (Hart, 1998; LEVY & ELLIS, 2017; Snyder, 2019). This is achieved through the comprehensive coverage of relevant knowledge within the given field of research, thereby broadening the understanding of the topic and the patterns and gaps in the state-of-the-art. Therefore, a systematic literature following the steps described by (Hart, 1998) was conducted after the completion of the case study to expand on the knowledge found in these and support the answer of RQ1. Furthermore, specific literature reviews with a narrow search field were conducted during the full length of the research project to ensure use of state-of-the-art design methods in the design cycle.

Action research focuses on research *in* action rather than research *about* action. This is based on the idea of using a scientific approach to study the resolution of problems together with those who experience these directly (Coughlan & Coghlan, 2002). The goal is improving the action, making it more effective, while simultaneously expanding the existing scientific body of knowledge. Through this research project action research has played an important role as the researcher for an extended period of time has interacted with the environment in which the challenges have been identified and tried answered by the case company.

Quantitative modelling can be divided into axiomatic research and empirical research. For this research project the axiomatic research methodology is used as it focuses on obtaining solutions within the defined model and ensure to create insights to the problem as defined within the model (Karlsson, 2010). The formal methods used with in the various artifacts developed created in this research project originate from the scientific branches: mathematics, statistics, and computer science (e.g. Cramer V, Fisher test, or association rules).

CHAPTER 4. SCIENTIFIC CONTRIBUTION

Chapter 4 summarizes the six appended papers which are presenting the scientific contribution generated through this research project. Implications of the research conducted for each paper is added at the end of each summation in order to clarify how this paper contributes to answering the overall research questions for this research project.

4.1. EXPLORING MANUFACTURING SYSTEM DEVELOPMENT AND THE USE OF PLATFORMS TO REDUCE TIME-TO-MARKET

PURPOSE

Manufacturing companies have for decades been under pressure to gain cost and time reduction when introducing new products is inevitable. Often, these introductions of new products are designed, developed, or realized through either stage-gate, largely iterative, ad-hoc, or informal approaches (Bellgran & Säfsten, 2009). Different methods for improving the effectiveness and decreasing the time-to-market for new product introductions have received much attention in both academia and industry (Ericsson & Erixon, 1999; Gerwin & Barrowman, 2002; Prasad, 1996; Simpson et al., 2006a). However, in these methods the development of the subsequent manufacturing systems is merely regarded as a less systematic step conducted after the specification of the product design (Bellgran & Säfsten, 2009). To address this, various methods for integrating the product development process with the manufacturing system development process through modular and platform-based approaches have been proposed (Bruch & Bellgran, 2014; ElMaraghy & Abbas, 2015; Michaelis & Johannesson, 2011). However, there is little empirical research of how modularity and platform-based development methods can support the development of manufacturing systems and the consequence of doing so in manufacturing companies. Consequently, there is no empirically based knowledge about how manufacturing companies are conducting manufacturing system design and development and which challenges should be addressed in order to increase the speed and effectiveness of this task. Therefore, is the objective for this paper to identify the main challenges in developing manufacturing systems by exploring three different cases of manufacturing system development projects in a Danish manufacturing company.

METHODOLOGY

To address the research objectives of this paper, a retrospective cases-study was conducted of multiple instances within the partnering company for this project. Case-study research is applied, as this method is well suited for generating theory in an industrial context and is not constrained by the rigid limits of questionnaires and models (Voss et al., 2002). Furthermore, case research has been found more suitable when analyzing and generating theory based on only few observations, where multiple variables are interacting in complex systems (Yin, 2002). In this research, three cases were chosen to obtain the right balance between the depth of the research and the external validity to guard against observer bias (Leonard-Barton, 1990; Voss et al., 2002). To further minimize the risk of observer bias, multiple respondents for each case instance were interviewed through semi-structured interviews (Rowley, 2012). Using semi-structured interviews allowed for comparison between respondents while remaining explorative.

PAPER RESULTS

The findings of this research indicate critical challenges for manufacturing companies when manufacturing systems are being designed and developed for new product introductions. One main challenge was found in the architecture of the existing manufacturing systems being integrated on equipment and tool level, hindering the reuse in new development projects. Moreover, this research indicates that the product to manufacturing interface is often a major cause of problems, especially on equipment and tool levels. Bruch and Bellgran (2014) identified information management as a key enabler for improved production system designs. In this research, dissimilar types of information and non-identical situations on multiple planning levels where information was either not available or not shared was found. Firstly, cross departmental information sharing between the product and manufacturing domains caused several challenges. These challenges were perceived to be on an operational level where relevant design information was not shared during the actual development phase. Secondly, on the tactical level, information sharing across previous and active development projects was not existing. And finally, on the strategic level, information sharing across domains involving; previous, active and planned development projects was found to cause critical challenges in the development of manufacturing systems. To summarize the findings of this paper:

- Lack of focus on the interfaces between the product and manufacturing system as well as internally in the manufacturing system causes challenges in manufacturing development.
- Lack of information stems both from availability and willingness to share.

IMPLICATIONS

This paper contributes to RQ1 of this thesis by identifying some of the main challenges manufacturing companies are encountering when co-developing products and manufacturing systems. RQ1 is motivated by the gap in empirical knowledge about the possible challenges of introducing modular and platform-based manufacturing systems to reduce time-to-market. The challenges identified in this paper provide the direction for the continuous research direction for this project. Furthermore, several potential topics for further research are identified to advance the knowledgebase on information management in co-development projects. In practice this research highlighted the challenges in some information not being shared across organizational boundaries while some information is simply not available when needed. This allows companies to distinguish between the two and take different measures to either share or create the information required. To summarize the implications of this paper:

- Generated empirical knowledge on the challenges in developing platform-based manufacturing systems.
- Classifying information into not-shared and not-available.
- Identified future research direction in generating methods for retrieving the information not available when conducting platform-based manufacturing systems.
- Information management should be managed in different planning levels (operational, tactical, and strategic).

4.2. MODULARIZATION ACROSS MANAGERIAL LEVELS AND BUSINESS DOMAINS; LITERATURE REVIEW AND RESEACH DIRCTIONS

PURPOSE

Manufacturing companies and academia have for more than 20 years focused extensively on modularization and platforms in both the product and manufacturing domains (Andersen & Rösiö, 2019; Silveira et al., 2001). In order to gain the full benefits of modularization and not only manage but to capitalize on the increasing product variety, modularization and platform development cannot only be seen as an engineering task (Sanchez & Mahoney, 1996). Modularization should rather be an initiative that is affecting all levels of the organization and across the entire value chain. However, companies are still struggling to fully transition into truly modular companies that take modularization beyond the technical aspects. Therefore, the objectives of this paper to identify which tools and methods exist on the different managerial levels and across the full value chain by conducting a systematic literature review.

METHODOLOGY

To address the research objectives of this paper a systematic literature review is made by following three overall steps: retrieval, exclusion, and classification (Hart, Christopher W., 1998). In order to retrieve as much relevant literature as possible, a search strategy was applied in two academic databases (Web-Of-Science and Scopus). After the retrieval of literature, 1927 articles were part of the first exclusion step. The first exclusion step was done by screening the titles of papers which resulted in 325 papers remained to be included in the second exclusion step. The second step was done by a more thorough examination of the remaining papers abstracts, leaving 47 papers to be included for classification. Based on a forward and backwards search from the initial list, 24 additional papers were included, resulting in a final list of 71 papers.

PAPER RESULTS

The bibliometric analysis showed that a large amount of literature exists on the subject of modularization. However, most of the literature is found to be grouped in clusters, focusing on similar problems and on similar managerial levels. Not surprisingly the largest cluster is found in the product domain where the literature is almost evenly spread out across the three planning levels: strategic, tactical, and operational. This focus on modularization in the product domain comes naturally as this is where the academic world first started its focus back in the 1980´s, based on the industries of personal computers and automotive. Focus has through in the last couple of decades moved to also include modularization in the manufacturing domain. Here literature including both the product and manufacturing aspects of modularization have gained more focus as it is widely recognized that co-development is a prerequisite for succeeding with modularization in the manufacturing domain. However, it is found that the focus in the current knowledge base is centered around the actual development of specific modular systems in both the product and manufacturing domains and less knowledge exist on tools and methods to assist in the selection of which systems to develop. To summarize the findings of this paper:

- 39 % of the literature on modularization is found in the product domain and 29 % in the cross section between the product and manufacturing domain with focus on co-development and co-platforming.
- 72 % of the literature is found on the operational and tactical levels with the focus on developing and utilizing specific modular product or manufacturing architectures.
- Only 27 % of the literature is found on a strategic level with a holistic view, including methods or tools to support top management.
- No literature is found on how modularization impact the selection of development project in the portfolio management process.

IMPLICATIONS

This paper contributes to both RQ1 and RQ2 of this thesis by identifying some of the challenges that manufacturing companies are facing when developing modular product and manufacturing systems and tools and methods developed to overcome these challenges. By identifying tools and methods to support the development of modular and platform-based product and manufacturing systems, this paper classifies these tools and methods according to business domain and planning levels. This classification of knowledge supports this thesis by setting the direction for further research. Furthermore, this study provides researchers with an overview of existing tools and methods within the specific planning levels and business domains thereby identifying several potential research directions with a more holistic approach.

- A consolidated overview of current tools and methods for developing modular product and manufacturing system architectures.
- A classification of existing tools and methods in different business domains and on different planning levels.
- Identification of research gab on tools and methods to me used by the higher managerial levels when manufacturing companies are introducing modularization.

4.3. DATA DRIVEN DECISIONS MAKING WHEN TRANSITIONING TOWARDS A MODULAR SETUP

PURPOSE

Manufacturing companies are starting to introduce modularization strategies and strategic initiatives (Løkkegaard & Mortensen, 2017; Sanchez & Collins, 2001; Thyssen et al., 2006). The task of implementing and operationalizing these strategies and initiatives are far from simple and affects the entire value chain (Hansen & Sun, 2010; Östgren, 1994; Sanchez & Mahoney, 1996). Many of the manufacturing companies that initiate these modularization strategies and initiatives have been unable to reach a setup that will realize the expected benefits (Hansen & Sun, 2010). Hansen & Sun (2010) concludes that a significant lack of methods and approaches are the main reason for companies to fail on implementing modularization strategies and initiatives and Bruch and Bellgran (2014) identified information management as a critical challenge when performing integrated product and manufacturing system development. Several methods for modelling product and manufacturing systems to be used for development purposes have been proposed (Brunoe et al., 2019; Claesson, 2006; Haug et al., 2010). However, most of these methods have been developed without consideration to what data manufacturing companies have available and more focused on which data should be generated and how it should be model. Therefore, the objectives of this research is to identify and present a method for collecting data, create information, and conduct analysis in order to support decisions regarding integrated product and manufacturing systems. The focus of this research will be on how manufacturing companies can identify, collect, and utilize existing data form existing IT systems to create models that can be used for both standard and one-of-a-kind analysis.

METHODOLOGY

To address the research objectives of this paper a mixed methods of design science and action research methodologies was used. Design science was used because of its focus on designing innovative artifacts to be used in different application domains e.g. organizations, people or systems whiles ensuring rigor and relevance (Hevner, 2007; Hevner, Allan et al., 2004). Action research was used because the researcher made continuous interactions with the people within the case company to both understand new discovered challenges and to propose potential solutions based on the possibilities found when conducting research. The formal methods used in this research were: data reengineering, UML- class diagrams and data modelling. (Westbrook, 1995)

PAPER RESULTS

The findings of this research suggest that is possible to utilize existing master data from a company´s existing IT infrastructure to create a system to support engineers and domain experts when developing modular product and manufacturing systems. However, the ontology and data model are highly dependent on the specific company context and the existing IT infrastructure. Even though only one case has been made, a few challenges were identified. Firstly, the complexity of the IT infrastructure in today´s manufacturing companies and the skill required to; extract, transform, and load the data into a suitable data model requires the collaboration between data scientist and domain experts. Furthermore, because of the requirements of data from various sources and from various places in the organization, stakeholder management is a critical challenge as multiple data owners are involved. However, when the infrastructure and data model is operational the benefit for the company is extremely high as it allows for automation of standard analysis and new more complex analysis. To summarize the findings of this paper:

- This research suggest that it is possible to model existing master data in new ways to support the development of modular products and manufacturing systems.
- Challenges with multiple IT-systems and data owners are identified which require stakeholder management.

IMPLICATIONS

This paper contributes to RQ2 of this thesis by identifying and mapping relevant available data from various IT systems used by the case company. This identification and mapping of available data is a prerequisite for any data modelling made within manufacturing companies, and this paper presents a method with focus on generating information to be used when developing modular product and manufacturing systems. This paper contributes to research by identifying actual data and how it is structured in ERP systems that researchers can utilize when developing future methods. This is of particular value as much research have been found to create methods requiring manufacturing companies to generate vast amounts of data. The implications for industry with this paper is the increased focus on the possibilities of collecting data with a holistic perspective and thereby generating new knowledge about the existing product and manufacturing system portfolios.

- Created data model to be used as foundation for this research project.
- Identified available data for future research on data modelling.
- Presented a method to be used by industry for collecting and utilizing company master data for development purposes.
- Stakeholder management is crucial, as data is required from multiple data sources and from different organizational departments.

4.4. PRODUCT ARCHITECTURE MINING; IDENTIFYING CURRENT ARCHTIECTURAL SOLUTIONS

PURPOSE

Product modularization is not new in either academia and industry as it was introduced in the 80´s by computer and automotive manufactures to deal with the high level of variety required to meet the demand for personalized computers and automobiles (Ikeda & Nakagawa, 2001; Ro et al., 2007; Worren et al., 2002). However, practitioners in the industry are still struggling to transition from a traditional non-modular product architecture to a portfolio of modular products (Levandowski et al., 2015; Sanchez & Collins, 2001). Two keys enabler to any modular system is strategic partitioning and strict interface management (Sanchez & Collins, 2001; Sanchez, 2004). Several methods for capturing and modelling product architectures with the intent to generate knowledge for product designers and developers have been proposed (Owen & Horváth, 2002; Pahl & Beitz, 2013). Other models have been developed for the purpose of developing portfolios of modular products (Claesson, 2006; Hvam et al., 2008; Levandowski et al., 2015). Similarly, approaches for modelling manufacturing system architectures have been developed and recently modelling approaches for co-developing products and manufacturing systems have been presented (Brunoe et al., 2019; Gruhier et al., 2016). However, the presented methods are information heavy and require vast amount of data from multiple sources.

Furthermore, much of the data required for most of the suggested approaches are often not available in the format required and therefore not possible for companies to generate. Therefore, the objective of this papers is to identify and present an approach that utilizes data mining on master data from a company´s ERP system to identify how the existing product portfolio have been realized through actual components and interfaces.

METHODOLOGY

In order to address the research objectives of this paper, a case-study was conducted in collaboration with an industrial partner to ensure relevance and give access to actual company data (Voss et al., 2002). For this research one case was created where the focus was one product architecture with more than six thousand variants. Firstly, semi-structured interviews were conducted to understand the requirement from product developers and product architects. Secondly, an analysis of available product data from the companies ERP system was conducted before being extracted to an external data base. Once all the necessary data was extracted from the ERP system it was transformed to fit the requirements of the product developers and product experts. Once the model was created it was tested with multiple product architectures and was validated together with product experts.

PAPER RESULTS

The result of this research is a method for utilizing data modelling and data mining techniques to generate and visualize valuable knowledge about an existing product portfolio. This is done by determining the number of unique component variants and interfaces and presenting various statistics on these. This is visualizations in different ways, dependent on the nature of the decision which it should support, e.g. figure 4.1, presenting different statistics and simple cost analysis for the product architecture of an electric motor.

The level complexity in the existing product portfolio can be displayed through the enriched interface matrix as visualized in figure 4.2. This enriched interface matrix shows the amount if unique variants that exist of each system element and the number of unique interface variants that exist between two specific system elements for a group of product variants with a similar architecture. Once an as-is model is created, this should be used for continuous management of product interfaces and future development.

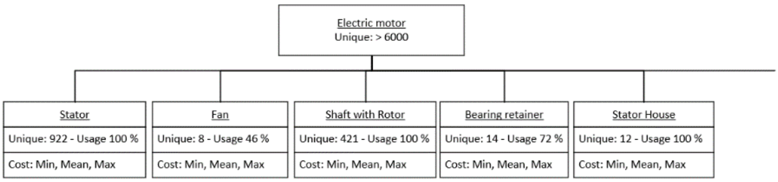

Figure 4.1: Visualization of statistics for a portfolio of product variants.

System element		Stator	Stator House	Fan	Shaft w/Rotor	Bearing Retainer
	#	933	13	8	419	12
Stator	933		8			7
Stator House	13	8				
Fan	8				4	
Shaft w/Rotor	419			4		
Bearing Retainer	12	7				

Figure 4.2: Enriched interface matrix for a portfolio of electric motors

- This paper presented a method for identifying and presenting product architecture on portfolio level.
- This paper presented a method for identifying and presenting the level of complexity for a portfolio of products.
- This paper presented a method for linking the market information to the product and the product architecture to the manufacturing.

IMPLICATIONS

This paper contributes to RQ2 of this thesis by identifying a method for mapping the relationship between the market, product, and manufacturing. Firstly, the connection between the market and the product is created by an overview of all the products and the actual sales history of these. Secondly by modelling the product architecture as presented in this paper the connection between the product and manufacturing is made. This is done through the breakdown of the product to components and connecting each specific component to a specific manufacturing system. This mapping creates the foundation for the remaining research projects as it provides the AS-IS picture for the current product portfolio and the resulting manufacturing. By modeling various data from the market, product and manufacturing domains in this way it could serve multiple purposes such as clean-up and standardization of an existing portfolio supported by cost-performance analysis, or a portfolio management process where a pre and post level of complexity can be displayed

- This paper presented a method for modelling the connection between market, product and manufacturing.

- This paper presented the enriched interface matrix which helps to identify the level of complexity within a portfolio of product variants.
- This paper presented the AS-IS situation for a portfolio of products and the resulting manufacturing.

4.5. A QUANTITATIVE METHOD FOR MAPPING FEATURE TO SYSTEM ARCHTICTURE WHEN DEVLOPING MODULAR PRODUCT ARCHITECTURES

PURPOSE

The concepts of product modularity and product platforms are well known methods for effectively designing and introducing a high number of product variants while still gaining the economies-of-scale and minimizing variety-induced complexity (Erens & Verhulst, 1997; Simpson et al., 2006b; Ulrich, Karl & Eppinger, 2011). The definition of a product platform is numerous but often focuses on commonality and reusability, e.g. *´a set of common components, modules, or parts of a product from which a stream of derivate products can be efficiently develop and launched´* (Meyer, 1997) and others (Erens & Verhulst, 1997; Simpson et al., 2006; Ulrich & Eppinger, 2011). A products level of modularity is derived from its product architecture and is dependent on the designer´s ability to create decoupled functional elements that are made interchangeable through fixed interfaces. Ulrich (1995) defines a product architecture as ´the scheme by which the function of the product is mapped to physical components´ and continues to clarify three requirements to describe a product architecture: 1) the arrangement of functional elements, 2) the mapping from functional elements to physical components, and 3) the specifications of the interfaces between the interacting physical components. When manufacturing companies are developing new products with the requirements of a modular product architecture, several design methodologies exist (Gershenson et al., 2004). Allen & Carlson-Skalak (1998) categorize the existing design methodologies into two categories: function-based and matrix-based. When function-based design methodologies are used, the link between product functions and physical components is required (Chen et al., 2017), as this is what Thumm and Goehlich (2015b) defines as “Product Architecture Drives” that is used to identify where in a product architecture variety is value adding and therefore should be allowed. However, this process of generating the link between product functions and physical components for existing product is a cumbersome task for manufacturing companies. Therefore, the purpose of this paper is to present a method that quantitatively link features and performance to physical components for a group of products with similar product architecture.

METHODOLOGY

In order to address the research objectives of this paper, design science is used because of its focus on designing artifacts (Hevner, 2007). Hevner (2007) describes design science through three cycles: environment, research, and knowledge base. The environment presents the: people, organizations, technology in which the problem resides. In this research, this has been approached through informal talks and observations done by the researcher within the industrial partner. The research cycle is where the artifact is developed and evaluated. It is in the intersection between these two the business needs and the application in practice the relevance of the research is found. In this research this has been approached through continuous dialog between the researcher and the subject matter experts in the industrial partner. Finally, the last cycle called knowledge base ensures the research is founded on empirical knowledge and known methodologies to ensure the rigor in the new research. In this research this has been approached by conducting a systematic literature review to identify relevant knowledge and methods in the existing knowledgebase.

PAPER RESULTS

The result of this research is a method for utilizing data modelling and data science techniques to quantitatively map the link between product features and physical components as described by Ulrich (1995). Furthermore, with this method it is also possible to identify the link between product performance characteristics and physical components making it possible to identify where changes are required if additional performance for a specific performance characteristic is requested. Finally, with this method it is possible to investigate if changes in either feature or performance requires changes to interfaces between system elements within the product architecture. This is done by modelling and restructuring master data from a company ERP system and using association rule mining techniques. By utilizing this method, it is possible to identify which physical components and interfaces in a product architecture are creating specific features and affecting performance of a product.

- A method for utilizing master data to perform feature to component mapping.
- A method for linking product performance characteristics to physical components.
- A method for linking product features and performance characteristics to specific interfaces within the product architecture.

IMPLICATIONS

This paper contributes to RQ2 of this thesis by identifying a method for mapping the link between product features and physical components. This method of identifying the relationship between product features and physical elements is significant and finds its relevance in multiple domains and for different purposes. For this research, this method provides an opportunity to quantitatively create this knowledge and incorporate this function when designing a model where future scenarios can be tested. In practice this method support designers and product architects to generate knowledge that would otherwise require time consuming manual work. In research, this method supports numerous existing methods created to support product modularization, because the link between product features and physical components required by these methods, previously required to be modelled manually. This furthermore supports research in product-platform and integrated product-production platform development.

- This method allows for the generation of knowledge which is used as input in multiple research papers on product platform generation.
- This method allows the company to generate knowledge that normally is generated manually through a time-consuming process be engineers.

4.6. SCENARIO-BASED PORTFOLIO MANAGEMENT: MODELLING FUTURE COST AND EFFECT ON MANUFACTURING

PURPOSE

Manufacturing companies are faced with the wicked problem of having to serve multiple markets with increasing amounts of product variants while still being able to produce at costs similar to mass production (Baldwin & Clark, 2003; Gilmore & Pine, 2000). Identifying and selecting which new product variants should be developed is done through a portfolio management process (Cooper et al., 1997) which consequently has a huge impact on manufacturing. It can however be difficult to predict and take into consideration the impact that the portfolio decisions will have on manufacturing (Adler, 1995; Lakemond et al., 2007; Miguel, 2008). Because new product development projects are often the result of incremental development of existing products, information on the already existing product portfolio and resulting manufacturing contain valuable information that can be used when setting the future product portfolio. Therefore, the purpose of this research is to present at method for creating a data model based on master ERP data that represents the product portfolio and the resulting manufacturing setup. Furthermore, this model should allow for the creation of hypothetical changes to the product portfolio and present the resulting product cost and effect on manufacturing.

METHODOLOGY

In order to address the research objectives of this paper, the design science methodology is used (Hevner, 2007). This method is used because of its focus on creating solutions to problems or improvements to existing solutions by designing novel artifacts (Hevner, Alan & Chatterjee, 2010a). Hevner (2007) describes the three main aspects of design science: environment, research, and knowledge base separately and how they interact. The environment presents the: people, organizations, technology in which the problem resides. In this research this has been approached through semi structured interviews, informal talks, and observations done within the industrial partner by the researcher. The research cycle is where the artifact is developed and evaluated. In this research this has been developed using methods like UML and evaluated with subject matter experts. It is in the intersection between the environment and research the business needs and the application in practice of the is found. In this research this has been approached through continuous dialog between the researcher and the subject matter experts in the industrial partner. Finally, the last cycle called knowledge base ensures the research is founded on empirical knowledge and known methodologies to ensure the rigor in the new research which has been ensured through a systemic literature review.

PAPER RESULTS

The result of this research is a method for creating a model based on standard master ERP data that will allow for the creation and validation of different product portfolio setting scenarios. This model will allow for scenarios of different architectural solutions in the product portfolio and display the resulting effect in the existing manufacturing setup. This is done by extracting and remodeling data from various IT systems to fit the requirements of displaying the current AS-IS product portfolio and its resulting manufacturing and its performance. Once the model displays the current situation, different scenarios can be made in order to see the expected result in the manufacturing domain. The paper concludes with a test and validation of the model and the learnings from this. Some learnings result in suggestions for future research on how the model can incorporate more detailed information within the manufacturing domain.

- This paper presents a model that will display the AS-IS situation of a product portfolio and the resulting manufacturing system performance.
- The model is tested and validated which provides learnings and suggestions for future research.

IMPLICATIONS

This paper contributes to RQ3 of this thesis by identifying a method for modelling the relations between market, product, and manufacturing in order to create and test various scenarios. For the case company this means that when a business case is brought forward based on changing market requirements, the expected changes to the product architecture can be incorporated into the model and the new expected overall cost and manufacturing performance can be estimated. Furthermore, this model will allow for the identification of which areas in the manufacturing domain is mostly affected by change in the product portfolio. For research, this information about the consequences to the manufacturing domain when changes are made in the product portfolio creates the opportunity to identify more precisely, where to utilize economy of scale VS economy of scope through either mass production or reconfigurable manufacturing principles.

- The case company is capable of creating different business case scenarios and compare and evaluate on these in terms of cost and performance.
- For research this provide a method for identification of where to incorporate different manufacturing principles.

CHAPTER 5. DISCUSSION

The research design and research contribution of this thesis that could be of interest to discuss in order to nuance the research conducted are elaborated in the following sections. Firstly, the methods used will be discussed, secondly the generalizability of the findings are elaborated and finally a conceptual model is presented to place the findings in a larger context.

5.1. METHODS

The first choice of method made for this research project was the choice of conducting the project in collaboration with only one case company as an industrial PhD and not as a traditional university employed PhD with multiple industrial case companies. This choice, however, was also the most influential in terms of research contributions and practical implications. By only collaborating with one case company, it has been possible to get deeper into that one case company and gain access to highly sensitive data and information which is believed not to have been the case if a multiple case study had been conducted. This access to data and information has only been possible through a close collaboration and mutual trust in the project. However, by only using one case company it could be argued that only company specific problems are identified through this research and that only the data and information used within the specific IT systems in the case company can be used to solve the specific problems. This challenge of generalizability will be further discussed in the following section. It is however the researcher’s firm belief that the close collaboration with only on case company which allowed the access to all the required data and information has been vital to this research project, and provided generalizable findings

5.2. GENERALIZABILITY

As this research is made in collaboration with only one case company it could be argued that the research contributions are company specific and therefore only partial or not at all generalizable. This is however not the case. Firstly, it was found through a literature review that the problem identified within the case company was described in multiple research contributions. Secondly, it is expected that the overall approach to building data models based on master data from various IT systems is not delimited to the specific case company. The IT infrastructure of companies will be different, thereby making the ontology of the data model company specific. However the ontology of the data model created in paper C is mostly created based on the ERP-system SAP which is commonly used in industry and therefore are directly applicable in other companies. Furthermore, other ERP systems generally apply the same basic table structure, and hence the results would likely be transferrable with a minimum of adaption. The methods presented in papers D and E where data mining techniques and mathematics is used to identify the current architectural solutions and quantitatively mapping product features to system elements can be utilized in other industries. These however are more suitable for manufactures with a broad product portfolio as this method is developed to create an overview of product families with a high number of variants. The last method presented in paper F is suitable for all manufacturing companies regardless of size and complexity. This method will generally create a model resembling the current product portfolio and the resulting manufacturing setup and allow for changes in the product portfolio through scenarios and present the expected consequence in manufacturing.

5.3. CONTEXT

A final thing that could be discussed is the combination of all the new knowledge gained through this research project and how to interpret this in a larger context. To discuss the findings in a larger context, figure 5.1 is created to show a simplified example of core business processes for a manufacturing company including: market analysis, business case creation, portfolio management, product and production development, and new product introduction and life cycle management. One of the core aspects of both mass customization and modularization is reuse. This could be reuse of physical components, design solutions, technology, and manufacturing process just to mention a few. Therefore, the potentials for reuse in both the product and production domains should be considered in all the core business process from market analysis through new product introduction and life cycle management. However, this is not an easy task and is further complicated by also having to consider both the future and the past, meaning what existing solutions should be reused and what should be developed with the intention of reuse in the future. All of these decisions are affected by the portfolio management process which are selecting which business cases are resulting in development projects. Therefore, the potentials for reuse both across business cases (and development projects) and existing products and production systems must be made explicitly clear when selecting and prioritizing future development projects in the portfolio management process described in figure 5.1.

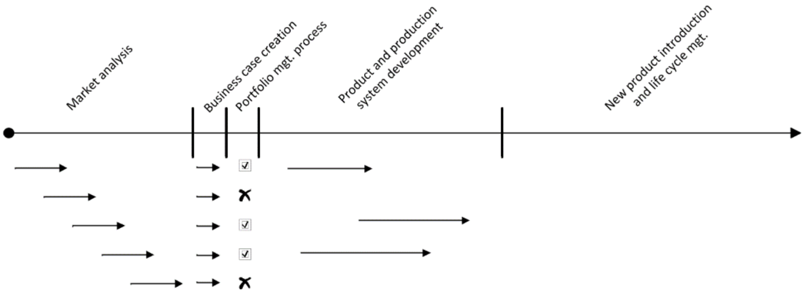

Figure 5.1: Simple example of core business processes.

The initial learnings from this PhD project concluded based on a multiple case study of previous conducted product and production system development projects (paper A) and a systemic literature review (paper B) that information management is a key challenge. One of the challenges identified was the lack of information sharing across development projects which suggest that information is not shared already in either the creation of business cases or in the portfolio management process. This constitutes a major problem as Kester er al., (2009) concludes that business cases and the resulting development projects cannot be evaluated based on individual characteristics but must be evaluated in context of the existing product and production system portfolio. To support the creation of business cases and the resulting development projects with information that allow them to be viewed in context of the existing product and manufacturing system portfolios, data regarding the: market, product, and manufacturing domains were collected, and model as presented in paper C. Because of the high variety of physical variants of all product architectures within the case company, the method for product architecture mining presented in paper D was created. This gives a clear overview of the composition of the existing product portfolio for that specific product architecture and the corresponding manufacturing system. Finally, paper F presented a method for creating a data model that allowed the creation and testing of different architectural scenarios within the specific product architecture. Based on this research it was concluded that it is possible to create a data model that combines product and manufacturing system master data that will allow for changes to be made in the product domain and show the expected result in the manufacturing system. To put all of this into context figure 5.2 presents an example of how the full product portfolio with all distinct product architectures and the resulting manufacturing systems could be created. If such a model were created, it could serve as a focal point for identification of reuse potentials within the business case creation and portfolio management process described in figure 5.1.

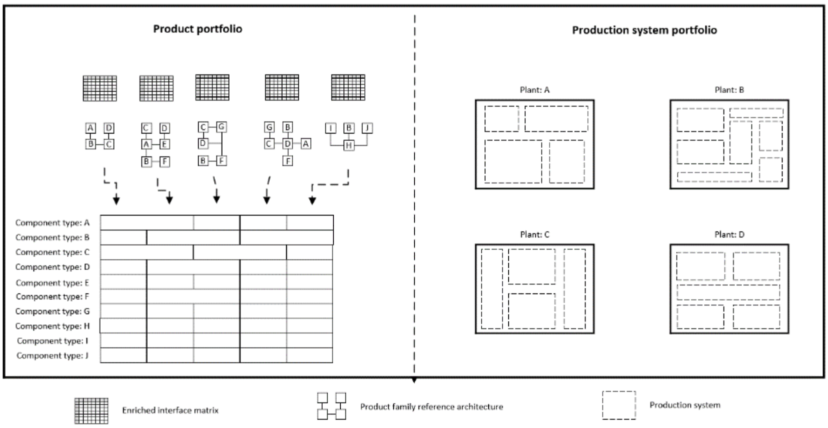

Figure 5.2: Combined product and manufacturing system overview.

This would be possible when business case is made based on incremental development of existing offerings. When the business case is based on the creation of a new version of an existing product architecture it is mostly also known where in the product architecture changes are required. If this is not known, paper E presents a quantitative method to link product feature and performance to specific architectural components and thereby provide this information.

The overall proposal is that all business cases are mapped into this model where each business case points out which product architecture is used and where in the product architecture changes are expected, as presented with a circle and a pentagon in figure 5.3. The model will present which other product architectures are potentially affected because they share the physical components which have been identified as requiring changes. Furthermore, it will be presented if one or more business cases are expected to require changes in the same manufacturing system because these are shared across product families (e.g. component manufacturing or assembly lines), thereby potentially allowing more business cases to be accepted, as manufacturing system development cost can be shared between multiple development projects.

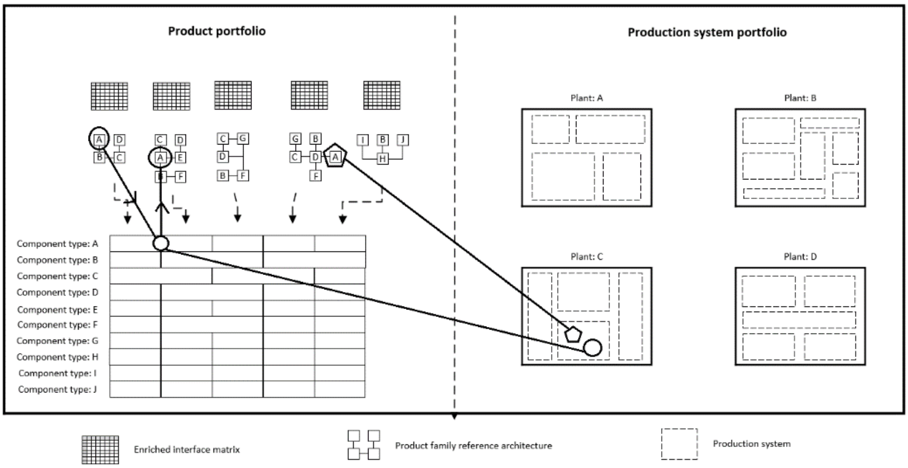

Figure 5.3: illustration of two business cases in the presented model.

It is, however, not possible at this time to work on a more detailed level in the manufacturing domain where it would be beneficial to link products to specific manufacturing equipment and tools. If this link is established, it would be possible to determine in more detail which types of manufacturing equipment could be shared across manufacturing systems. This would also allow for the model to present the full impact in the product domain if new manufacturing technology is presented. The IT structure in the case company would support this creation, however it was found that the data quality within the manufacturing domain was not sufficient at this time.

CHAPTER 6. CONCLUSION

The final chapter of this thesis concludes on the research project with an outset in the main research objectives. Furthermore, conclusions related to the individual research questions are elaborated on. The main objectives of this PhD project were to develop concepts and methods for developing and managing a portfolio of product and manufacturing system architectures based on a long-term and full-cost perspective.

6.1. RESEARCH CONTRIBUTION

The main objectives of this research project were addressed by asking three research questions, which are summarized and answered in relation to this thesis.

RQ 1: What challenges emerge when manufacturing companies transition from a traditional to a modular and platform-based product and manufacturing development setup?

This RQ has been answered through paper A which is based on case research and through paper B which is a systematic literature review. Based on these papers it is found that information management is a critical issue, both within the individual development projects but equally on a portfolio level across multiple development projects. It is found that some of the challenges arise from a lack of willingness to share information across departments within the individual development project. The types of information where the willingness to share often cause challenges are typically forward looking, such as plans and intentions. These challenges are only reinforced when looking on portfolio level and information is not shared across development projects. Other challenges emerge when the information is simply not available. These types of information can be divided into "current state" and "forward looking". The missing information on "current state" can be caused by a lack of documentation, inappropriate type of documentation, or no holistic approach to documentation in previous development projects.

RQ 2: How is it possible to quantitatively model the relations between current market requirements and the existing product and manufacturing system architectures in terms of cost and performance?

This RQ have been answered through papers: B, C, D and E. Firstly, paper B is a systematic literature review which identified several quantitative methods for developing product platforms and other modular development methodologies. Secondly, paper C describes what data is identified in multiple IT systems to quantitatively describe each domain individually and how these are modelled to create the foundation for the remaining research. Paper D presents a new method for utilizing data mining techniques on the data model created in the previous paper in order to identify the current architectural product solutions. This is done by identifying the actual number of unique interfaces and component variants for a given product architecture. Lastly paper E presents a method for quantitatively mapping the relationship between product features and system elements, also known as feature to component mapping which is crucial when developing modular architectures.

RQ 3: How can the model developed in RQ 2 be used to create and validate different portfolio scenarios in terms of expected cost and performance?

This RQ have been answered through paper F which presents a method for quantitatively modelling relevant data that will allow for the creation of different scenarios in the product portfolio and present the resulting effect in the existing manufacturing setup in terms of cost of the product and the utilization of the manufacturing equipment.

6.2. INDUSTRIAL IMPLICATIONS

Conducting integrated product and manufacturing systems portfolio management could potentially have a large impact on the overall profitability of a manufacturing company. If the potentials for reuse in both the product and manufacturing domains are identified in the earlier phases before the portfolio management process described in figure 5.1, it could result in more innovation and shorter development time within both domains at the same cost. Furthermore, if data is utilized as presented within this research project, the possibilities of reviewing each business case in relation to the existing portfolio will improve. This will increase the possibility of revising the business case in context of the existing portfolio in both technical and financial terms. The technical context is evaluated through the changes required in the product architecture and the resulting changes in the manufacturing setup. Here the enriched interface matrix presented in paper D can be utilized to show the level of complexity in the current state as a baseline and an expected level of complexity as an result outcome of a development project. On the financial part it would be possible to isolate the financial elements to those where changes are required in the product architecture and the resulting manufacturing system. Once a new expected cost of these elements is determined, this cost can be combined with the cost of the existing portfolio and provide a new overall expected cost, leading to a foundation for making better holistic decisions

6.3. FUTURE RESEARCH

The research conducted during this project opens several potential future research directions.

- *Manufacturing system master data:* The models presented in paper D, E, and F all focused on presenting and creating scenarios for changes in the product architecture and the derived effects on the manufacturing systems. It was however learned that the data structure on manufacturing data within the ERP system is similar to that of the product data. Therefore, future research should be made on improving the manufacturing part of this data model and especially the connection between the product and manufacturing. When master data is improved, it is possible to connect each component to specific equipment thereby providing a much more precise model and clear picture.

- *Financial calculations:* Business cases today are often selected and prioritized based on financial performance parameters such as: size of investment, return of investment, and return on assets. With the possibilities identified within this research project to utilize master data to model the existing product and manufacturing system portfolios it would be beneficial to include more detailed financial calculations. It would be beneficial to research the cost-of-complexity as this research created a method to display the current level of complexity within a portfolio of existing products. Furthermore, research in applying optimization methods in combinations with models of products and manufacturing systems may also have potential to identify better courses of action in product and manufacturing system portfolio development.

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