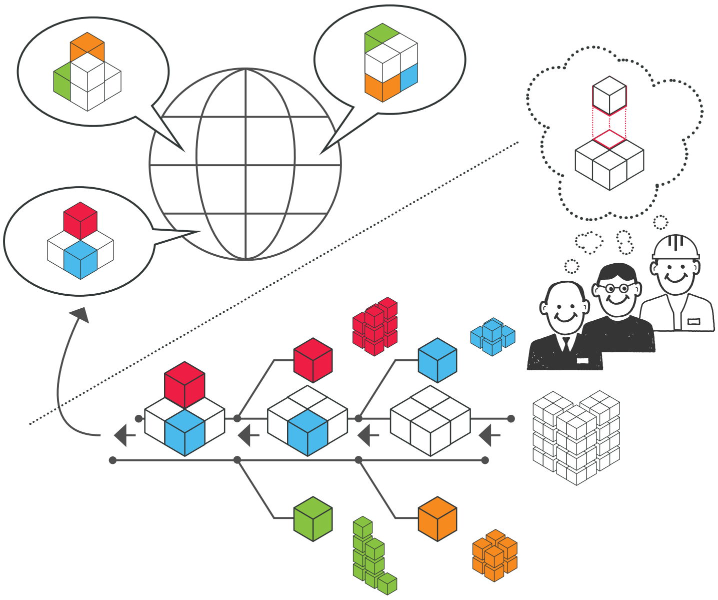
Top-Down Financially Driven Modularization

PhD Thesis



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Top-Down Financially Driven Modularization

By

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Abstract

This thesis presents methods to support industrial companies in applying modularization, on a portfolio level, as a strategy for product and production development. This includes a focus on how argumentation for modularization can be supported by assessing financial effects and a focus on how critical modularization decisions can be captured and communicated to support the realization of these effects.

Modularization denotes a decoupling of dependencies in a system, such as a product, to create a number of independent modules, which can be easily replaced, updated, or shared among different systems. The benefits include an ability to improve time-to-market for new product introductions, reduce complexity and cost, and efficiently reach out to niche markets through the mixing-and-matching of modules. Applying principles of modularization as a strategy for development is generally seen as an enabler for improving the competitiveness of companies.

Despite having received much attention from researchers and industrial practitioners over the years, a number of critical challenges still exist. (1) The effects of modularization are difficult to quantify and are often realized over an extensive timeframe. (2) The task of harvesting these effects is often seen as a technical issue handled by designers and engineers in individual projects. (3) The top-down communication of critical design decisions on modularization is difficult and not well supported. A need exists for supporting strategic and long-term decision-making on modularization and for communicating strategic decisions on the sharing of modules and design principles in day-to-day design activities. The research presented in this thesis supports these needs through the following two main contributions:

- The Architecture Mapping and Evaluation (AME) approach is introduced as tool to assess the potentials of modularization across an industrial multi-architecture portfolio.
- A principle for modeling business critical design rules (BCDR) is introduced to capture and communicate decisions on modularization across an industrial portfolio.

The methods have been tested in a number of case studies. The results illustrate an approach to elevate discussions on modularization from an engineering/project level to a strategic management level. The end-results are significant effects in shorter time-to-market and cost reductions.

Resumé

Denne afhandling præsenterer en række metoder til at støtte industrielle virksomheder i at benytte modularisering som strategi for produkt- og produktionsudvikling. Dette inkluderer fokus på, hvordan argumenter for modularisering kan blive skabt ved at estimere de finansielle effekter, og fokus på, hvordan kritiske designbeslutninger om modularisering kan dokumenteres og kommunikeres for at understøtte en realisering af disse effekter.

Modularisering beskriver afkoblingen af afhængigheder i et system f.eks. et produkt for at skabe et antal uafhængige moduler, som nemt kan udskiftes, opdateres eller deles mellem forskellige systemer. Fordelene er en forbedret time-to-market for nye produkter, en reduktion af intern kompleksitet og omkostninger, samt muligheden for at række ud til nichemarkeder ved sammensætning af forskellige moduler. Generelt ses modularisering som et middel til at øge konkurrencedygtigheden for nogle virksomheder.

Selvom feltet har meget fokus i både forskningsverdenen og i industrien, så er der stadig udfordringer: (1) Effekterne er svære at kvantificerer og er ofte realiseret over lang tid. (2) Ansvaret for at høste effekterne ses ofte som en opgave håndteret af ingeniører og designere i individuelle projekter. (3) Kommunikation af kritiske designbeslutninger om modularisering er ikke optimalt understøttet. Der er behov for metoder til at støtte strategiske og langsigtede beslutninger om modularisering og for at kommunikere beslutninger om deling af moduler og designprincipper i daglige designaktiviteter. I denne afhandling præsenteres forskningsresultater, som bidrager med to metoder til at understøtte ovenstående behov:

- Metoden Architecture Mapping and Evaluation (AME) er introduceret til at vurdere et potentiale for modularisering på tværs af et industrielt produkt program med mange arkitekturer.
- Et princip til at modellere Business Critical Design Rules (BCDR) er introduceret til at dokumentere og kommunikere beslutninger om modularisering på tværs at et industrielt produktprogram.

Metoderne er testet i en række casestudier. Resultaterne giver et samlet bidrag til at hæve diskussioner om modularisering fra ingeniør/projekt-niveau til et ledelsesniveau. Dette viser betydelige effekter i forhold til reduktion af time-to-market og reduktion af omkostninger.

Preface

This thesis is titled *"Top-Down Financially Driven Modularization"* and documents the outcome of a three-year PhD project starting in August 2014 and ending in October 2017. The project was carried out in collaboration with the Manufacturing Academy of Denmark (MADE) and the Section of Engineering Design and Product Development, Department of Mechanical Engineering at the Technical University of Denmark (DTU).

The scoping of the research project and formulation of the research questions were done in collaboration with my supervisors, Professor Niels Henrik Mortensen and Professor Lars Hvam. Through investigation and a number of different research activities, I was able to provide answers to these questions. Just as the task has been extensive and difficult, it has also been exiting and enlightening.

This is a paper-based thesis, meaning that the primary purpose is to tie a number of research results together into a collective contribution. The individual results are presented in six appended papers.

I would like to thank all industrial partners who have been involved in this research project. I have experienced only openness and willingness to test and discuss my ideas. Furthermore, I have learned a great deal through our close collaboration. I would also like to thank the MADE for creating a network of researchers through which ideas could be shared and matured and for creating a network of industrial companies with a genuine interest in applying the research. I would like to thank my colleagues in the Section of Engineering Design and Product Development for support and good discussions throughout all three years. Finally, I would like to thank my supervisors, Niels Henrik Mortensen and Lars Hvam, for excellent guidance and support during the process.

Lastly, I would like to give a special thanks to my family and closest friends for supporting me through stressed times.

I hope you enjoy reading this thesis.

Martin Løkkegaard
Copenhagen, October 2017

List of Papers

Paper A:

Mortensen, N.H, Hansen, C.L., Løkkegaard, M. & Hvam, L. (2016). Assessing the cost saving potential for shared architectures. *Concurrent Engineering: Research and Applications*, 24(2), pp. 153-163.

Paper B:

Løkkegaard, M., & Mortensen, N.H. (2017). Assessing the financial potential for modularization: A case study in a global OEM. Proceedings of the 21st International Conference on Engineering Design (ICED17), Vol. 3: Product, Services and Systems Design, Vancouver, Canada 21-25.08.2017.

Paper C:

Løkkegaard, M., Mortensen, N.H., & Hvam, L. (2018). Using Business Critical Design Rules to Frame New Architecture Introduction in Multi-Architecture Portfolios. *International Journal on Production Research, (in press).*

Paper D:

Mortensen, N.H., & Løkkegaard, M. (2017). Good Product Line Architecture Design Principles. Proceedings of the 21st International Conference on Engineering Design (ICED17), Vol. 3: Product, Services and Systems Design, Vancouver, Canada 21-25.08.2017.

Paper E:

Løkkegaard, M., Mortensen, N.H., & McAloone, T.C. (2016). Towards a Framework for Modular Service Design Synthesis. *Research in Engineering Design,* 27(3), pp. 237-249.

Paper F:

Løkkegaard, M., Mortensen, N.H., Jensen L.S., & Christensen, C.F.K. (2018). Assessing Increased Product Line Commonality's Effect on Assembly Productivity and Product Quality. Proceedings of the 15th International Design Conference (DESIGN 18), Dubrovnik, Croatia, 2018.

Table of Contents

1 Introduction

This chapter describes the background and overall focus for a top-down and financially driven approach to modularization. The research addresses the tasks and challenges in applying modular principles.

1.1 Background and industrial challenges

Globalization and increasing competition put pressure on industrial companies developing, manufacturing, and distributing products. Differences in customer demands, legislations and approvals etc. require a diverse product portfolio and an ability to respond quickly to market changes and to new market opportunities. This often results in a need for several R&D sites, several factories, numerous sales teams, and an extensive supply chain. All this adds to the internal complexity in a company, which comes at a cost (Hansen, 2013; Hansen et al., 2012; Mortensen et al., 2010). Companies are adopting modularization principles (Figure 1) to deal with this complexity, basically meaning that instead of designing products from scratch every time, a number of building blocks or modules can be mixed-and-matched i.e. configured, as basis for launching a new products or product variants (Andreasen, Mortensen, & Harlou, 2004; Baldwin & Clark, 1997; Meyer & Lehnerd, 1997; Simpson et al., 2014).

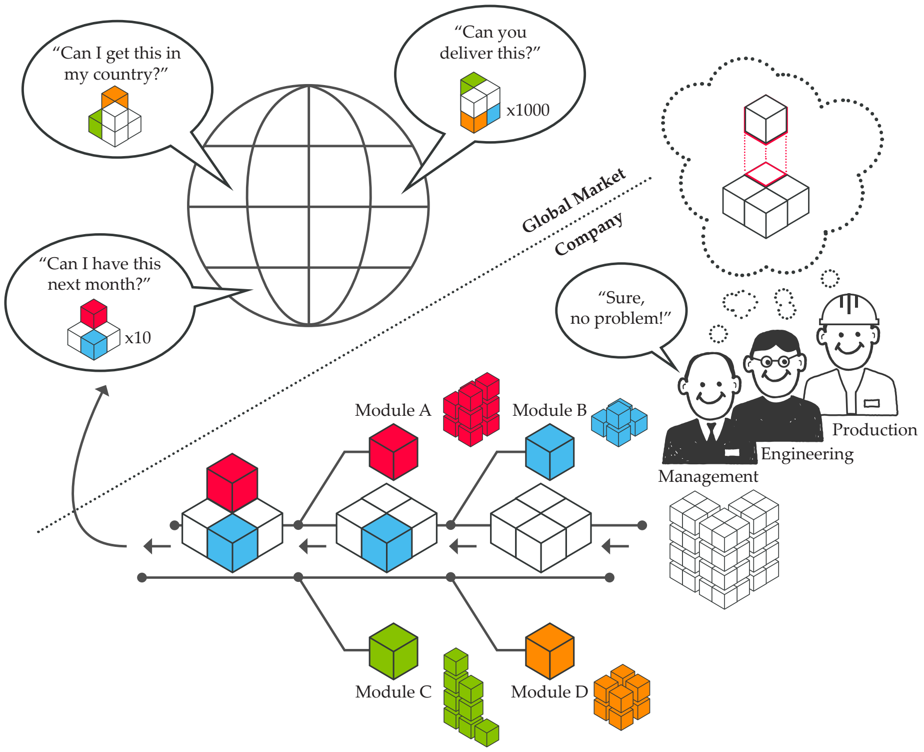

Figure 1: Applying modularization principles as the basis for product delivery

Fundamentally, modularization describes the decoupling of dependencies in a complex system – in other words, minimizing dependencies between subsystems - allowing, for example, the easy replacement of or updates to these decoupled subsystems without affecting overall system functionality (Baldwin & Clark, 1997). The decoupling of dependencies is facilitated through the standardization of interfaces within the system (Ulrich, 1995). The approach is used in a different applications ranging from physical products to services and software. In this thesis a perspective borrowed from mechanical engineering defines the basis for understanding modularization. Inherent in modularization is a strategic intent. The decoupling of system dependencies and interface standardization are only justified if some kind of purpose exist, such as supporting technology updates, outsourcing, or as means for pursuing market opportunities (Baldwin & Clark, 2000; Meyer & Lehnerd, 1997; Mikkola, 2006).

Modularity is embedded in the architecture of a system, which describes the functional and structural composition of the system and interfaces within the system and the surrounding environment (Harlou, 2006); it is a relative attribute, which can generally be described as ranging from integral to modular (Mikkola, 2006; Ulrich, 1995). An integral system is often designed with the highest possible performance in mind (Ulrich & Eppinger, 2012), where modularization can be based on a number of different strategic drivers (Ericsson & Erixon, 1999). Finally, the term "platform" is used to describe the collection of modules from which specific products can be derived and efficiently launched (Meyer & Lehnerd, 1997). Modules do not necessarily have to be physical building blocks but can also be collections of processes, knowledge or people and relationships (Robertson & Ulrich, 1998). Figure 2 illustrates the basic understanding of modularization used in this thesis.

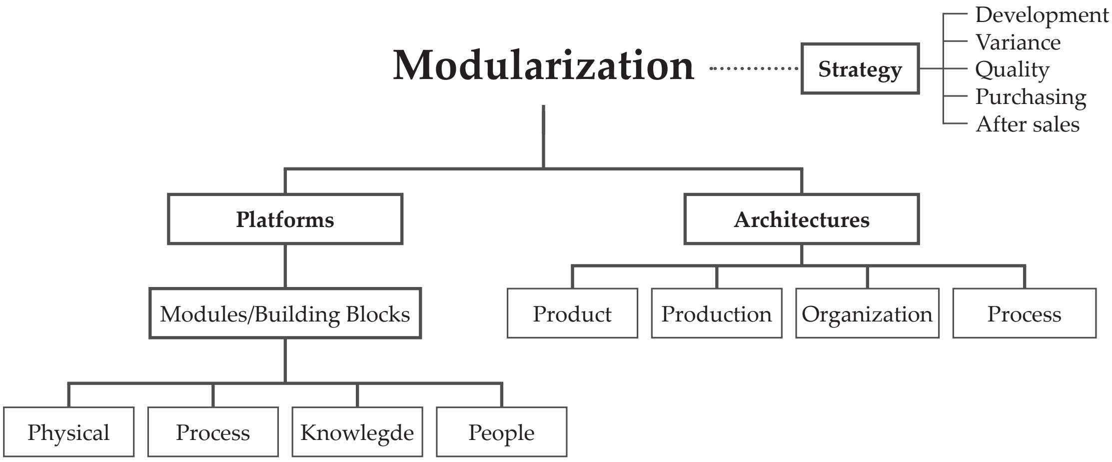

Figure 2: Modularization as defined in this thesis

Designing products based on principles of modularization is generally understood to improve a company's ability to leverage economies of scale as reduction of unit cost can be achieved by increasing the volume of standardized modules used across several products. Economies of scope can be achieved through the mixing-and-matching of modules to reach niche markets or pursue new market opportunities. Thus, the collection of common modules can provide a competitive advantage (Baldwin & Clark, 1997; Meyer & Lehnerd, 1997; Simpson et al., 2014; Ulrich, 1995). For further elaboration of theory related to modularization see Section 3.2.

Changing from sequential project-to-project development to a strategy based on application modularization principles demands top-management commitment and organizational changes to succeed (Sanchez, 2013). A number of challenges exist, which are part of the reason why modularization is something many companies talk about but an area where few report successful implementation.

1.1.1 Resources, capabilities and prioritization

Much of the research and development of methods and tools supporting modularization come from the automotive and aerospace industries. Successful stories are demonstrated by, for example, the VW MQB, General Motors D2XX, or Daimler MRA platform initiatives (Lampón, Cabanelas, & González-Benito, 2017). In the aerospace industry, Airbus achieved a competitive advantage by applying principles of modularization to their cockpit design (Simpson, 2005). Common to these two industries are that investments in manufacturing and unit cost are so extreme, that few alternatives exist to re-use a level of standardized components across both products and production to sustain competitiveness.

The challenge is that not all companies have the resources and capabilities to successfully apply tools and methods, which are generally detailed in nature and demand that an extensive level of expert knowledge be applied. Furthermore, even if the capabilities exist, commitment from managers is needed to secure prioritization and resource allocation. Sanchez (2013) argues that in many companies modularization is something that exists in name only. He introduces the Modularity Maturity Model (Table 1), describing different viewpoints on modularization that companies can apply. He concludes that a majority of companies are located in the lower levels of the scale. As a result, if a company has a relatively low maturity level, and modularization is not seen as an essential part of a company strategy, limited effects should be expected.

Table 1: Modularity maturity model, adopted from Sanchez (2013)

Maturity level	Management understanding	Design and development activities
7	*Modularity as framework for identifying and developing new strategic competences*	*Architectural management function is directly involved in identifying goals for strategic competence development*
6	*Modularity as framework for strategic integration*	*Architectural management function is directly involved in setting market, technology, and business strategies*
5	*Modularity as framework for knowlegde management*	*New architectural knowledge created in development is captured in improved interface specifications*
4	*Modularity seen as means to reduce time-to-market*	*Modular development process based on "new rules and new roles" enables concurrent component development*
3	*Modularity seen as means to increase product variety*	*Strategic partitioning decouples stable from variable components to enble low-cost configuration of product variations*
2A and 2B	*Modularity seen as means to reduce product cost*	*Early form of modular development process seeks to design (2A) common components and (2B) re-usable components*
1	*Modularity seen only as engineering issue*	*Conventional development process uses technical modularity to moderately reduce design time and cost*
0	*Unaware of modularity*	*Conventional development process makes no systematic use of modularity*

A need exists to support companies wanting to harvest the potentials of modularization in moving from a lower maturity level (0-5) to a level where modularization is seen as a key strategic element (6-7).

1.1.2 Uncertainty of effects

A common understanding exists that applying modularization principles as the foundation for product development brings a number of benefits and drawbacks. However, the assessment and quantification of effects are mainly based on company-specific case study research. Several researchers request further evidence of the related benefits (Bonvoisin et al., 2016; Campagnolo & Camuffo, 2010; Piran et al., 2016). The result is that, on top of demanding resources and expert capabilities, the direct effects of applying modularization principles as a strategy for product development are to some degree uncertain. The challenge here is, if companies want to pursue the potential effects of modularization, to create top-management commitment and engagement. This can be supported by, for example, making modularization comparable with other major strategic initiatives, such as the implementation of LEAN practices (Womack, Jones, & Roos, 1990), production and R&D outsourcing, and cost-out initiatives, to allow managers to make informed decisions on the strategic direction of their companies. A need exists to support companies in assessing the potentials of modularization to generate this decision base.

1.1.3 Long-term effects

The effects associated with modularization – for example, time-to-market reductions, production economies of scale, and the reduction of risk (Cameron & Crawley, 2014) – are often realized over time when new product variants are derived based on the defined modules. The over-specification of modules to allow sharing across several products can be costly (Thyssen et al., 2006), and studies report that the implementation of modularization strategies can lead to increased up-front investments multiple times larger than those for designing individual products (Cameron & Crawley, 2014; Halman et al. 2003; Ulrich & Eppinger, 2012). Thus, when the effects are, to some extent, uncertainty, long-term and extensive resources are needed for realization, it can be challenging to argue for investing in modularization initiatives. This is especially challenging for companies under pressure from shareholders to deliver quarterly growth.

A need exists to highlight the long-term potentials of modularization and to ensure, if implemented as a strategy for development, that the principles are documented and communicated in a way that can secure compliance with the strategy.

1.1.4 Modularization is seen as a technical issue

A low modularity maturity level indicates that modularization is seen as an engineering issue. Designing modularity into a system is something that is done on a “nice-to-have” basis and is handled by the technical staff. The result is that modularization is seen as something handled within individual projects, and decisions on applying modularization principles reside with project managers. If these managers are measured on the ability to deliver within a defined timeframe and budget, the prospects of cost associated with the over-specification of modules limits the incentive for sharing design principles across projects. Moving up the corporate hierarchy, where such critical design decisions should be made, strategic managers are often not deeply involved in the technical details of every project. The result is, on a technical and strategic level, that we lose a clear focus on what long-term and cross-portfolio decisions on modularization – the standardization and reuse of key design principles, technologies, manufacturing solutions, and parts – can do for an industrial company. The challenge is that these critical design decisions cannot be made within individual projects.

A need exist for supporting companies in capturing, formulating and communicating critical design decisions across an industrial portfolio to create a reference for new product introductions based on modularization strategy.

These challenges define a need for highlighting the potentials of thinking long-term and cross-portfolio, with a focus on modularization. In this thesis a method is suggested for assessing the financial potential of implementing a strategy based on shared product and manufacturing architectures. This is backed up by a method for documenting and governing key design rules to capture and communicate a strategy for modularization. The goal has been to provide an operational approach for industrial companies wanting to explore the potentials of modularization and implement modularization principles as a corporate strategy for product development. Collectively we call this *"Top-Down Financially Driven Modularization"*.

1.2 Academic challenge

Generally consensus exists of the validity of the prevailing methods and tools to reason on modularization, cluster the functional and structural elements of systems into modules, and optimize designs based on drivers for modularization, such as cost, time-to-market, or quality (Baldwin & Clark, 2000; Eppinger & Browning, 2012; Meyer & Lehnerd, 1997; Ulrich, 1995; Ericsson & Erixon, 1999). However, seen from the perspective of embedding modularization as a cross-portfolio strategy to improve overall competitiveness, support is lacking in a number of dimensions.

Even though much has generally been achieved within the field of modular product development, including the development of families of products and related product platforms (ElMaraghy et al., 2013; Jiao, Simpson, & Siddique, 2007), reviews of existing publications describe the need for further work. Relevant highlights are shown in Table 2.

Table 2: Relevant review papers and areas where further research is needed

Relevant review papers	Research focus and basis	Areas for future research
Jiao et al. (2007)	Review of product family and platform-based product development. (Based on 246 references)	• Need for holistic and system-wide solutions in relation to product family design. • Need for coherent framwork including front-end issues: Customer integration, market segmentation and economic evaluation; and back-end issues: Manufacturing and supply chain considerations.
Campagnolo and Camuffo (2010)	Review of modularity in management studies. (Based on 125 references.)	• Need for all-around framework bringing light to relationships between product, production, and organizational modularization • Need for studying cost of developing modular product architectures
Bonvoisin et al. (2016)	Review of modular product design. (Based on 163 references)	• Need to define modularization metrics to achieve a level of definition that is practical enough for engineers. • Research is needed to embed principles of modularization in day-to-day design activities.
Piran et al. (2016)	Review of modularization strategy in production and operations management. (Based on 81 references.)	• Need for studying background for modularity in production • Need for quantifying effects of modularization

To summarize, methods, tools, and approaches exist when it comes to designing modular systems. But steps prior to the design or optimization activities – in other words, where to focus modularization efforts across an industrial portfolio – and operational steps – meaning how to communicate and operationally describe a modularization strategy – lack support. Based on the industry challenges and gaps in the existing literature two areas were identified as relevant focus areas for this research project, as follows:

- ***Argumentation:*** Improve the understanding of the potentials and effects of modularization to support strategic comparison with other major strategic initiatives and to support increased top-management focus. *– To support the implementation of the strategy*
- ***Operationalization:*** Improve the capturing and communication of critical modularization principles across an industrial portfolio, including the product and manufacturing domains, to support design activities on a daily basis. *– To support compliance with the strategy*

1.3 Background for the research

The results are generated based on a three-year research project focused on supporting companies in the integration of modular principles as a strategy for developing new products and production solutions, with the goal to speed up time from development to earnings.

The research project has been associated with MADE – an organization with the vision of supporting Danish industry in improving competitiveness and making Denmark an attractive location for production companies in spite of having some of the highest levels of labor cost in Europe (Eurostat). This should be achieved through means of long-term industrial research, education, and strong networks across companies and political initiatives. MADE is funded by companies (48%), the Innovation Fund Denmark (38%), universities and approved technological service providers (GTS institutions) (8%), and private foundations (6%). The industrial partners include more than 80 companies ranging from small to medium-size enterprises (SMEs) with less than 250 employees, to larger organizations such as LEGO GROUP, MAN Diesel and Turbo, Danfoss A/S, Siemens Gamesa Renewable Energy, Vestas A/S, and Grundfos A/S.

The research in MADE is divided into nine work packages (Figure 3), each defining the scope and focus of associated research projects. The bottom tier focuses on technology development, and going up in the matrix, the focus gradually becomes broader and orientated toward strategy and operational research. This research project related to work package 1 (WP01): High Speed Product Development. No further attention will be placed on the other work packages in MADE in this thesis. For more information on the individual work packages visit www.made.dk.

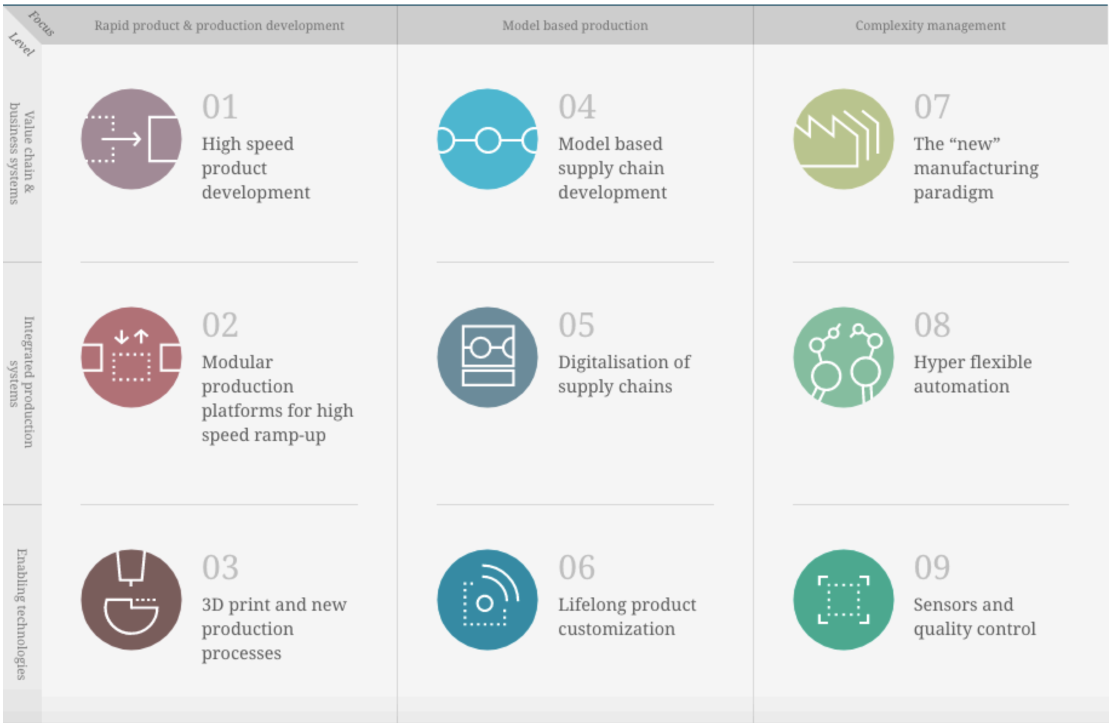

Figure 3: MADE Work Packages

1.3.1 MADE work package 01

The focus of WP01 is to support industrial companies in speeding up the product developing process and reducing time-to-profit. This has been seen as a critical element in supporting the competitiveness of Danish industry. The challenge is described by MADE as follows:

> *"It is crucial for Danish companies to reduce the time from product development to when the product is delivered to the customer. If a company can reduce the time from development to earning, they can increase production; but the challenge is to do this in a complex and constantly changing world."*
>
> made.dk

The work package covers a broad research area, and several ways exist to achieve a reduction in time from product development to when profits are generated. Portfolio management and planning (Cooper et al., 2001), concurrent engineering practices (Andreasen & Hein, 2000), and LEAN practices (Womack et al., 1990) are some examples. The scope of this research project is, however, focused on how modularization principles can be applied and implemented in the product development process to the reduce time from development to earnings. The overall goal for the research in WP01 was formulated as follows:

> *"Develop processes for product development using modular principles in product design and the use of supportive IT tools in order to achieve rapid development and introduction of new products."*
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The focus on IT has been covered by other research projects within MADE WP01, with a focus on the research, development, and applications of configurations systems (Hvam et al., 2008). Thus, the scope of this the research project has been to support companies in speeding up the time from development to when the product is delivered to the customer and earnings are generated, by supporting the application of modular principles.

1.4 Research objectives and research questions

Within the title of this thesis, *Top-Down Financially Driven Modularization*, the modularization part describes a desire to drive the strategy into companies to harvest potential benefits and improve overall competitiveness. This is a response to the trend of globalization, where market demands drive internal complexity up in industrial organizations. Challenges still exist in this area even though the general methodology is well known. The financial aspect should be seen as a response to industry challenges based on a desire to elevate discussions on modularization to a management level with cross-portfolio perspectives. The top-down aspect represents a desire to improve the operationalization of the approach by focusing on the big picture – that is, across product and production solutions and the identification of the main drivers for cost, lead-time, and so on – before going into detail with specific modularization activities.

The following research questions (RQs) describe a collective frame for the research project and have guided the project based on the defined objectives. The first question is exploratory in nature and focuses on understanding the challenges in applying modular principles in an industrial context.

RQ1: What are the strategic and operational challenges in reducing the time from development to earnings using principles of modularization?

To answer the question the existing literature was analyzed, and a number of case studies were carried out in different industries. The cases involved interviews with domain experts and managers and the analysis of company-specific data.

Following the exploratory investigation of the existing challenges, a prescriptive approach was used to answer RQ2, RQ3, and RQ4. The following research question was formulated as a basis for understanding how a top-down and cross-portfolio perspective to modularization could be supported.

RQ2: How can a top-down and cross-portfolio approach to modularization be supported by means of multi-architecture modeling?

A suggested approach for multi-architecture modeling was introduced in two case studies and evaluated in collaboration with industrial partners. Building on multi-architecture modeling principles, RQ3 focused on how to use the cross-portfolio architecture mapping as basis for assessing potential effects of modularization.

RQ3: How can the financial potential for sharing modules and design principles be assessed across an industrial portfolio?

The final research question addressed the challenge related to capturing and communicating a modularization strategy as a basis for supporting day-to-day compliance with the strategy.

RQ4: How can critical decisions on the application of modularization principles be captured and communicated and used as reference for new product and production introduction?

To answer the question a method for capturing the most critical design decisions related to modularization across a multi-architecture portfolio was evaluated in a prescriptive study. Details on the research approach will be explained in the next chapter.

1.5 Thesis structure

Figure 4 provides an overview of the chapters included in this thesis. Chapter 4 presents summaries of the individual research results. For details, including related studies of the literature and detailed descriptions of the individual research designs, see the appended paper in Chapter 9.

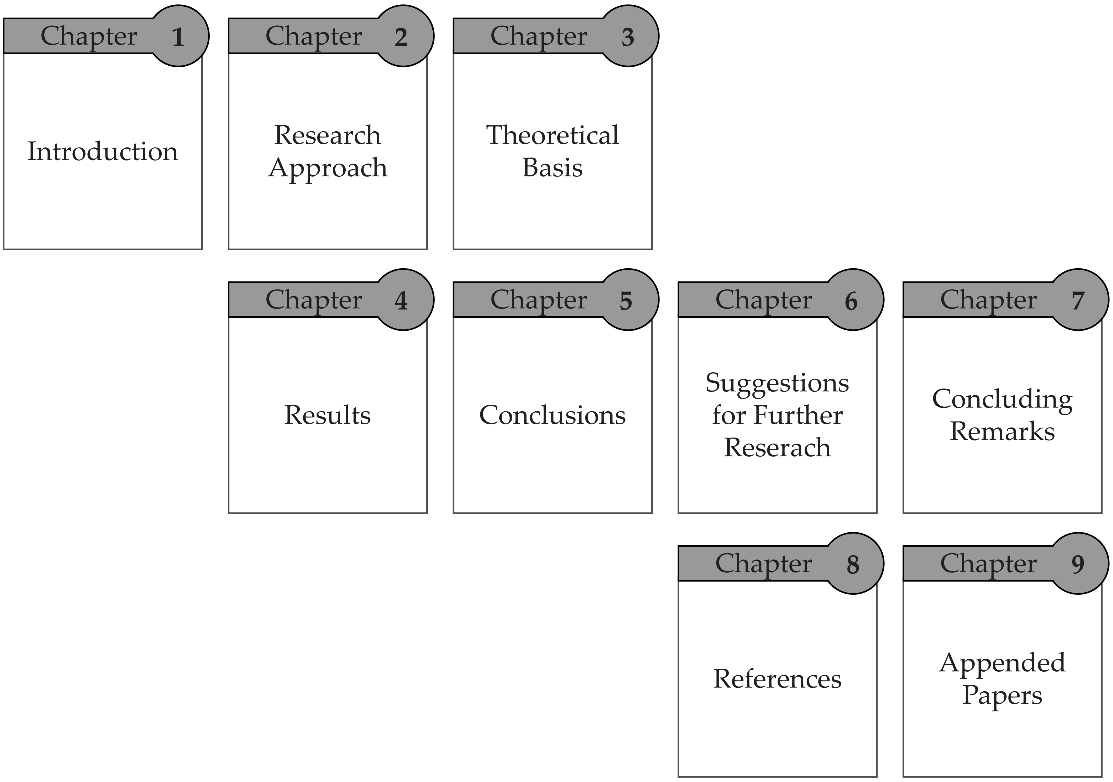


Figure 4: Overview of chapters

2 Research approach

This chapter presents the research approach, scope, and limitations followed by the research methods and the approach to research evaluation.

A number of research activities have been carried out as part of this research project. This includes activities grounded in both practical/problem-based research and in theory-based research.

2.1 Research area

The Areas of Relevance and Contribution Diagram (ARC diagram) (Figure 5), by Blessing and Chakrabarti (2009), is used to illustrate how the project has been scoped. The diagram shows relevant research topics related to this project.

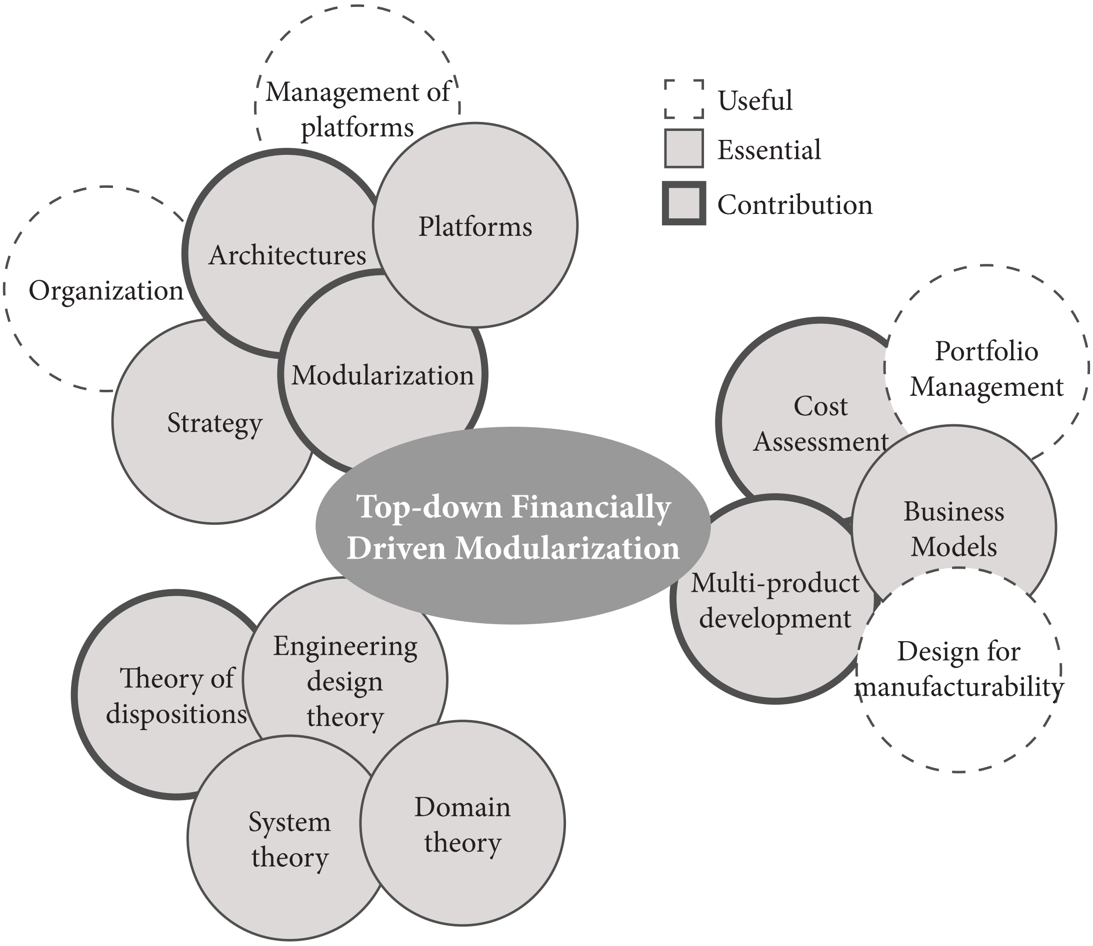


Figure 5: ARC diagram

The center of the model represents the main research subject: “Top-down financially driven modularization.” Relevant research areas were found in engineering design theory, modularization, and multi-product development. The top left cluster represents modularization, including theories of architectures and platforms. This has been a cornerstone of this research project. The management of platforms and organization for platform-based development are areas found useful for bringing insights to the research project. The existing research within engineering design theory (the bottom left cluster) has created the foundation for understanding systems, such as modeling principles and functional decomposition of products, production, and service systems and how dispositional effects influence the lifecycle of systems. Finally, the right cluster represents the field of multi-product development, including a focus on cost assessment. An area of interest has been portfolio management and how high-level decisions are made on portfolio optimization.

2.2 Research methodology

Design Research Methodology (DRM), by Blessing and Chakrabarti (2009), has been used as research framework in this research project. DRM is widely recognized in the field of Engineering Design and is well suited for research focused on developing support for various disciplines in engineering design. Furthermore, the research approach applied in this project draws on the Problem-based and Theory-based approach by Jørgensen (1992).

2.2.1 Problem-based and theory-based approach (PbTb)

The PbTb approach suggested by Jørgensen (1992) provides the basic understanding, that a research problem can be approached with a theory-based perspective and a problem-based perspective (Figure 6). The theory-based track represents studying the state-of-the-art within the existing literature as the basis for synthesis and model generation. The problem-based perspective focuses on industrial challenges and how empirical studies, diagnosis, and synthesis can lead to new scientific acknowledgements. Jørgensen (1992) argues that attention should be paid to both tracks to ensure results grounded in both theory and real-world problems. Both perspectives have been applied in this research project as integrated parts of the DRM stages.

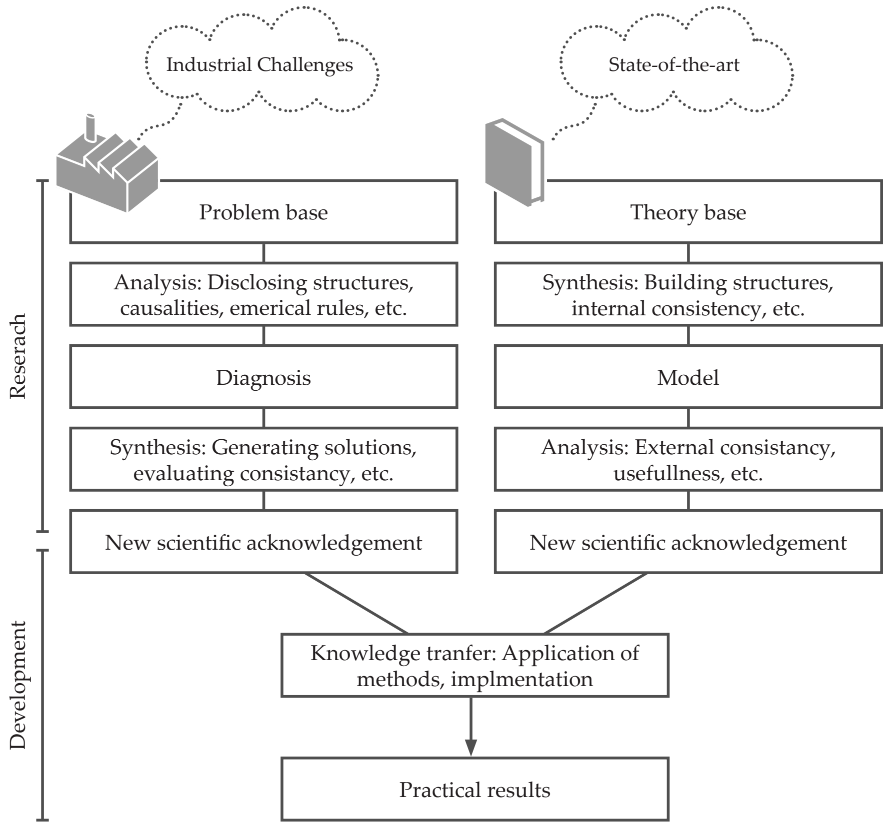


Figure 6: Problem-based and theory-based approach, redrawn form Jørgensen (1992)

2.2.2 *Design Research Methodology (DRM)*

DRM includes four main stages, which together frame the process of developing design support (i.e., knowledge, guidelines, checklists, methods, tools, etc.). The stages are not necessarily seen as a chronological list of activities, but rather as a guide for stages to go through. The four stages are as follows:

- Research clarification (RC): In this stage the research is framed and an idea of a desired future situation is formed on a conceptual basis.
- Descriptive study I (DS-I): The descriptive stage focuses on the analysis of the literature and empirical data to build up further understanding of the research problem, relations between factors involved and further clarification of the desired future situation. An initial reference and impact model is created. The model provides an overview of the research scope and how measurable success criteria for the research can be formed.
- Prescriptive study I (PS-I): The prescriptive study is focused on introducing the developed support on a conceptual basis. This should be done so that it is possible to evaluate its effects.
- Descriptive study II (DS-II): The second descriptive stage aims to create an understanding of the situation where the developed support has been

introduced. The main activity in this stage is to assess the impact on the existing situation and to suggest improvements for the support. Thus, this is not necessarily the final stage but can lead to further descriptive studies or successive prescriptive studies.

Figure 7 illustrates the stages, main outcomes and basic means in the DRM framework.

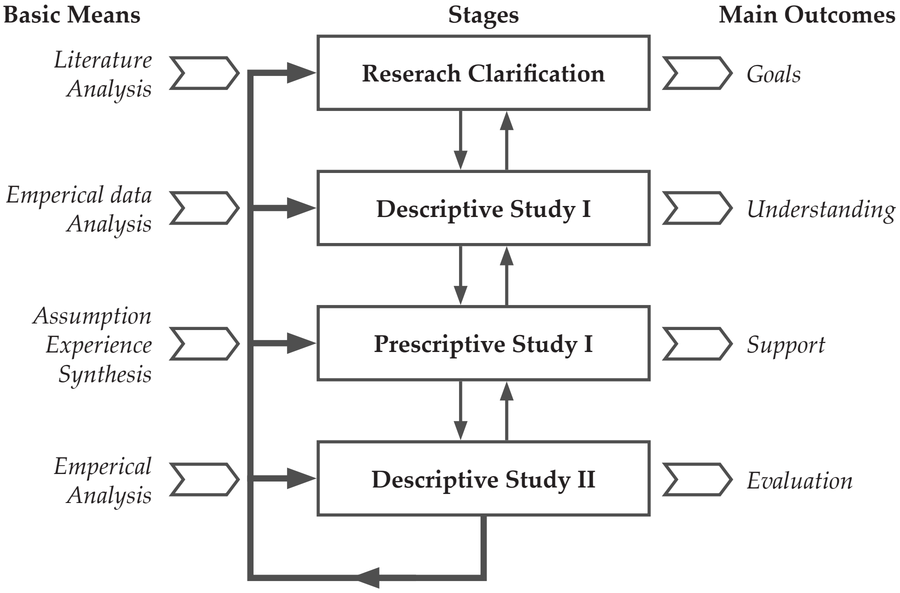


Figure 7: Stages, basic means and main outcomes in the DRM framework, redrawn from Blessing and Chakrabarti (2009).

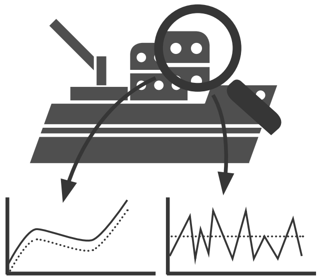
2.3 Research design and activities

The following will describe the DRM stages and activities carried out during this research project. The process has not been linear, and input from the descriptive and prescriptive stages has continuously contributed to the research clarification.

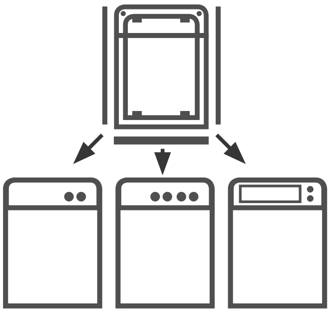
2.3.1 Research clarification (RC) and descriptive study I (DS-I)

The initial clarification was from an academic and practical perspective focused on scoping the project relative to MADE WP1 (reducing time from development to earnings by means of modular principles).

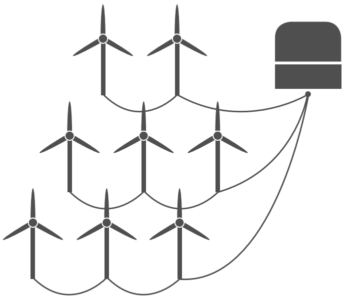
From a problem-based perspective, the first research clarification was based on four case studies in different industries. Studies A, B, C, and D have all contributed to an understanding of the challenges in industry related to applying modular principles and the needs for support. The contributions from the cases to the DS-I stage are described in brief in the following paragraphs. Details on the individual cases are elaborated in Section 2.4.1.



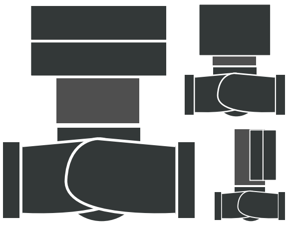
CASE A: In an engineering consultancy with activities in the maritime, energy and transportation sectors, former projects were mapped and analyzed to understand the challenges in delivering consultancy services to a broad spectrum of customers in different industries and different geographical location. This included analyzing the profitability of the individual projects and challenges related to execution. The study created the foundation for the development of a top-down approach to service delivery based on a set of modular principles. The approach and results are described in Paper E.



CASE B: Engagement with management from a large manufacturer of white goods gave insights into the modularization challenges in a company focusing on high product variance and high sales volumes. The company had extensive experience with modularization and had recently increased its focus on the financial aspects with the intention to drive the initiative further in the organization. The study gave input to the methods and challenges in assessing financial potentials for modularization. The study contributed to the validation of the Architecture Evaluation and Mapping (AME) approach, presented in Paper A.



CASE C: For a contractor of large-scale wind farms, the roadmap of projects was analyzed. Different architectures for wind farms were mapped, and discussions of where similarities should exist and the need for customization were held with management. The installation process was in focus with the purpose of identifying how the decoupling of system dependencies could help speed up time from construction to the first power generation. This was directly linked to potential financial gains for the company. The study gave insight into the challenges existing in developing very large and complex systems. The study contributed to the understanding of how to map multiple architectures across a portfolio and use this mapping as a basis for synthesizing future scenarios. This study contributed only to the descriptive stages of this research project.



CASE D: A comprehensive study was executed in collaboration with a large pump manufacturer. This study was divided into three stages. The first focused on the DS-I stage, and the next two on the PS-I stage. The analysis of former projects focused on new product introductions, giving input to the DS-I stage. This analysis included assessing planned vs. actual delivery performance in terms of investments, development time, and cost levels. The company had historically developed product families with a level of embedded modularity to enable Mass Customization (MC) (Pine, 1993; Hvam et al., 2008). The study gave in-depth insights into the challenges existing in executing a strategy based on modularization principles in a "high product variance and high volume" context. The two subsequent stages focused on the introduction and evaluation of suggested methods and tools. This is further elaborated in Section 2.4.1 and in papers B and C.

The main inputs to the RC and DS-I stages from the case studies area as follows:

- Modularization received relatively low priority – one reason being that the effects were long-term and considered unclear.
- Previous modularization initiatives had varying effects when launching new products or product variants.
- There was limited organizational responsibility for cross-portfolio decisions, for example, the sharing of standardized solutions.

From a theory-based perspective the literature within relevant areas was analyzed (Figure 5: ARC diagram) as input for the RC and DS-I stages. This was a continuing process as new insights were obtained throughout the project. Figure 8 gives an overview of how the areas of relevance relate to the papers and research questions. The search for relevant literature was done using Mendeley and Google Scholar, linking to major indexing databases, such as Web of Science and Scopus. An elaboration of the key literature can be found in Chapter 3.

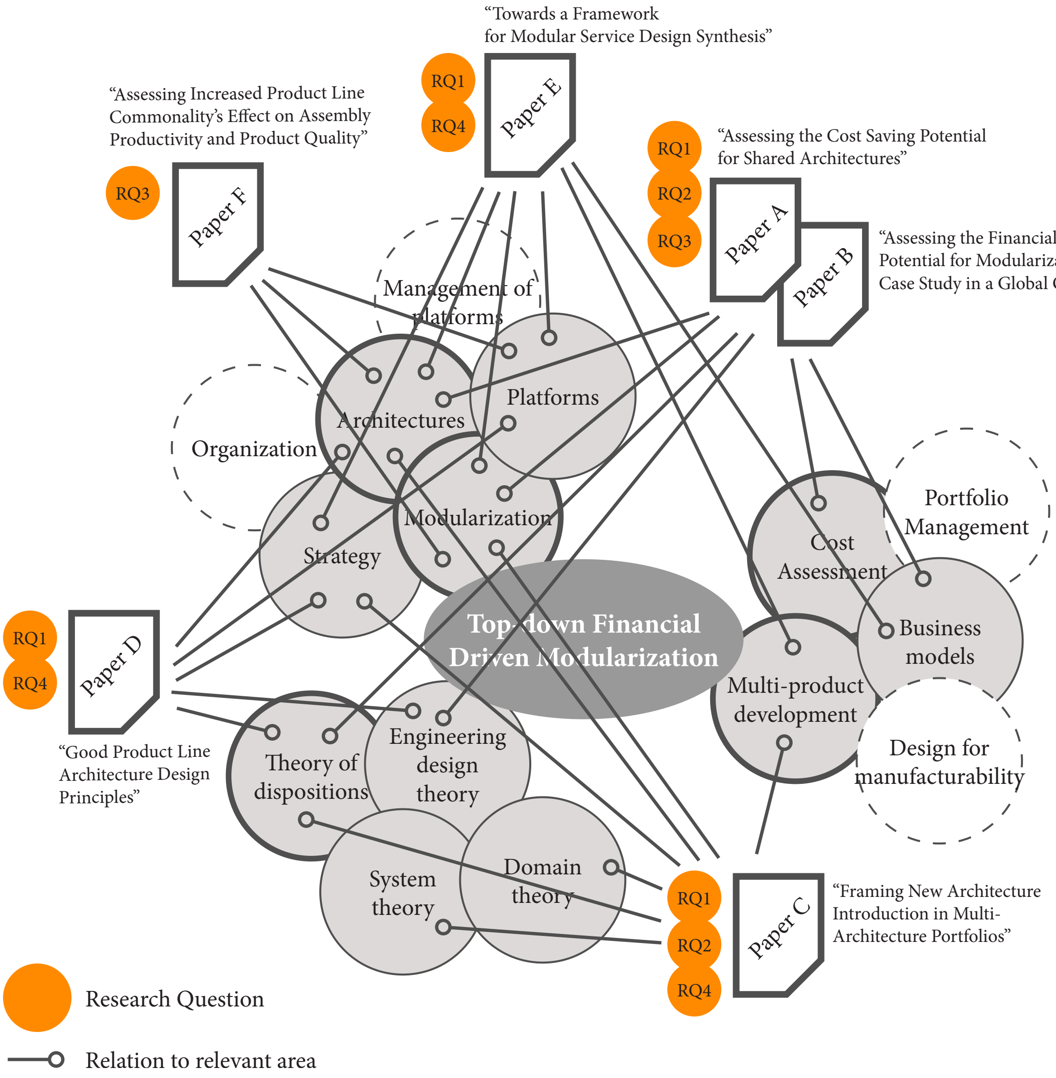


Figure 8: Relating ARC Diagram, Papers and Research Questions

As described in the introduction, a number of papers reviewing the existing literature in the field of modularization, platforms and architectures have, furthermore, been used to establish a preliminary and overall understanding of existing theoretical gaps (Bonvoisin et al., 2016; Campagnolo & Camuffo, 2010; ElMaraghy et al., 2013; Jiao et al., 2007; Piran et al., 2016).

2.3.1.1 *Reference model and measurable success criteria*

A general challenge recognized in the research clarification was the difficulty in assessing the impact of the research over a longer time period, for example, MADE: "strengthen the competitiveness of Danish industry" and the WP1 goal: "reducing time from development to earnings using modular principles." To be able to assess whether the suggested support would have a direct effect, a project had to be followed from concept to product launch and further, when earnings were generated. In the industries involved with this research project, this would demand years of engagement, and still data would be limited to a few projects. Thus, the reference model (Figure 9) illustrates how this challenge was broken down into a number of measurable success criteria and key factors: “number of architectures in portfolio” and “%-reuse of standardized modules and design principles.”

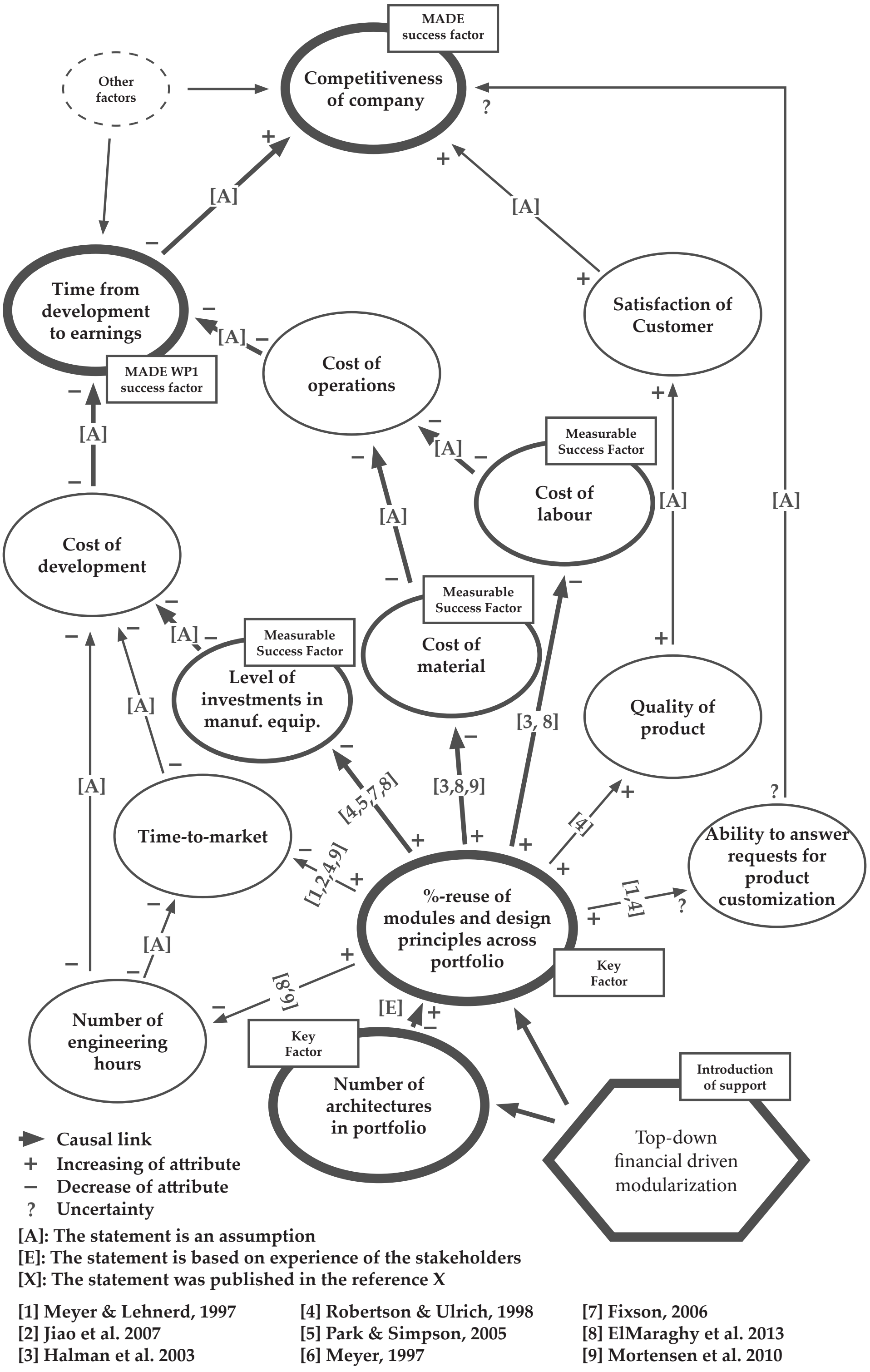


Figure 9: Reference model

The key factors are formulated with input from related theory and the identified industrial challenges. Generally, the focus was to increase the cross-portfolio reuse of standardized modules or design principles. Several effects are documented, as can be seen in the model. The other key factor was defined as "number of architectures in portfolio." Industrial companies often develop and launch new products in a sequential process, one at a time, leading to growing portfolio complexity, as indicated in papers A, B, and D. The result is an undesirable number of architectures across an industrial portfolio. As illustrated in the Reference Model, a hypothesis in this research is that the number of architectures can be reduced to improve the overall ability to implement modular principles and improve the sharing of standardized elements across the portfolio.

Through the use of causal links, the key factors were connected to the overall research goals. "Other factors" play a role in this as well, for example, maintenance and overheads will also influence the "cost of operations." Generally many other factors can also influence the overall research goals; however, the reference model gives an overview of the thinking pattern applied in this research project. The suggested support for top-down financially driven modularization was generally considered successful if it was able to support the key factors assessed through the measurable success criteria. The qualitative and quantitative assessments of the support are discussed in Chapter 5.

2.3.2 Prescriptive study (PS)

The prescriptive part of the research focused on the introduction and test of suggested methods and tools in an industrial context. This has allowed the evaluation and further development of these tools.

- A top-down approach to modularization was introduced and tested in Case A. The results led to a suggested approach for modular service design synthesis (as described in Paper E).
- The suggested Architecture Mapping and Evaluation (AME) approach was introduced in Case B (as described in Paper A). This was an extensive study, and only parts of the prescriptive application were linked to this research project. However, the initial study allowed an evaluation of the effectiveness of the approach to further develop and formulate the concept.
- The AME approach was applied in another prescriptive study, in Case D, to further evaluate and validate the approach (as described in Paper B).

- The suggested principle of modeling Business Critical Design Rules (BCDR), was finally applied in Case D as a basis for evaluating the suggested method (as described in Paper C).

2.3.3 Descriptive study II (DS-II)

The final descriptive stage focused on an overall research evaluation of the suggested tools and methods. The evaluation was based on the results generated in the prescriptive stage in relation to the individual contributions. The overall purpose of the evaluation is to build confidence in the method's ability to improve the key factors (Figure 9). The research evaluation of methods and tools can generally be difficult as rigorous and quantitative validation based on mathematical or statistical means is often difficult (Frey & Dym, 2006; Seepersad et al., 2006). The Validation Square (Pedersen et al., 2000) was instead used as a framework for the research evaluation (Figure 10). The framework considers the appropriateness of the examples/cases and the effects of the contribution. The framework argues that the usefulness of the contribution can be evaluated based on both qualitative and quantitative measures.

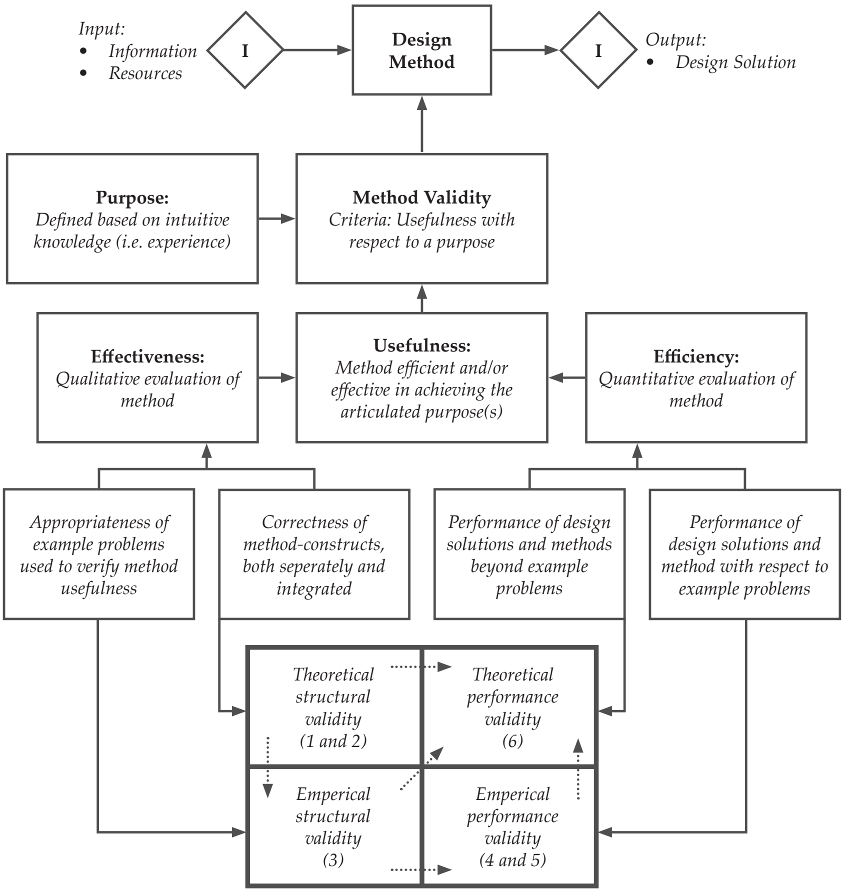


Figure 10: The Validation Square, redrawn from Pedersen et al. (2000)

Pedersen et al. (2000) formulated six theorems (1,2,3…,6). One through three are formulated to ensure the effectiveness of the research results:

(1) Accepting the individual constructs constituting the method
(2) Accepting the internal consistency of the way the constructs are put together in the method
(3) Accepting the appropriateness of the example problems that will be used to verify the performance of the method

Four through six are formulated to ensure efficiency of the research results:

(4) Accepting that the outcome of the method is useful with respect to the initial purpose for some chosen example problem
(5) Accepting that the achieved usefulness is linked to applying the method
(6) Accepting that the usefulness of the method is not limited to and extends beyond the case studies

The individual theorems are discussed in Section 5.3 in relation to the individual contributions presented in this thesis

2.4 Methods

This part describes the research methods used in the descriptive and prescriptive parts of the research. The selected methods were highly participatory, where the research was done in close collaboration with industry with the starting point in industrial problems. This approach was selected, as the research goals were to develop applicable tools and methods addressing industrial challenges. As indicated in Section 2.2.1, this was backed by a theory-based approach drawing on the research fields as shown in Figure 5: ARC diagram. Two basic methods are used: (1) Case Study Research (CS) and (2) Action Research (AR). In short, the difference between the two methods in this project is as follows:

- In CS the researcher primarily acts in an observer role.
- In AR the researcher interacts with the case company as part of the design team on equal terms with other parties, such as company employees.

It is possible to apply an AR approach in a case study, thus both observing and interacting with the case company.

2.4.1 *Case study research (CS)*

The conduction of case studies as a basis for collecting empirical data is a well-established practice within several research fields. Yin (2009) argues that CS is a good option when the research focus is on contemporary phenomena within a real-life context. As described in Section 2.3.1: Research clarification (RC) and Descriptive study I (DS-I), fours cases were used as the empirical basis for this research project. The individual studies were not direct replications and cannot be seen as forming a multi-case design. However, the focus and goals for each study have revolved around the research questions and, thus, can be seen as contributing to the support of top-down financially driven modularization. Table 3 provides an overview of the cases.

Table 3: Overview of cases

Case	Case company	Business sector	Comapny size	Duration of case study	Research activities
A	Engineering concultancy	Service	>500	6 months	Case study research Action research
B	White goods manufacturer	OEM	>50.000	1 month	Case study reserach
C	Wind turbine installer	Contracting	>5.000	1 month	Case study reserach
D	Pump manufacturer	OEM	>15.000	27 months	Case study reserach Action reserach

Case A: Semi-structured interviews were held with specialists and managers to (1) understand how applying principles of modularization could support operations, (2) clarify the challenges and obstacles in applying modular principles in the company context, and (3) evaluate the suggested design support for top-down modularization. Workshops were held with specialists and managers with a focus on synthesizing the contextual design support. Furthermore, a data-driven approach was applied in the clarification of the existing challenges. The analysis focused on the cost and performance of former projects, such as activities performed, profitability, timeframes, and deviations from planned vs. actual execution. The analysis later allowed an evaluation of the developed support by comparing the existing situation (as-is) with the potential new situation (to-be). See Paper E for more details.

Case B: Semi-structured interviews were used to understand the managerial challenges of modular platform-based product development and production in a large organization. A workshop was held with executive managers where the suggested principles for top-down financially driven modularization were discussed; special focus was on the mapping of the as-is scenario, including the use of financial data and how the mapping could be used as an argument for modularization. Furthermore, the suggested AME approach was tested, as presented in Paper A.

Case C: Semi-structured interviews with managers and senior specialists provided insights into the challenges of large-scale wind turbine installation and an understanding of how the decoupling of system dependencies could support an improved business case. Conceptual scenarios of possible future and modularized designs for wind farms were discussed. The case provided input to the mapping of existing architectures and the discussion of optimal number of architectures in a portfolio.

Case D: This study was divided into three stages. The first stage focused on the clarification of the challenges in the organization related to modularization and platform-based product development. Former projects were analyzed through interviews with project managers and specialists, going through project reports (e.g., status reports and CAD drawings), and analyzing financial data (e.g., sales numbers, cost levels, and investments). The two following stages included prescriptive elements. In the first, support was introduced for assessing the financial potential for modularization. This was done through weekly “meet-and-work” sessions in the case company. In each session specialists and managers engaged in mapping the “as-is” and “to-be” scenarios and the assessment of the financial potential based on a delta between the two scenarios. The second stage was focused on further synthesizing the future scenario for top-down, portfolio-wide modularization. The suggested support for framing the new product development was based on a number of business critical design rules (BCDRs) that were introduced. The two last stages were executed in close collaboration with a core team of 20 specialists, engineers, researchers and managers.

It must be recognized that challenges exist in CS. This includes biases of the parties involved possibly influencing the direction of the findings. The selective nature of the studies makes broad coverage difficult, for example, in several cases it was difficult to give all areas of a large industrial portfolio the same attention, which can be a disturbing factor in the conclusions made in the specific studies. However, the approach was considered the best possible way to ensure the research was anchored in industrial challenges. The validity of the research results and case studies is discussed in Chapter 5.

2.4.2 Action research (AR)

The practical problem-based perspective applied in this research draws a great deal on elements of AR. AR methods seek to create knowledge that is based on practices with the aim of solving practical problems and extracting emerging theories and results. In AR the researcher engages a real-world problem with research themes and takes part in the situation, which enables reflection on the involvement. This leads to findings and new research themes (Checkland & Holwell, 1998). Different definitions exist of what AR is, but commonly the emphasis is on the participation of the researcher *in* action, in contrast to researching *about* action (Coughlan & Coghlan, 2002). Kemmis and Wilkinson (1998) describe the conduction of AR as a spiraling process, going through planning, acting and observing, reflecting, and then re-planning. The process can go in several loops as findings are continuously generating. This is somewhat similar to the descriptive/prescriptive loop in DRM, and the AR method was used in the cases A, B, and D.

Commonly an AR-based approach is criticized for resembling pure practical problem-solving. If the research does not have a strong offset in related theory, this criticism can be legitimate. By the researcher, reflections must be made from a theoretical perspective to formulate a research contribution. If executed correctly this is, however, one of the strengths of AR as the theory-based and problem-based perspectives are considered concurrently. Thus, the approach was found to be well-suited as a research method in this project.

2.5 Overview of DRM stages

Figure 11 provides an overview of how each DRM stage relates to the defined research questions and which research methods have been used.

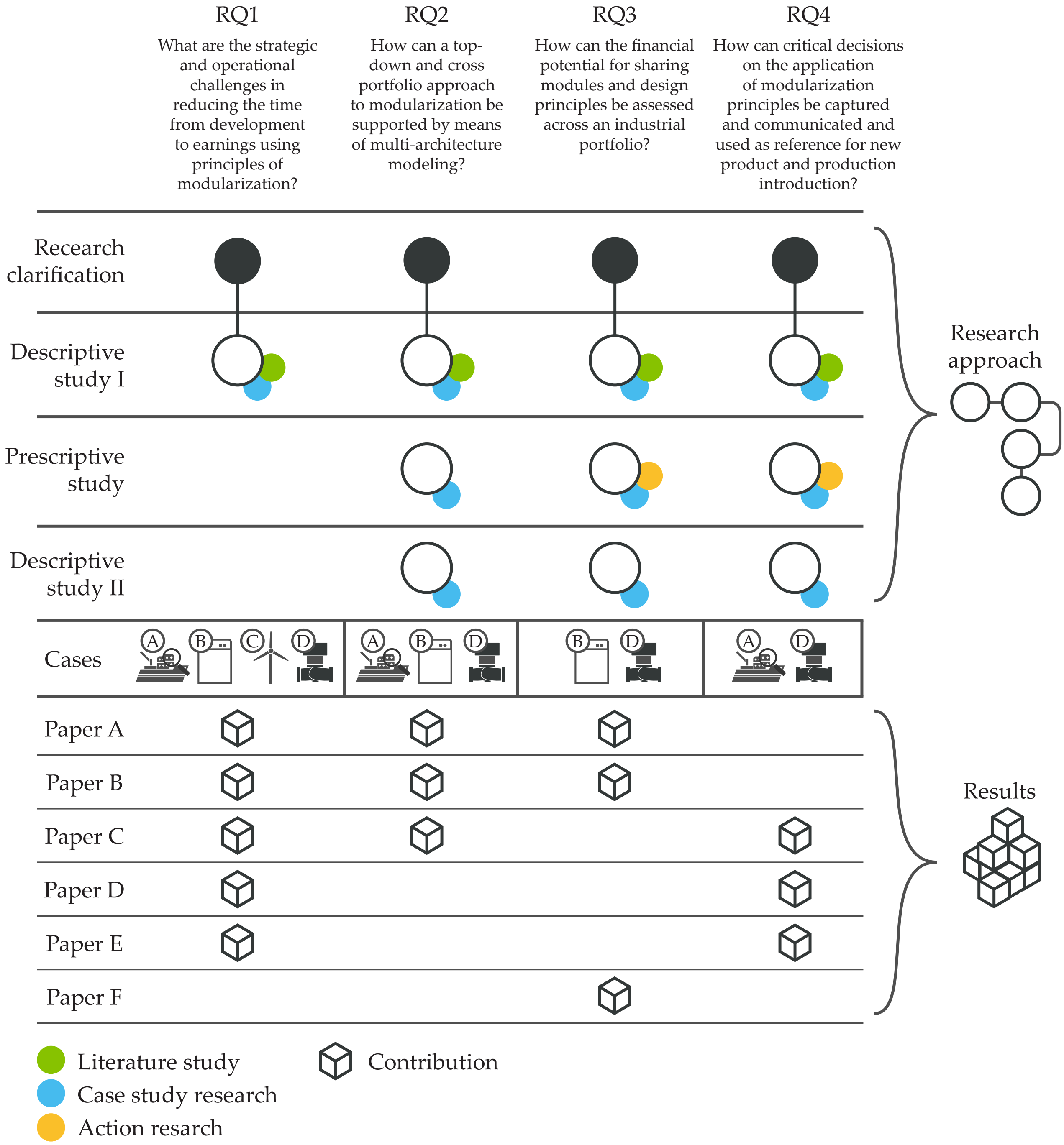


Figure 11: Research approach and contributions

The results of this research project are presented in the appended papers. A summary of each paper can be found in Chapter 4. The collective contribution to Top-Down Financially Driven Modularization is discussed in Chapter 5.

2.6 Other research activities

A number of other activities have been part of this research project. This includes the dissemination of knowledge, workshop sessions and discussions on suggested methods and tools, and a number of courses.

2.6.1 Dissemination of knowledge

Throughout the project preliminary results, theories and concepts have been shared with peers from both industry and academia. This has helped to form and scope the research project. The following outlines the essential activities:

- Seminar on modularization, Grundfos A/S, Bjerringbro, February 2015
- Presentation of methods at MIT, Cambridge, MA, USA, July 2016
- Presentation at MADE PhD Conference; Aalborg University, Denmark, 2015
- Workshop at MADE PhD Conference; Technical University of Denmark, 2016
- Workshop at MADE PhD Conference; University of Southern Denmark, 2017
- Presentation MADE Mini conference, Danish Technology Institute, 2017
- Presentations at steering group meetings MADE WP1: 2015, 2016, 2017.
- PhD Seminar, DTU, 20th April, 2017
- Presentation at MADE Annual meeting, Bjerringbro, Denmark, 2016

2.6.2 Courses

- *Design Research Terms and Methodology for PhD Students (Special Course)*
    - Held at the Technical University of Denmark. Focused on research methodology, primarily DRM.
- *How to Write a Scientific Paper (Course 11621)*
    - Held at the Technical University of Denmark. Focused on increasing skills in scientific writing.
- *IS3E 2016 (4th International Spring School on Systems Engineering)*
    - Held at the Technical University of Denmark. Focused on gaining insights into state-of-the-art in Systems Engineering.
- *Design of Lean Production and Service Systems*
    - Held at the Technical University of Denmark. Focused on design of production systems based on LEAN principles.
- *Product Platform and Product Family Design: From Strategy to Implementation*
    - Held at Massachusetts Institute of Technology. Focus on product platform development, methods and terminology.

2.6.3 Alexander Foss MADE Award nominee

In 2015 the project was nominated as one of three for the Alexander Foss MADE Award. The award was given to a researcher working on a MADE-related project (this counted around 30 in 2015) based on anticipated industrial impact and likelihood of implementation. The nomination was based on the preliminary results generated in the prescriptive stage of this project. Comments from the case company leading to the nomination included the following:

"What is special in Martin's work is to see the architecture and platform work as an integrated process covering both the product and production. We are convinced that when both product and production architectures have been defined and we have appointed a fewer number of platforms across the product portfolio we will achieve a simplified development task. That means a better hit rate and significant faster time-to-market. Operations expect better equipment utilization and as a whole more efficient production. (The company) is therefore convinced that when the current architecture and platform work have been implemented it can contribute to a significantly improved competitiveness and business for (the company)."

Director of Technology, Case Company

"From the very beginning of Martin's project at (the company), we have seen that his research approach has brought new insights and learning to (the company), which are directly applicable to meet the challenges that the company currently is struggling with. It is our strong believe that Martin's way of working, by for example including and involving relevant persons from all over the organization, will contribute to a successful implementation of new knowledge to (the company). Without compromising his basic ideas, Martin, furthermore, effectively managed to adapt his research approach to (the company's) way of thinking in order to meet the actual industrial context. This means that the involved industrial practitioners understand and respond positively to new ideas. Hence, Martin's ability to have research theory meet the practical world will definitely improve the chances for a constructive and successful implementation process."

Chief Engineer, Case Company

3 Theoretical basis

This chapter describes the theoretical basis for the research project.

Before presenting and discussing the research results, it is necessary to create an understanding of (1) how systems are understood and defined in this research project, (2) what defines modular principles, and (3) the implications of the development of new and multiple products and production systems based on modularization principles.

3.1 Systems theory

Systems theory creates the foundation for how systems are understood – that is, which laws, methods, and modeling principles exist for systems – objects with a system nature (Mortensen, 1999). With a basis in mechanical engineering, the Theory of Technical Systems (TTS), presented by Hubka and Eder (1988), represents a major contribution to the understanding of systems. TTS defines a technical system as a concept used for describing a set of related elements. The system is delimited by a system boundary, which separates the elements from their surroundings. Relations exist between the elements of the system and elements outside the system boundary. Together these relations and elements are what describe the system's structure. As a system can be many things, Hubka and Eder (1988) classify different types of systems to give an understanding of what a technical system is (Figure 12).

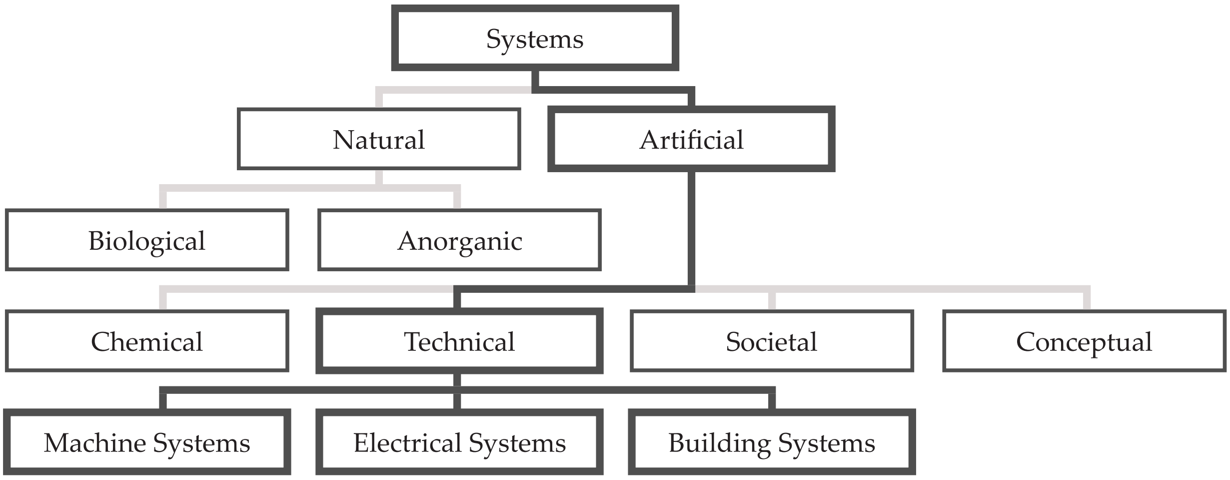


Figure 12: Types of systems, redrawn from Hubka and Eder (1988)

Building on the theory, Andreasen et al. (2015) provide a definition of a system as follows:

> *"a system is a model of an object (a real or connived product or activity) based on a certain viewpoint, which defines the elements of the system and their relations. A system carries structure, i.e. the elements and their relations (arrangement, architecture) and behavior, i.e. the system's response to a stimulus depending on stimuli, structure, and state."*
>
> (Andreasen et al., 2015)

Based on this definition and adopted from Hubka and Eder (1988), Figure 13 illustrates the general model of a system.

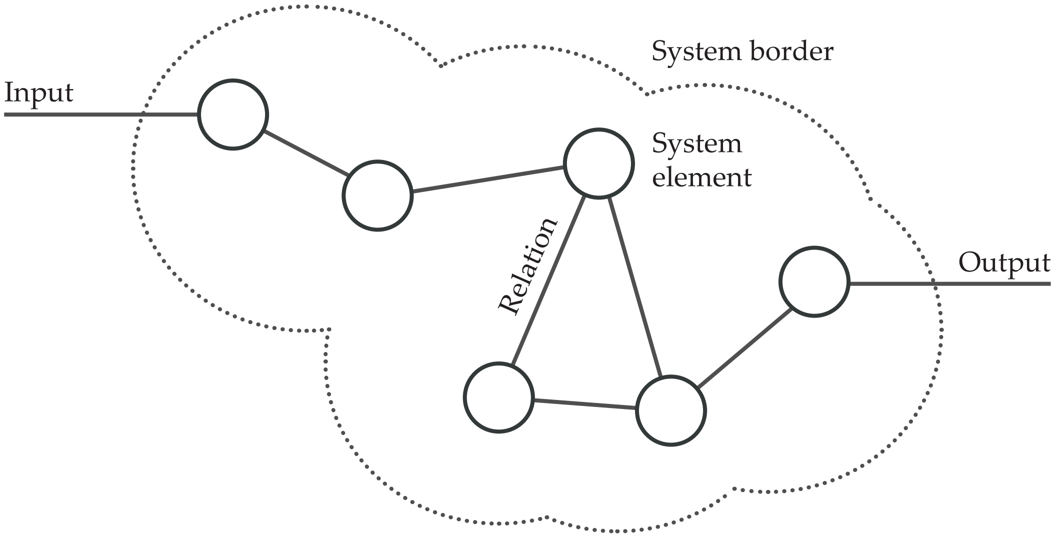


Figure 13: Model of system in general, redrawn from Hubka and Eder (1988)

It is necessary to go a step further to understand what defines the relations between elements in a system. This is the prerequisite for the decoupling of system dependencies and system modularization.

In TTS the Transformation System describes how a system works – that is, transforming an input to an output. With input from the human system (the user), the technical system (the product), the information system, and the management system, the transformation process converts an operand from an input to an output within a defined environment (Figure 14).

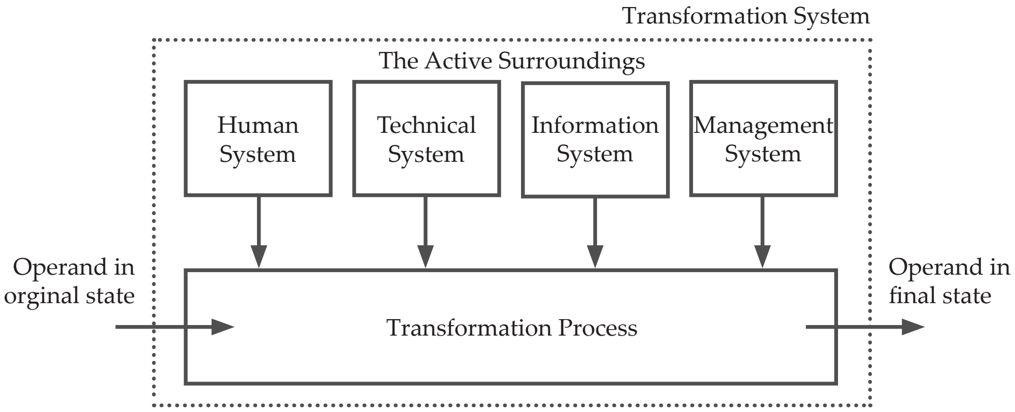


Figure 14: The Transformation System, redrawn form Hubka and Eder (1988)

The operands are generally defined as material, energy, information, or living things. The transformation system gives an idea of the nature of interactions and relations in a system. Andreasen (2011) proposes, more generally, that the attributes of a system can be defined as follows:

- Characteristics: structural attributes defining what the system *is* – the system elements and relations.
- Properties: Behavioral attributes, describing what the system *does* when exposed to an input.

This means, that a system's structure can be seen as a composition of characteristics, where some define the system elements and others the system structure – that is, elements and their relations. The properties are contextual and are present when the system operates in synergy with someone or something. In his Domain Theory Andreasen (1980) proposed concepts to articulate the relations between system characteristics and properties. The Domain Theory introduces three views, including the activity view, the organ view, and the part view. The three views describe how the product is used, how it functions and how it is built up.

- **The activity domain**: Single or a sequence of transformations in which the product system is used. When the product system is in use, it contributes to the transformation of operands – material, energy, information, or biological objects characterized by the input and output state.
- **The organ domain**: Functional elements of a product. An organ is an object that acts when external effects act upon it, delivering an effect on its surroundings. The input and output may be in the form of material, energy, information, or biological objects.

- **The part domain:** Material elements of the system. Parts are the building elements of an organ, realizing the organ's function. The parts interfaces with other parts and the surroundings, creating the effect of the part.

The Domain Theory allows the linkage between views as a concept for relating, for example, functions to parts in a system. Andreasen et al. (2004) generalize the system relations and suggest a focus on functional relations (organ logic), flow relations (material, energy, information), space relations (arrangement), and disturbing relations (emissions, safety, etc.), when designing modularity into a system.

Parslov (2016) builds on TTS and DT to generally and explicitly define system relations – in other words, the interfaces in the architectural decomposition of complex systems. He distinguishes between *interactions* and *interfaces* and describes an interface as an *infinitely thin plane*, without function, between two system elements. *Interactions* are described as the functions and processes acting across an *interface*, for example, material, energy, or information flows.

Bruun et al. (2014) introduce the interface diagram as a visual representation of a complex system illustrating interfaces and interactions between system elements (key components). Figure 15 is an example of such a diagram, where key components are modeled and interfaces/interactions are illustrated. The Interface Diagram can be seen as illustrating the architecture of the system.

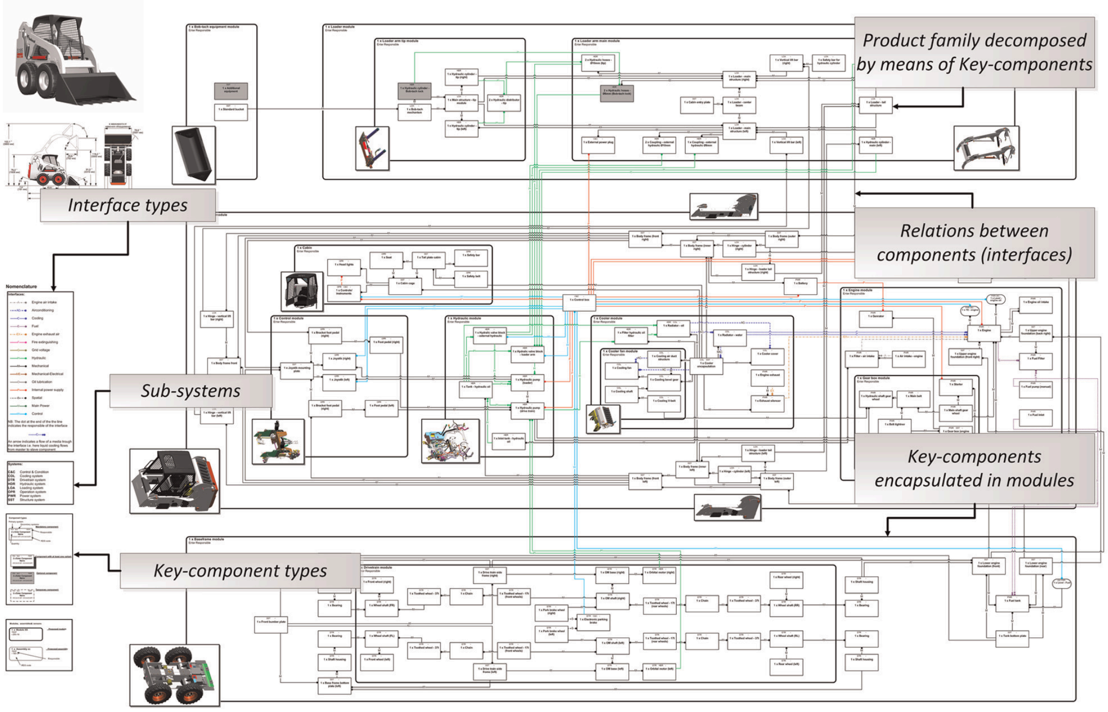


Figure 15: Interface Diagram for a complex system, adapted from Bruun et al. (2014)

The Interface Diagram builds on Domain Theory and provides a basis for an understanding of how complex systems can be modeled with respect to relations between system elements. The diagram provides a basis for modularization and is in this research used as the basis for system modeling.

3.2 Modularization

The basic concept of modularization is described in the introductory parts of this thesis. This part focuses on the definition of the key constructs within the field of modularization. The core concept is to embed a degree of modularity in the architecture of a system (Mikkola, 2006), thus decoupling dependencies between system elements (Baldwin & Clark, 1997). Doing so will result in the creation of a number of modules. Several definitions can be found of what a module is, and this research applies methodology from Engineering Design as basis for the understanding the phenomenon.

Ulrich (1995) applies a function perspective and defines a modular architecture as including: "*a one-to-one mapping from functional elements in the function structure to the physical components of the product and specifications of de-coupled interfaces between components.*" This means that a module holds a specific functionality, defined by a set of components. A module can be changed without having to redesign other components in the system; this is facilitated through interface specification. Baldwin and Clark (2000) extend the definition to generally include relations between system elements. Thus, they use the definition of a module as: *"a unit whose structural elements are powerfully connected among themselves and relatively weakly connected to elements in other units,"* meaning that modules are units in larger systems that are structurally independent but work together. A key concept is interface standardization as an enabler for the decoupling of dependencies in a system.

The module drivers introduced by Östgren (1994) describe 12 heuristics for modularization. The Module Drivers provide a general description of the reasons for embedding modularity in the architecture of systems (Ericsson & Erixon, 1999).

Table 4: Module drivers

Product development and design	
Carry-over	To be re-used in next generation
Technological evolution	To enable new solutions from suppliers
Planned design changes	To be improved separately
Variance	
Technical specification	To isolate variance

Styling	To isolate design, brand, etc.
Production	
Common unit	To protect high volume
Process and/or organization re-use	To protect scarce resource/process
Quality	
Separate testing of functions	To be tested separately
Purchasing	
Supplier offers black box	To be developed, produced, etc. by partner
After sales	
Service and maintenance	To be easy to replace in the field
Upgrading	To increase after sales
Recycling	To protect environment

Thus, when talking about modular principles in this research project, it should be seen as the meaningful decoupling of dependencies within the architecture of a system to create modules, which are strongly connected among themselves and weakly coupled to other parts of the system, to achieve the selected effects of the modular drivers. The decoupling of system dependencies is facilitated through interface standardization achieved on an abstraction level, as illustrated in the Interface Diagram.

3.2.1 Modularization in different domains

Principles of modularization can be found within different fields, such as software, services, biology and production. Different approaches and methodologies exist within the fields. However, the approach applied in this research is based on TTS, DT, and the theory of dispositions (TD) and is grounded in mechanical engineering. The hypothesis is that the theoretical basis and core principles, such as interface standardization, can support modularization within the domains of service and production systems.

3.3 Multi-product development

Modularization can be used as basis for multi-product development, such as by enabling the mixing-and-matching of modules to create new products, as known from MC. Architecture is a key concept related to modularization and mulit-product development and can be seen as a carrier of structural and functional design decisions (Fixson 2005; Gudlaugsson et al. 2014). The following definitions of architectures create the theoretical basis used in this thesis:

- An architecture is “(1) the arrangement of functional elements, (2) the mapping from functional elements to physical components, (3) the specification of interfaces among interacting physical components" (Ulrich, 1995).

- "An architecture is a purposefully aligned structure of a system." (Andreasen et al., 2004).
- An architecture is "a structural description of a product assortment, a product family or a product. The architecture is constituted by standard designs and/or design units. The architecture includes interfaces among units and interfaces with the surroundings" (Harlou, 2006).

Describing the architecture of a system is an essential enabler for platform-based product development (Simpson et al., 2014); and where the architecture represents the structural and functional decomposition of a product, a platform describes the collection of modules or parts from which specific products can be derived and efficiently launched (Meyer & Lehnerd, 1997). Robertson and Ulrich (1998) expand this definition to describe a collection of components, processes, knowledge, and people and relationships shared by a set of products.

Meyer and Lehnerd (1997) introduced the Power Tower, which links platforms to different market segments. Four inputs are used to define the platform – consumer insights, product technologies, manufacturing processes, and organizational capabilities (Figure 16).

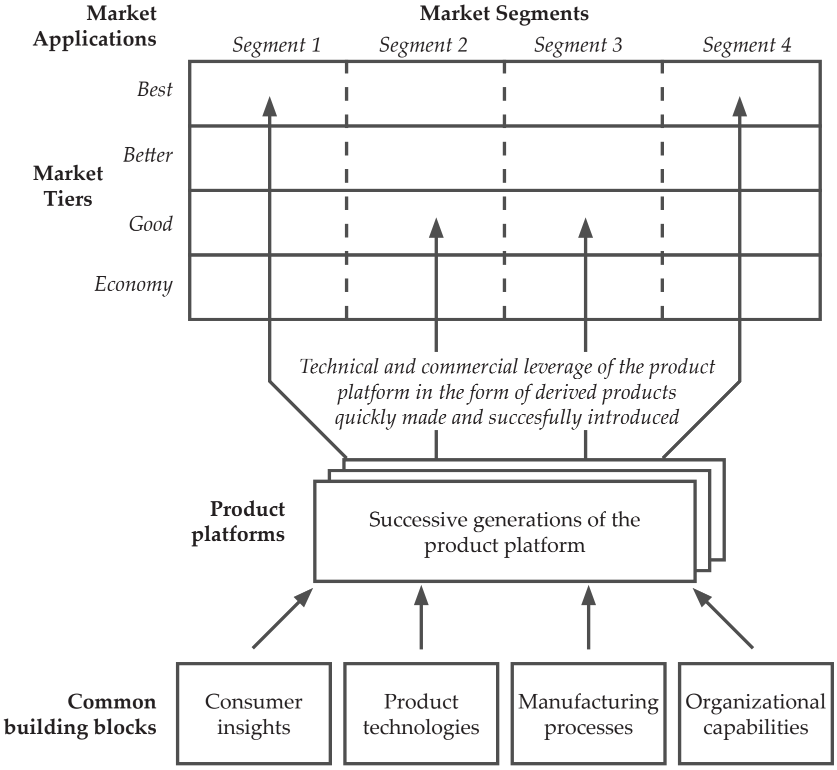


Figure 16: Power Tower, redrawn from Meyer and Lehnerd (1997)

As defined by Andreasen et al. (2004), an architecture design contains a purpose. The Power Tower is one way to illustrate this purpose, such as how common building blocks should be deployed to satisfy requests from specific market segments. Platform assets can go across market, product, productions and organizational capabilities. This is supported by Hansen et al. (2012), who illustrate the alignment of market, product and production architectures as shown in Figure 17.

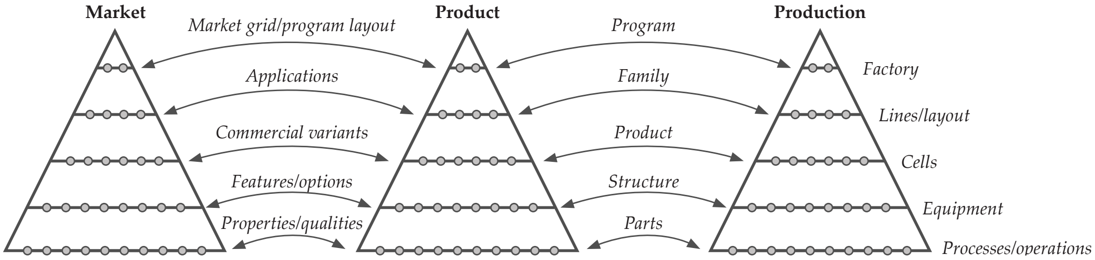


Figure 17: Alignment of market, product, and production architectures, redrawn from Hansen et al. (2012)

3.3.1 Top-down modularization

The top-down perspective applied in this research is based on the understanding that a company portfolio can be seen as hierarchical structure (Hansen et. al., 2012; ElMaraghy et al., 2013; Krause, 2013). A bottom-up approach is considered a focus on the bottom 2-4 levels illustrated in Figure 17 – that is, part sharing to product family design. A top-down approach to modularization starts from the portfolio level and includes the top 2-3 levels, such as considering the number of architectures in the portfolio, platform coverage in relation to market segments, the modularization principles to be shared across several product families, and so on.

Architectures and platforms are essential elements for this research; the two terms define how modularization is captured (in the architecture) and applied (through the platform) to achieve a strategic intent, for example, growth (new market entries, market strategies based on the Power Tower) or rationalization (sharing effects).

3.3.2 Dispositions

The Theory of Dispositions (TD) was proposed by Andreasen and Olesen (1990) and suggests that dispositions made during development affect later stages of the product's life cycle. The theory suggests a number of mechanisms covering essential dispositional effects as results of decisions made in relation to new product development.

- A strategy effect: Capturing the strategic decision-making of, for example, technologies
- A group effect: Capturing the learning effect arising from implementing, for example, group technology principles
- A standardization effect: Capturing the repetition effect from the re-use and limited variation of modules, components, material process instructions, methods etc.
- An optimization effect: Capturing the effects of an optimal fit between, for example, product and production parameters
- A resource effect: Capturing the effects of the optimal exploitation of staff and machines
- A correctness effect: Capturing the necessity of having correctness of data as a prerequisite for achieving the previously mentioned effects

These effects are realized as during its lifetime the product encounters a sequence of *meetings*. These meetings are moments in time when the product takes part in an action, where the product, an operator, and a life cycle phase interact. This is illustrated by Olesen (1992) in Figure 18.

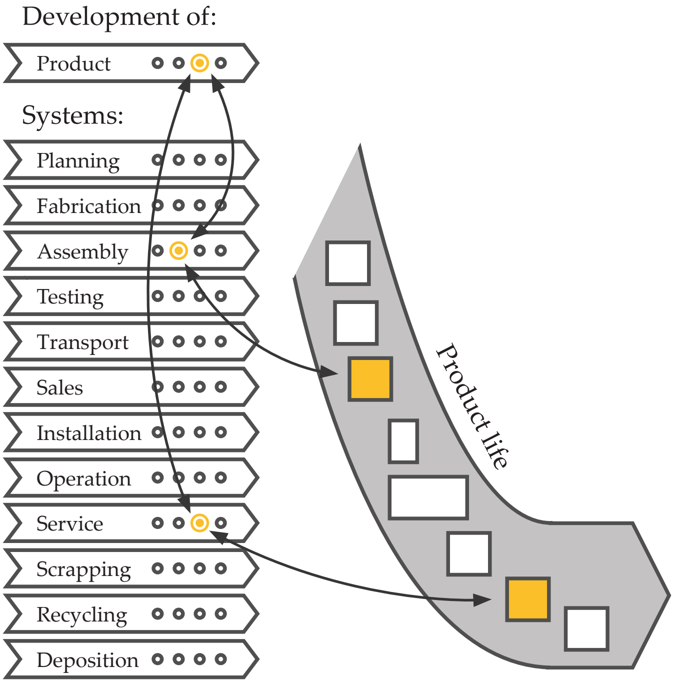


Figure 18: Theory of Dispositions (TD), redrawn from Olesen (1992)

TD is an acknowledgment of the importance of making good design decisions in the development of systems and applying a life cycle thinking pattern. Related to modularization, the theory is important as modularization efforts reach beyond the development of single products. Successful architecture development and the sharing of architectures as the basis for multi-product development can be seen as balancing a number of trade-offs related to dispositional effects.

3.3.3 Cost and multi-product development

Initiating a development task is often based on the idea that revenue can be created through new offerings to a market segment. This is typically formulated in a business model "describing the rationale of how an organization creates, delivers and captures value" (Osterwalder & Pigneur, 2010). The business case can be seen as describing a delta between two scenarios – that is, what happens if the product is launched vs. no launch, considering expected cost and gains in relation to the life cycle. Several methods exist for assessing the financial value of launching, including the assessment of Net-Present-Value (NPV), Internal Rate of Return (IRR) etc. (Cooper et al., 2001). Often the calculations create the basis for stop/go decisions in large industrial organizations, and even in the early phase of development important financial dispositions are made. A popular notion in relation to product development is that in the design phase 70% of the cost is determined (Andreasen & Olesen, 1990). However, even as this number is difficult to validate (Barton et al., 2001), the effects of early design choices in product development are considered significant for financial performance (Baxter, 1995). When companies focus on multi-product development and make design decisions with a portfolio perspective, the effects multiply. Thus, it is important to make the right decisions if modular principles are applied to achieve an effect, such as sharing modules, upgradability, and sharing processes. Instead of focusing on NPV or IRR for individual projects, financial considerations are needed for the valuation of platform initiatives, which stretch across industrial portfolios. The financial perspective applied to modularization, in this research, is based on elements found in existing methods to valuate new product introductions – that is, assessment related to direct material cost, direct labor cost, and investment. The assessment is built on the understanding that in assessing the delta between two scenarios (the as-is scenario and the to-be scenario), a type of business case for modularization can be created.

3.4 Reflections on the theoretical basis for the research project

Together, the three theoretical branches define the basis for this research project by describing how systems are understood, what is meant by modularization, and how modularization is executed as strategy for multi-product development (Figure 19).

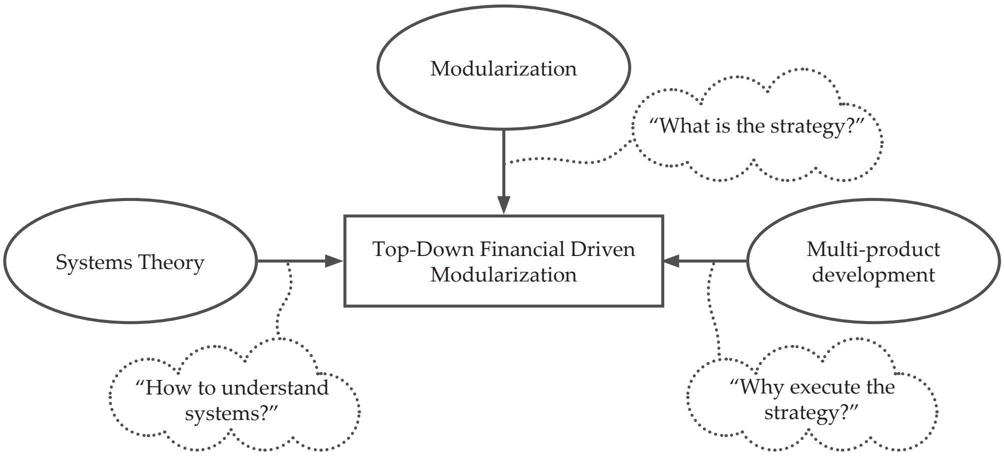


Figure 19: Theoretical basis for this research

Top-down financially driven modularization is generally intended to support a focus on dispositions from a strategic level, in determining how key cost drivers can be decoupled to allow the sharing of solutions and design principles across the portfolio. The hypothesis is that important modularization decisions cannot be made in individual development projects but should rather be driven from a top-down and financial perspective. Figure 20 illustrates the idea of how key modularization decisions are made on a strategic level and applied in individual development projects.

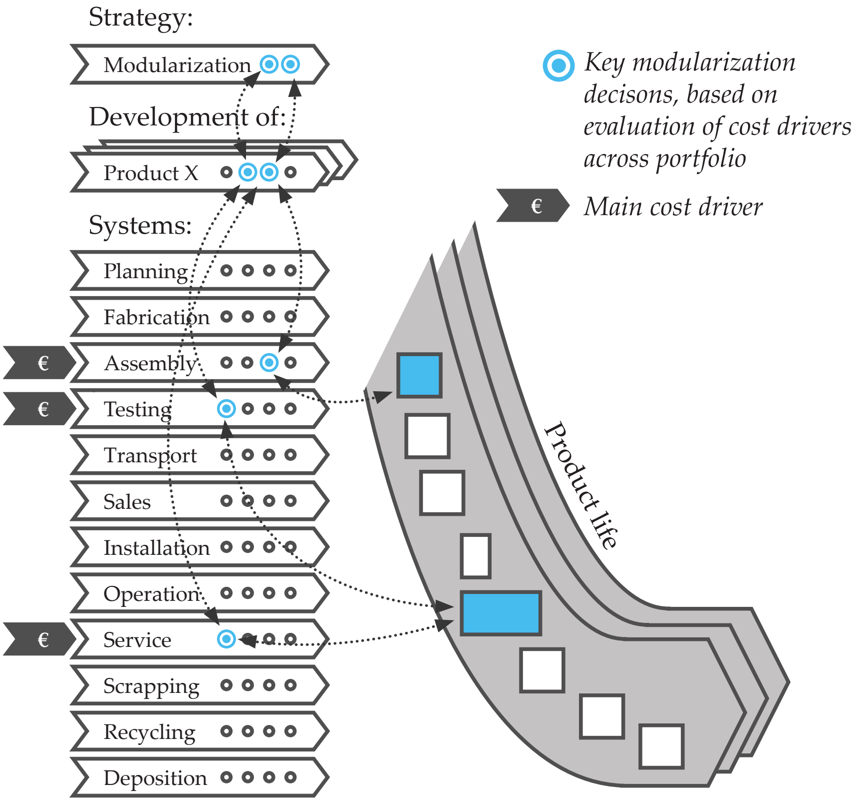


Figure 20: Dispositions related to a modularization strategy, based on Olesen (1992)

4 Results

This chapter presents the research results as summaries of the appended papers. Each summary links the specific paper to the research questions, presents the research method, and reflects on the individual research contributions.

The appended papers make up the collective research contribution of this project (Figure 21). The strategy for communicating the results has included the submission of scientific papers to engineering conferences and ISI-indexed journals.

The order in which the papers are presented fits the main research areas, as highlighted in the introduction and as follows:

(1) Argumentation: Improve the understanding of the potentials and effects of modularization to support strategic comparison with other major strategic initiatives to support increased top-management focus.

– Paper A, Paper B, and Paper F

(2) Operationalization: Improve the capturing and communication of critical modularization principles across an industrial portfolio, including the product and manufacturing domains, to support compliance with the modularization strategy in daily design activities.

– Paper C, Paper D, and Paper E

Standard Article

Assessing the cost saving potential of shared product architectures

Niels Henrik Mortensen[1], Christian Lindschou Hansen[1], Martin Løkkegaard[1] and Lars Hvam[2]

Concurrent Engineering Research and Applications
1–11
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DOI: 10.1177/1063293X15624133
cer.sagepub.com
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21ST INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED17
21-25 AUGUST 2017, THE UNIVERSITY OF BRITISH COLUMBIA, VANCOUVER, CANADA

ASSESSING THE FINANCIAL POTENTIAL FOR MODULARIZATION: A CASE STUDY IN A GLOBAL OEM

Løkkegaard, Martin; Mortensen, Niels Henrik
Technical University of Denmark, Denmark

INTERNATIONAL DESIGN CONFERENCE - DESIGN 2018
Dubrovnik - Croatia, May 21-24, 2018.

DESIGN 2018

ASSESSING INCREASED PRODUCT LINE COMMONALITY'S EFFECT ON ASSEMBLY PRODUCTIVITY AND PRODUCT QUALITY

M. Løkkegaard, N.H. Mortensen, L.S. Jensen and C.K.F. Christensen

Abstract

We present results of an experiment focused on quantifying effects on assembly productivity and product quality by introducing a product platform and increasing commonality between variants in a product family. The experiment was set up with 50 engineering students, who over three rounds produced a family of LEGO car models. Over the rounds a product platform was introduced and the Commonality Index was increased from 47,8% to 88,4%. Compared to productivity and quality results show an increased output of 118% and a decrease in product defects by 31% when applying a platform-based approach.

Keywords: Product platforms, commonality, experimental, product families

1. Introduction

Developing families of products, based on shared and standardized platforms assets and with high

Res Eng Design
DOI 10.1007/s00163-016-0215-6

ORIGINAL PAPER

Towards a framework for modular service design synthesis

Martin Løkkegaard[1] · Niels Henrik Mortensen[1] · Tim C. McAloone[1]

21ST INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED17
21-25 AUGUST 2017, THE UNIVERSITY OF BRITISH COLUMBIA, VANCOUVER, CANADA

GOOD PRODUCT LINE ARCHITECTURE DESIGN PRINCIPLES

Mortensen, Niels Henrik; Løkkegaard, Martin
Technical University of Denmark, Denmark

INTERNATIONAL JOURNAL OF
Production Research
Official Journal of the International Foundation for Production Research
Editor-in-Chief: Alexandre Dolgui
55th
Taylor & Francis

Framing New Architecture Introduction in Multi-Architecture Portfolios

Figure 21: Overview of the appended papers

Papers A, B, and F are mainly concerned with the argumentation for modularization and the related research questions:

- RQ2: How can a top-down and cross portfolio approach to modularization be supported by means of multi-architecture modeling?
- RQ3: How can the financial potential for sharing modules and design principles be assessed across an industrial portfolio?

Papers C, D, and E are mainly focused on how to operationalize modularization as a strategy. This relates mainly to the following research questions:

- RQ2: How can a top-down and cross-portfolio approach to modularization be supported by means of multi-architecture modeling?
- RQ4: How can critical decisions on the application of modularization principles be captured and communicated and used as reference for new product and production introduction?

The first research question was used as a guiding factor for all the papers and defined the focus on top-down financially driven modularization.

- RQ1: What are the strategic and operational challenges in reducing time from development to earnings using the principles of modularization?

Each paper highlights individual challenges, which are summarized in the introduction. Contributions to the individual research questions are further discussed in the next chapter.

4.1 Publications within this research

Paper A: Mortensen, N.H, Hansen, C.L., **Løkkegaard, M**. and Hvam, L. (2016). Assessing the cost saving potential for shared architectures. *Concurrent Engineering: Research and Applications*, 24(2), pp. 153-163

Paper B: Løkkegaard, M and Mortensen, N.H. (2017). Assessing the financial potential for modularization: A case study in a global OEM. In: Proceedings of the 21st International Conference on Engineering Design (ICED17), Vol3: Product, Services and Systems Design, Vancouver, Canada 21-25.08.2017

Paper C: Løkkegaard, M., Mortensen, N.H. and Hvam, L. (2018). "Using Business Critical Design Rules to Frame New Architecture Introduction in Multi-Architecture Portfolios". *International Journal on Production Research, (in press).*

Paper D: Mortensen, N.H. and **Løkkegaard, M.** (2017). Good Product Line Architecture Design Principles. In: Proceedings of the 21st International Conference on Engineering Design (ICED17), Vol3: Product, Services and Systems Design, Vancouver, Canada 21-25.08.2017

Paper E: Løkkegaard, M., Mortensen, N.H., and McAloone, T.C. (2016). Towards a Framework for Modular Service Design Synthesis. *Research in Engineering Design*, 27(3), pp. 237-249.

Paper F: Løkkegaard, M., Mortensen, N.H., Jensen L.S., & Christensen, C.F.K. (2018). Assessing Increased Product Line Commonality's Effect on Assembly Productivity and Product Quality. In: Proceedings of the 15th International Design Conference (DESIGN 18), Dubrovnik, Croatia, 2018.

4.2 Paper A

Title: "Assessing the Cost Saving Potential for Shared Architectures"
Journal: Published in Concurrent Engineering: Research and Applications, 2016
Contribution to work: Third author, main contributor Mortensen, N.H. (primary supervisor). My contribution exists in the form of input for conceptualizing the suggested AME approach and the generation of the visual models used as a basis for assessing cost saving potential.

4.2.1 *Associated research questions:*

- RQ1: What are the strategic and operational challenges in reducing the time from development to earnings using principles of modularization?
- RQ2: How can a top-down and cross-portfolio approach to modularization be supported by means of multi-architecture modeling?
- RQ3: How can the financial potential for sharing modules and design principles be assessed across an industrial portfolio?

4.2.2 *Research method:*

The suggested AME approach was developed taking from both the existing literature and building on the experience of practitioners. The basis for the approach was created through three MCs projects and two PhD projects at the Technical University of Denmark, Department of Mechanical Engineering, Section of Engineering Design and Product Development. The approach was tested through a case study running from 2012 to 2014 in a global company with a portfolio counting approximately 75,000 commercial product variants.

4.2.3 *Research contribution*

The core contribution in this paper is the suggested AME approach, which is a relatively simple method for assessing the cost saving potential of sharing architectures across an industrial portfolio. The approach applies a perspective across the market, product, and manufacturing domains. Included in the method is an operational way to describe and count the number of architectures in a portfolio, a method to evaluate cost/performance for module areas across architectures, and support for top-down reasoning concerning the number of architectures. The approach is intended for strategic discussion making at the management level on defining the right number of architectures across an industrial portfolio.

The financial potential is indicated by a comparison of the current situation (as-is), including the number of architectures, market coverage, and performance across architectures, with a to-be scenario, where future product and manufacturing architectures are identified based on an assessment of optimal market coverage and input from the company roadmap. The financial potential is summed up based on a delta between the two scenarios in terms of direct material cost, direct labor cost, and avoidance of capital expenditures (CAPEX). One of the main advantages of the AME approach is to allow an initiative with a focus on the sharing of architectures across an industrial portfolio to be comparable with other strategic initiatives, such as outsourcing or automation. Figure 22 gives an overview of the step-based approach.

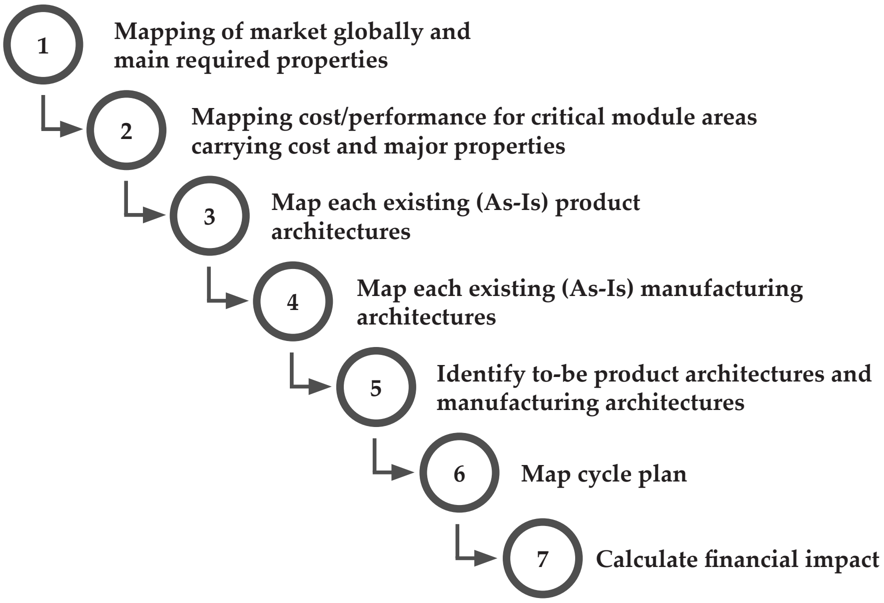


Figure 22: AME approach

4.2.4 *Reflections*

The AME approach addresses the challenge of assessing the effects of sharing architectures and modules across an industrial portfolio. It does so to allow the elevation of the discussion of sharing architectures to a management level. The approach is designed to be operational and has, as indicated in the case study, proven useful to support top-down reasoning on modularization. Discussing number of architectures across a portfolio, including optimal market coverage and considerations across the product and manufacturing domains, is considered critical in defining a strategy for modularization.

4.3 Paper B

Title: "Assessing the Financial Potential for Modularization: A Case Study in a Global OEM"

Conference: 21st International Conference on Engineering Design (ICED17), 21-25 August, 2017

Contribution to work: First author

4.3.1 Associated research questions

- RQ1: What are the strategic and operational challenges in reducing the time from development to earnings using principles of modularization?
- RQ2: How can a top-down and cross-portfolio approach to modularization be supported by means of multi-architecture modeling?
- RQ3: How can the financial potential for sharing modules and design principles be assessed across an industrial portfolio?

4.3.2 Research method

In this paper we apply the AME approach in a large and global original equipment manufacturer (OEM) as the basis for further verification of the approach. The case study was carried out from August to December 2015. During this period 40 days were spent in the case company, working closely together with a project team consisting of resources from production, R&D, and business development. To limit the scope of the study, the focus was on the electronic control box included in the majority of products in their portfolio.

First the global market and related key design driving properties were mapped, followed by the mapping of existing product (24 in total) and manufacturing (20 in total) architectures (Figure 23). Cost/performance was then evaluated for selected and critical functional units, such as cooling (product) and testing (manufacturing). Rationalization based on the as-is situation – for example, how many architectures should exist to ideally cover the market, where to apply the optimal-performing cooling and test solutions, and input from the company roadmap to identify windows of opportunities – allowed the evaluation of the potential for the increased sharing of architectures and the decoupling and sharing of critical cost drivers across the portfolio. The potential was estimated at 220 mill. DKK over five years. In 2017 around 40 mill. DKK of this potential had been realized. Benchmarking with the company cost base, the potential savings equaled a potential for reducing cost by 15% by applying a strategy based on modularization principles.

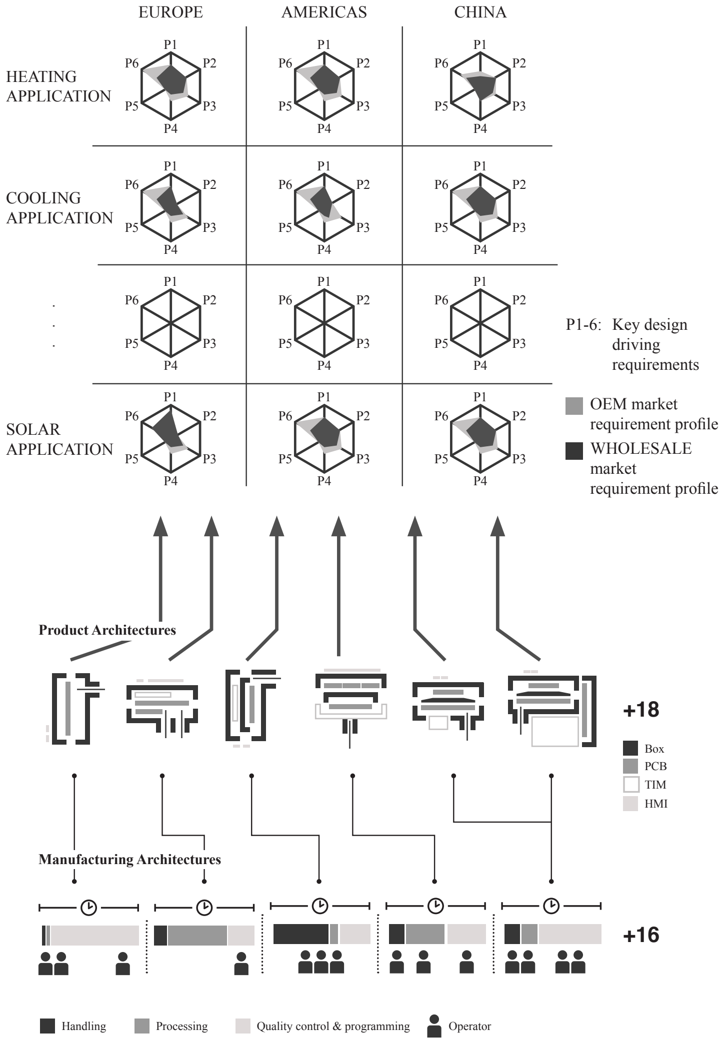


Figure 23: Mapping of market and existing architectures

4.3.3 Research contribution

The core research contribution is in this paper the operational application of the AME approach and related results; this includes top-down reasoning on modularization across multiple architectures.

4.3.4 Reflections

The case study indicated the usefulness of the approach in highlighting a financial potential for modularization across an industrial portfolio. In the case company this supported an improved argumentation for modularization. The Chief Operating Officer (COO) and Chief Technology Officer (CTO) entered the steering group on modularization in the case company, after the results of the approach indicated a significant cost saving potential. This indicates that the approach helped to bring the discussion of applying modularization principles as the basis for product and production development to a top-management level.

4.4 Paper F

Title: "Assessing Increased Product Line Commonality's Effect on Assembly Productivity and Product Quality"
Conference: 15th International Design Conference (DESIGN18), 21-24 May, 2018
Contribution to work: First author

4.4.1 *Associated research question*

- RQ3: How can the financial potential for sharing modules and design principles be assessed across an industrial portfolio?

As indicated in the reference model (Figure 9), the effects of increased commonality are seen as linked to the financial performance of a company. Thus, even as the experiment presented in Paper F is not directly linked to a financial assessment, the results are believed to provide some important insights into the discussion of the effects of the increased sharing of modules in a portfolio.

4.4.2 *Research method*

The paper address one of the key factors as illustrated in the reference model (Figure 9) – how the increased sharing of common modules across products and support an improved overall industry competitiveness. This is a fundamental question, and several studies highlight the need to quantify the effects of increasing commonality. This quantification is difficult, and in this paper we do not argue that we have a final definition. But we have, using an experimental setup, been able to simulate an industrial assembly process, and by increasing commonality in a family of products we have been able to collect data on production output and product quality. The experiment was setup at the Technical University of Denmark with 50 Engineering Students, who were set to produce small LEGO cars in a controlled setting.

Figure 24: Pictures from experiment

4.4.3 *Research contribution*

The results indicate that when the commonality between product variants is doubled, production output can be increased by more than a factor two and at the same time reduce the number of product defects by around one-third. Figure 25 shows the data collected over the three rounds of the experiment. In round 1 the students had only to produce one car variant. In round 2, three car variants with a low commonality had to be produced, and, finally, in round 3, the same three car variants, however slightly redesigned to increase commonality, were to be produced.

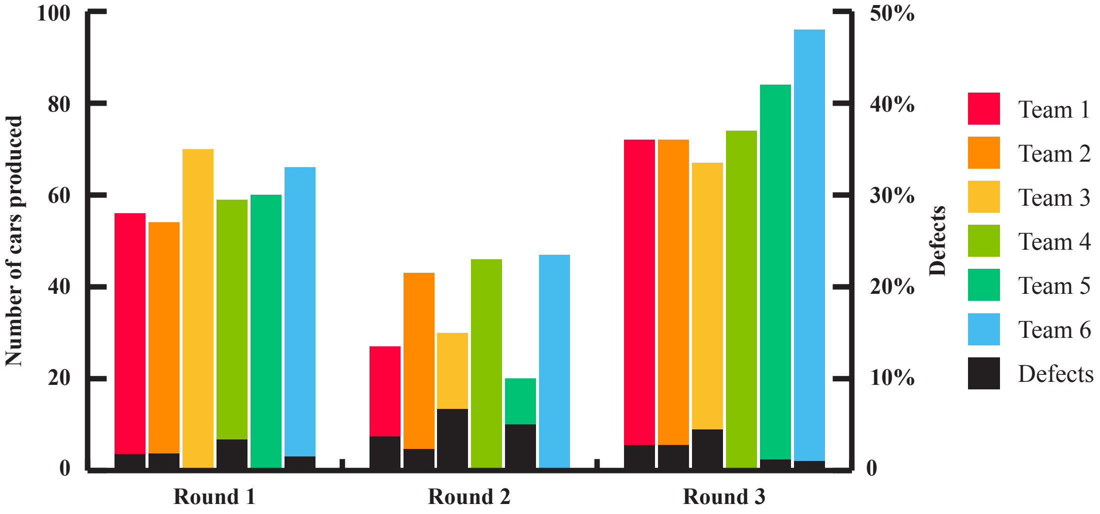


Figure 25: Data collected form the experiment

4.4.4 *Reflections*

Several challenges exist in quantifying the effects of increased commonality. The experimental setup was designed with two different goals: (1) give the participating students hands-on experience with the effects of modularization, and (2) collect the data to assess the effects of increased commonality. The results indicate significant potentials for increasing commonality across products variants in terms of assembly productivity and product quality, which to some extent can be translated to a real-world context in terms of potential for performance optimization and financial gain.

4.5 Paper C

Title: “Using Business Critical Design Rules to frame New Architecture Introduction in Multi-Architecture Portfolios”
Journal: International Journal of Production Research, 2018
Contribution to work: First author

4.5.1 Associated research questions

- RQ1: What are the strategic and operational challenges in reducing the time from development to earnings using principles of modularization?
- RQ2: How can a top-down and cross-portfolio approach to modularization be supported by means of multi-architecture modeling?
- RQ4: How can critical decisions on the application of modularization principles be captured and communicated and used as reference for new product and production introduction?

4.5.2 Research method

A suggested principle for modeling Business Critical Design Rules (BCDR) as a frame for architecture introduction into multi-architecture portfolios was synthesized based on existing theory and tested in a case study as part of the prescriptive stage of this research project. We worked closely together with a team of 20 specialists, engineers and managers from the company to generate results based on the suggested approach. In total, the study had a duration of 12 months, starting in August 2015, and in the final six months, the focus was to define and document BCDRs. BCDRs were derived by combining a data-driven approach, where critical cost drivers and drivers for time-to-market were identified with an evaluation of the findings with domain experts in workshop formats.

4.5.3 Research contribution

The paper presents the suggested modeling principle for BCDRs, which denote the most critical features of the product and manufacturing architectures, which should be considered a reference for new designs. The BCDRs were derived at the portfolio, architecture, and module levels, and included the modeling of the most critical links between the product and manufacturing domains. Figure 26 illustrates the concept of capturing BCDRs across an industrial portfolio.

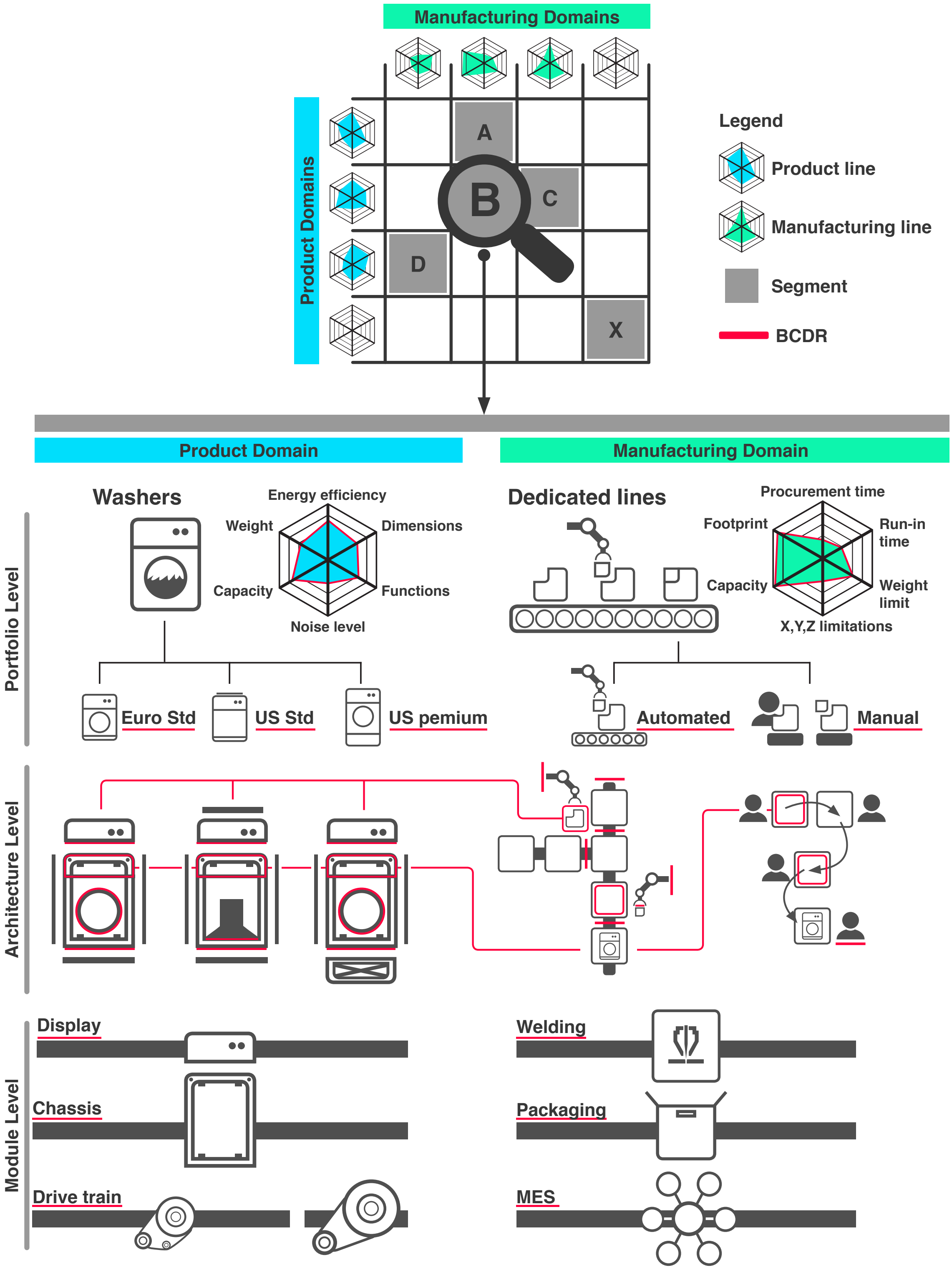


Figure 26: Visualization of Business Critical Design Rules

In the case study it was possible to define and consolidate a number of BCDRs as a frame for new architecture introduction. The indications were that defining and deciding on a number of “game rules” for development, could cut two months on average off all new product introductions. Furthermore, the definition of BCDRs allowed the company to communicate existing manufacturing capabilities in ongoing projects, and, as a result, defining BCDRs revealed a potential for cutting up to 35% of the investments in manufacturing equipment when new products were introduced into the company's portfolio.

4.5.4 Reflections

The modeling of BCDRs should allow the communication of important design decisions on modularization within project teams. The list of BCDRs denotes the most critical design decisions and should be considered an obligatory reference for new designs. This allows the top-down communication of where the sharing of design principles is obligatory to reuse, where predefined modules exist, and with what reference architecture a new product should comply. The modeling principle provides a core contribution to the challenge of the operationalization of modularization and ensures that new projects are compliant with strategic decisions on modularization across an industrial portfolio.

4.6 Paper D

Title: “Good Product Line Architecture Design Principles”

Conference: 21st International Conference on Engineering Design (ICED17), 21-25 August, 2017

Contribution to work: Second author

4.6.1 Associated research questions

- RQ1: What are the strategic and operational challenges in reducing the time from development to earnings using principles of modularization?
- RQ4: How can critical decisions on the application of modularization principles be captured and communicated and used as reference for new product and production introduction?

4.6.2 Research method

The 10 principles for good product line architecture design have been derived based on a study of the existing literature and drawing on the extensive experience on modularization residing in the Section of Engineering Design and Product Development at the Technical University of Denmark. More than 200 projects on design and reasoning on modular product architectures created the basis for identifying the principles.

4.6.3 Research contribution

This paper summarizes some of the essential considerations to be made when applying a strategy of shared architectures and the sharing of design principles across an industrial portfolio. The 10 central principles are illustrated in Figure 27.

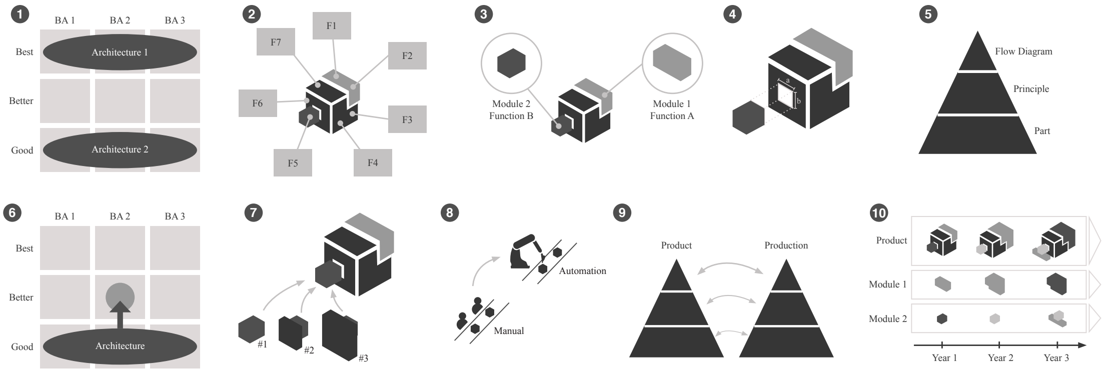


Figure 27: Good product line architecture design principles

1. Determine the right number of product architectures, which can be justified from a market point of view.

2. Isolate low volume selling features and options from the core product architecture.
3. Decompose the product architectures in to key module areas based on stable and non-stable key properties.
4. Identify key interfaces that shall be stable over time.
5. Identify right product architecture detail level – ranging from e.g. flow diagram to physical components.
6. Design product architectures to be upwards scalable from low performance to high performance – never from high performance to low performance.
7. Design each key module area to have balanced performance steps aligned between properties in the market and cost in production, supply and delivery. There are discrete performance steps and continuous performance steps.
8. Ensure that product architectures are stable from a production volume point of view.
9. Establish clear link between product architecture and production/supply/delivery architecture, e.g. late customer order decoupling points.
10. Be explicitly prepared for next product launches, e.g. by establishing roadmaps on module level.

4.6.4 Reflections

Despite that the studied companies all applied some kind of product planning and road mapping, all were non-compliant with the first principle – having the right number of product architectures. The conclusion in the paper is that this has a significant negative impact on financial and innovative performance. Situations observed in the studied cases include the following:

- Product architectures are taken into market areas they technically can cover but have bad cost/performance. This will lead to low margins.
- Product architectures are too many and overlapping. This means that there are multiple ways of serving the same customers or segments. This, again, will lead to increased complexity in engineering, production, quality, purchasing etc.
- Product architectures do not cover "the middle" areas". In some of the observed companies this was important due to unexpected high sales volumes in the middle area between two product architectures.

Applying the principles as the basis for modularization cannot be handled in individual development projects, and the paper highlights the need for top-management involvement in strategic decision-making in regard to number of architectures. The 10 principles can provide operational support for companies wanting to define a strategy for modularization and input for defining BCDRs.

4.7 Paper E

Title: "Towards a Framework for Modular Service Design Synthesis"
Journal: Research in Engineering Design, 2016
Contribution to work: First author

4.7.1 Associated research questions

- RQ1: What are the strategic and operational challenges in reducing the time from development to earnings using principles of modularization?
- RQ4: How can critical decisions on the application of modularization principles be captured and communicated and used as reference for new product and production introduction?

4.7.2 Research method

A conceptual model for service modularization was synthesized based on an approach where methodology known from the world of mechanical engineering and manufacturing companies was combined with the non-technical elements of services. The suggested model is based on principles of top-down modularization and was tested in a case study. Over six months, company-specific data on service execution and performance were analyzed, and workshops were held with management and consultants responsible for service delivery. This allowed the development and presentation of a conceptual model within the company context as reference for service delivery.

4.7.3 Research contribution

The core contribution in this paper is a step toward defining a framework for modular service design synthesis. The principles presented in the paper provide a contribution in regard to how pure service companies can develop and deliver services based on principles of modularization. Figure 28 illustrates how a cleaning service can be delivered at three performance levels based on a platform containing a number of standardized service modules and the arrangement of these modules using the Service Architecture Layout as a reference architecture.

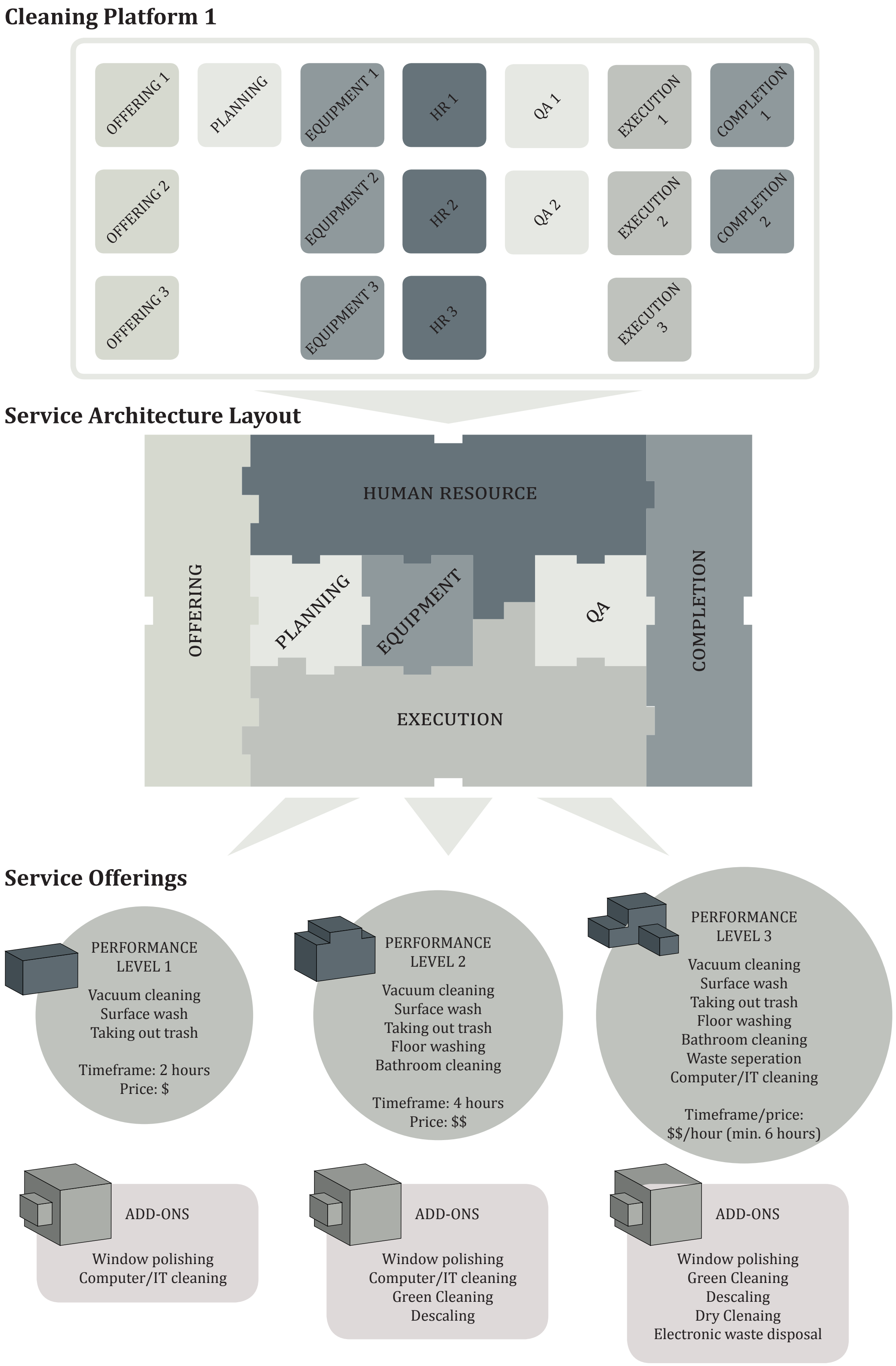


Figure 28: Conceptual model for modular service design synthesis

4.7.4 Reflections

The conceptual model is built on the understanding that a reference can be defined and serve as guide for future designs and service delivery. The concept holds similarities to the definition of BCDRs and builds on the understanding that it is important to define the number of architectures across a portfolio from a top-down perspective. However, rules for design are not described across a portfolio and across domains. The associated research question (RQ4) is focused on how to capture and communicate modularization principles as a basis for product and production development. Thus, the service focus does not harmonize directly with the question. However, the key concepts of describing a reference architecture (the Service Architecture Layout) and defining a platform consisting of standardized modules from which specific market segments can be efficiently served created the foundation for establishing a frame for new product introduction.

5 Conclusions

In this chapter the combined contribution of the research project is discussed. The focus is on research validation and a discussion of the research impact.

This research project has sought to support companies in approaching modularization from a top-down and financial perspective. It has done so based on the understanding that modularization as strategy for product and production development and with a portfolio perspective, cannot be efficiently handled within individual development projects. A top-down perspective is needed, where number of architectures and optimal market coverage is considered and where top-down decision are made on cross-portfolio modularization as obligatory reference for new designs i.e. sharing of design principles, modules and reference architectures. A financial perspective is needed to increase the managerial awareness of the importance of making these critical decisions. Based on the identified challenges, two research areas were identified: (1) improving the argumentation for modularization to support top-management engagement and (2) supporting operationalization by improving the ability to define and communicate critical modularization principles across an industrial portfolio, this should support compliance with the cross-portfolio modularization initiatives in day-to-day design activities. Contributions of this thesis include methods to support a top-down financial driven approach to modularization.

5.1 Answering the research questions

Four research questions framed this project. Related contributions are summarized in Chapter 4 and presented in detail in the appended papers. This section will in more general terms discuss the contributions.

The first question focused on identifying existing challenges in using modularizations as means to reduce time from development to earnings. The question has been answered within papers A, B, C, D, and E. It is an exploratory and fundamental question, which led to the focus on top-down financially driven modularization.

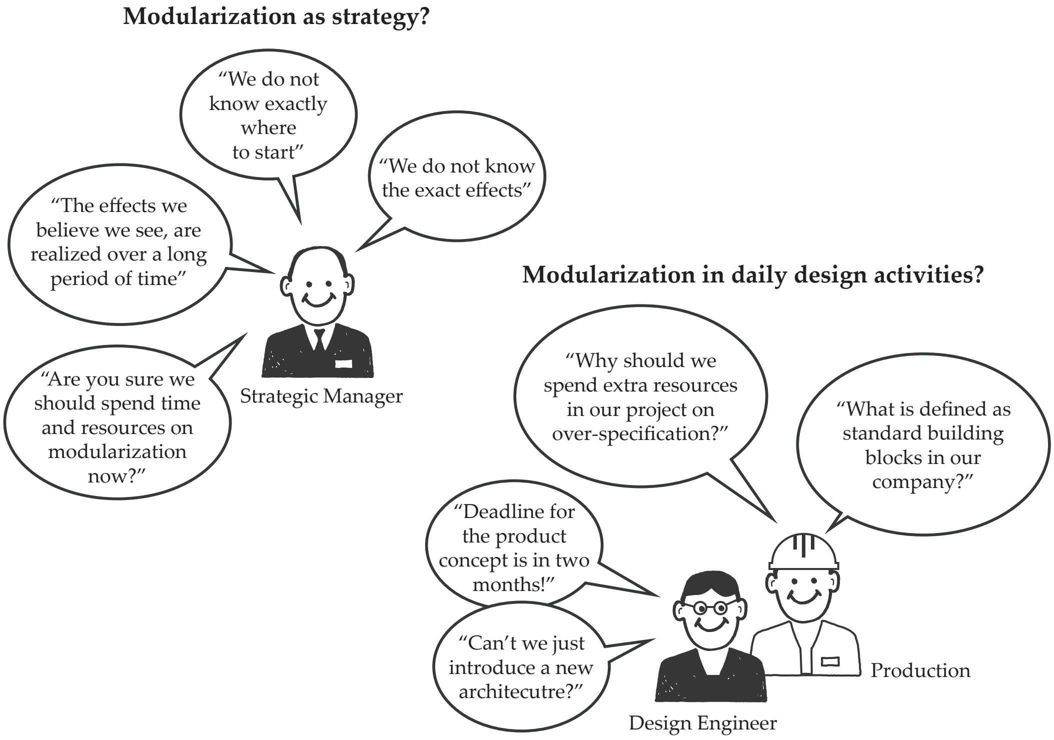
RQ1: What are the strategic and operational challenges in reducing the time from development to earnings using principles of modularization?

The main challenges were identified through the case studies, through a review of the existing literature and with input from the knowledgebase existing within the Section of Engineering Design and Product Development at the Technical University of Denmark, on the practical application of tools and methods for embedding modularity in the architecture of systems. Summarized, the main challenges were, on a strategic level, identified as follows:

- The effects of modularization are to some extent uncertain and are realized over time. Thus, modularization initiatives often do not receive the management focus they require to increase the likelihood of successful implementation.
- Modularization is often seen as a technical issue handled by engineers in individual development projects. If limited incentive for sharing design principles and modules across projects exists, limited effects should be expected.
- Top-management prioritization is needed to secure long-term commitment. This is a key enabler for harvesting associated effects of cross-portfolio modularization initiatives.
- Sequential introduction of product and production systems, without focus on sharing of architectures, modules and design principles, results in too many solutions across an industrial portfolio. With it follows undesirable cost/performance levels and significant complexity cost.

On an operational level, the main challenges were identified as follows:

- Existing methods and tools are generally detailed in nature, require expert capabilities and often assume modules and platforms to be defined, prior to application, to allow evaluation of different modularization alternatives.
- Responsibilities for cross-portfolio/cross-project sharing of modules and design principles are often weakly defined and communication of decisions on modularization is not optimally supported.



The next research question focus on how multi-architecture modeling could support top-down reasoning on modularization.

RQ2: How can a top-down and cross-portfolio approach to modularization be supported by means of multi-architecture modeling?

Papers A, B, and C address research question 2. In the papers, the mapping of multiple architectures across an industrial portfolio is used as a basis for assessing the financial potential for modularization and as a basis for defining Business Critical Design Rules (BCDRs). The collective contribution of the papers is the understanding that it is a few critical decisions, which needs to be consolidated across a portfolio to achieve the effects of top-down modularization. Across the product and manufacturing domain it is the balance of these important decisions on modularization, that yields a positive effect.

Research question 3 focuses on how multi-architecture modeling can be used as basis for assessing the financial potential for modularization.

RQ3: How can the financial potential for sharing modules and design principles be assessed across an industrial portfolio?

Paper A introduces the Architecture Mapping and Evaluation (AME) approach, and Paper B describes the application of the approach. The papers contribute to the understanding that a financial potential for embedding modularization principles across an industrial portfolio can be achieved by comparing an *as-is* situation with a desired *to-be* situation. The potential is calculated based on the delta between the two scenarios by assessing potential savings in direct material cost, direct labor cost, and CAPEX avoidance. The assessment is relatively simple. However, as indicated in the case studies, the AME approach provided valid and valuable input for the discussion of how to approach modularization across an industrial portfolio, including discussion on the number of architectures across a portfolio. The approach supports a comparison with other strategic initiatives in an industrial organization and an elevation of discussions on cross-portfolio modularization from the engineering-level to the top-management level.

The fourth research question focuses on how to improve the day-to-day communication of the critical design decisions made across multiple architectures.

RQ4: How can critical decisions on the application of modularization principles be captured and communicated and used as reference for new product and production introduction?

The principle for modeling Business Critical Design Rules (BCDR), from the perspective of a portfolio level, an architecture level and a module level, was suggested in Paper C. The BCDRs provide a way for companies to describe and communicate the most critical design decisions made in relation to modularization across an industrial portfolio. The definition and communication of BCDRs are intended to support the integration of important modularization principles in daily design activities as engineers and production managers will have a reference for new product or production system introduction, such as what standard modules exist, which design principles are obligatory, and so on. The 10 principles presented in Paper D provide a frame of reference for formulating a strategy for modularization and can guide the identification of BCDRs.

5.2 Main contributions

The main contributions of this research project are placed within the areas of augmentation for modularization and the operationalization of a modularization as a top-down portfolio-wide strategy.

Argumentation for modularization – to support the implementation of the strategy

- The definition and application of the *Architecture Mapping and Evaluation (AME) approach,* as a tool for assessing the financial potential for modularization across a multi-architecture portfolio and across the product and production domain.
- The quantification of increased commonality's effects on assembly productivity and product quality as support for understanding the related benefits of modularization.

Operationalization of modularization principles – to support compliance with the strategy

- The definition of *Business Critical Design Rules* (BCDRs), as the basis for documenting and supporting top-down communication of the most important decisions on modularization across an industrial multi-architecture portfolio, including consideration across the product and production domains.
- Conceptual model for *modular service design synthesis* as the basis for understanding how the principles of top-down modularization can be applied to the domain of service systems. This includes capturing the most important decisions on modularization in a reference architecture (the service architecture layout).
- Presentation of *good design principles* for modularization as support for formulating a modularization strategy.

5.3 Evaluation of the research

The papers describe the methods and tools developed and tested primarily though CS. To evaluate the research the six theorems of the Validation Square (Figure 10), presented in Chapter 2, are used to assess the effectiveness and efficiency of the results.

5.3.1 AME approach – Paper A and Paper B

Effectiveness

Accepting the individual constructs: The AME approach is based on constructs found in the literature on architecture modeling and platform development. This includes the widely accepted market segmentation grid by Meyer and Lehnerd (1997) and the product family master plan (Harlou, 2006) as the basis for architecture mapping. This is combined with a general approach to valuating platform and modularization initiatives by assessment of a delta between two scenarios (Gonzalez-Zugasti et al., 2001; Moon & Simpson, 2014).

Accepting internal consistency: The method is based on a sequential step-based approach, and each step is grounded in the theoretical basis described in Chapter 3. Reasoning based on the AME approach, for example, discussing a number of architectures across a portfolio combines the perspectives of the market, product, and production domains and is a widely accepted way of rationalizing across domains (Harlou, 2006; Andreasen et al., 2004; Mortensen et al., 2010).

Accepting the appropriateness of the example problems: The approach has been tested with two large global companies who had a desire to investigate the potential for modularization to drive the initiative further in their organizations. Both companies were experienced in product platform and product family design; however, the portfolio perspective on modularization had not been strongly exercised. Thus, the example problems are considered highly relevant for testing a top-down and cross-portfolio approach to modularization based on multi-architecture modeling.

Efficiency

Accepting the usefulness of the outcome: The application of the AME approach indicated in one case a cost-saving potential in the scale of 0.9 to 2.1% of turnover by reducing the number of architectures from 60 to 25. In the other case a financial potential of 15% reduction in the cost-base was indicated. Furthermore, the application of the approach led in both cases to discussions at the management level on applying modularization as the basis for new product and production development.

Accepting the achieved usefulness is linked to the applied method: No other competing approaches were applied in the case companies for the same purpose as the AME approach.

Accepting the usefulness extends beyond the case studies: The approach was tested in two cases in large global companies. However, no claims can be made that the approach is directly applicable beyond the example problems. However, in one of the case companies, the approach was taken further. Where the AME approach was applied to evaluate the financial potential for modularization for one major subsystem (the electronic control box), the company continued to apply the approach to other major subsystems, such as hydraulics and motors. This indicates the usefulness of the approach beyond the cases described in the appended papers.

5.3.2 Framing new architecture introduction based on BCDRs – Paper C

Effectiveness

Accepting the individual constructs: The individual constructs for modeling BCDRs are based on the existing literature on architecture and platforms – that is, the hierarchical breakdown of a portfolio (ElMaraghy et al., 2013; Krause et al., 2013), architecture modeling (Bruun et al., 2014; Harlou, 2006; Jiao et al., 2007), and the identification of critical interfaces and design principles in relation to modularization (Parslov & Mortensen, 2015; Baldwin & Clark, 2000)

Accepting internal consistency: The method combines existing elements to reason on, formulate, and document critical design decisions at different portfolio levels and across domains. Thus, the internal consistency is considered valid.

Accepting the appropriateness of the example problems: The principle of identifying and modeling BCDRs was tested in a large global company. The company had significant experience with product platform and product family design but had experienced challenges with ensuring compliance with modularization initiatives in individual development projects. Furthermore, limited focus had historically been put on modularization decisions across the portfolio and domains. This made the example problem highly relevant for the evaluation of the suggested approach.

Efficiency

Accepting the usefulness of the outcome: The application of the suggested approach in the case study illustrated that it was possible to identify and document a number of critical decisions on modularization across an industrial portfolio. The evaluation of the suggested method indicated a potential to significantly reduce investments and time-to-market for new product and production introductions by using the BCDRs as a frame for new architecture introduction.

Accepting the achieved usefulness is linked to the applied method: No other competing methods were applied in the case company and the key stakeholders agreed that the positive effects were related to the modeling of BCDRs

Accepting the usefulness extends beyond the case studies: The suggested principle for modeling BCDRs is intended to be applicable beyond the example problem. However, as the approach was applied in only one study, no claims can be made on direct transferability. Research is needed to further generalize the concept.

5.3.3 Ten good modularization principles – Paper D

Effectiveness

Accepting the individual constructs: The 10 principles are derived from reviews of the existing literature on product architectures and from experience in more than 200 projects, focused on the development of modular architectures across a variety of industries. The industrial projects have all to some extent all been connected to the Section of Engineering Design and Product Development at the Technical University of Denmark.

Accepting internal consistency: The 10 principles are complementary but not necessarily linked and not forming a coherent method or approach. The principles should be seen as a guide and support for formulating a modularization strategy.

Accepting the appropriateness of the example problems: The experience from a variety of industries was used as part of the basis to derive the 10 principles. These industries range from large to small and from mass-producing companies to Engineer-to-order companies. Experience was gathered through MSc projects, PhD projects and postdoc projects.

Efficiency

Accepting the usefulness of the outcome: The key conclusion was that very few companies have the right number of architectures across their portfolio to serve market needs in the best possible way. The result is high complexity cost and high material and labor cost. The derived principles can support companies in focusing on the critical aspects of defining a cross-portfolio strategy before going into detailed design on architectures, platforms and product families.

Accepting the achieved usefulness is link to the applied method: Studies indicate that companies who are compliant with the 10 principles, or at least some of them, experience improved performance – for example, as reported in Paper A and Paper B in this thesis.

Accepting the usefulness extends beyond the case studies: The basis for the suggested principles indicates usefulness across several industries and companies.

5.3.4 Conceptual model for service modularization – Paper E

Effectiveness

Accepting the individual constructs: The individual constructs in the conceptual model are based on theory on platform and architecture development borrowed from the world of mechanical engineering (Meyer & Lehnerd, 1997; Harlou, 2006).

Accepting internal consistency: The conceptual model consists of elements from the existing literature and applies the generally accepted approach of reasoning across domains – market, product (in this case service), and production (in this case service configuration).

Accepting the appropriateness of the example problems: The conceptual model was applied as a reference for modularization in an Engineering Consultancy with more than 500 employees. The company performed highly complex consultancy services in the energy and maritime sectors. The company situation – with challenges related to the consistency and scoping of services, which had led to a decreased profitability – made the case an appropriate example problem.

Efficiency

Accepting the usefulness of the outcome: Applying the method in the case company allowed the identification of a number of standard modules from which service offerings could be configured through the Service Architecture Layout. This allowed a 56% increase in the standardization of service offerings, which were believed to support a more cost-efficient delivery process.

Accepting the achieved usefulness is linked to the applied method: Strategic managers in the case company expressed a clear understanding that potential effects were related to the application of modularization principles for service delivery and that the suggested conceptual model had a direct influence on improving the understanding of how these principles could be applied in the company.

Accepting the usefulness extends beyond the case studies: The conceptual model was tested in only a single case study with a focus on pure service delivery. No evidence exists that it can be transferred directly beyond the case study. However, as seen in the world of product-centered modularization, the methods and tools are applied to a variety of companies. As the conceptual model presented in paper E is based on constructs found in the related literature, the conceptual model is believed and intended to also be applicable beyond the problem example.

5.3.5 Assessment of effects of increased commonality – Paper F

Paper F presents a number of findings in relation to the effects of increased commonality across product variants. The paper is based on an experimental setup.

Effectiveness

Accepting the individual constructs: The experiment was setup as a game where students were challenged to build small cars of LEGOs. Using a game setup to extract data on a specific phenomenon has been used with success in several cases (Badurdeen et al., 2010; Paasivaara et al., 2014; Sánchez & Olivares, 2011). The assessment of commonality between product variants was based on calculations of the Product Line Commonality Index (PCI), which is considered a recognized approach (Simpson et al., 2006).

Accepting internal consistency: The conclusions presented in the paper are based on an analysis of the collected data on number of cars produced and number of defects per team.

Accepting the appropriateness of the example problems: The assembly of simple LEGO car models was used as basis for simulating the effects of modularization. This is a much-simplified scenario relative to a real-world context, where complex products often consist of more than 25 parts on average. However, it is possible to clearly design different levels of commonality and modularity into the LEGO cars. Thus, as a basis for quantifying the effects of increased commonality, the example problem is considered to be appropriate.

Efficiency

Accepting the usefulness of the outcome: The findings from the experiment indicate a significant potential to improve assembly productivity and product quality by increasing product line commonality.

Accepting the achieved usefulness is linked to the applied method: The main variable parameter in the experiment was the commonality between product variants. Thus, the findings are believed to reflect the effects of an increase in this parameter.

Accepting the usefulness extends beyond the case studies: It has been shown to be very difficult to quantify the effects of increased commonality in industrial settings. Several reasons exist for this. However, the results of the experiment indicate a potential and can provide useful input for the argumentation for modularization in a company context.

5.4 Impact of the research

To conclude the research evaluation, this section summarizes the research impact in terms of academic impact and industrial impact.

5.4.1 Academic impact

As illustrated in the ARC diagram (Figure 5), the academic contributions relate to a number of relevant research areas.

5.4.1.1 Modularization and architectures

Paper C on BCDRs uses a multi-architecture mapping approach as the basis for formulating and capturing critical design decisions on modularization. The academic contribution lies in the definition of BCDRs at the portfolio, architecture, and module levels. The core element is the clear focus on that a few critical decisions on modularization across a portfolio can brings much value to companies wanting to use modularization as a strategy for product and production development. Paper E provides a contribution to how such critical decisions on modularization can be made in a service context. Paper D contributes to the existing knowledgebase by introducing good principles for product line architecture design. These principles can be used as a guide for making the important decisions on modularization across an industrial portfolio. Paper F contributes to the understanding of the effects of modularization.

5.4.1.2 Multi-product development, cost assessment and production introduction

Papers A and B introduce the AME approach. The academic contribution is the approach for assessing the financial potential for sharing architectures, modules, and design principles across an industrial portfolio as a basis for multi-product development. The approach provides a relatively simple tool that can be applicable in contexts where extensive expert capabilities in the field of modularization do not necessarily exists. The approach can be used as a basis for elevating discussions on modularization to a management level. The AME approach and the modeling of BCDRs both include a production perspective and provide a contribution to the understanding of the relationships between product architectures and production architectures.

5.4.1.3 Theory of dispositions (TD)

The collective contribution from this research project adds to the theory of dispositions by extending the perspective to a multi-architecture and cross-portfolio focus. The papers collectively emphasize the criticality of making good design decisions on modularization, decoupled from individual projects, to harvest potential effects. The collective contribution lies in the support for using modularization as an overarching strategy for product development.

5.4.2 Industrial impact

The industrial impact is evaluated in relation to the overall goal-setting of MADE: “Strengthen the competitiveness of Danish industry”. The results from this research project are not necessarily linked solely to Danish companies, but many companies in Denmark are believed to experience the challenges discussed, as indicated in the introduction part of this thesis.

The specialists, engineers and managers involved in the prescriptive application of the suggested tools and methods were in Case D asked to rate the contribution of applying a top-down and financially driven approach to modularization with a focus across product families and across the product and production domains. As displayed in Figure 29, a general agreement exists in regards to the importance of modularization and that applying the suggested methods and tools led to positive effects in the company.

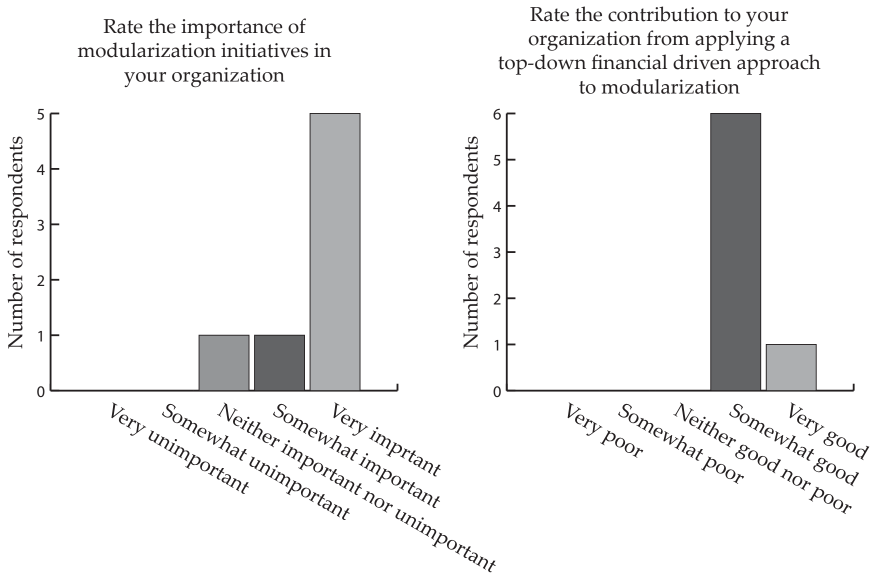


Figure 29: Results of the survey in the case company

Generally, different management perspectives exist as to what modularization is. This is described as different modularity maturity levels in Table 1. As concluded, despite seeing modularization as important, many companies do not possess the maturity level needed to see modularization as a top-management concern, able to drive the strategic direction of a company. The result is that modularization is often seen as a technical issue. The prescriptive stages of the project allowed the application of the suggested methods and tools for support to elevate modularization to a management level and to communicate critical design decisions on modularization. This has allowed the acquisition of direct feedback from practitioners and managers and generated a number of measurable results. Table 5 describes the direct industrial impact associated with this research project.

Table 5: Industrial Impact

Cases	Results	Future perspectives
Argumentation for modularization		
Case B	Potential cost reduction in the scale of 0,9-2,1% of turnover	On-going modularization initiatives with top-management focus
Case D	Potential cost reduction in the scale of 15% of existing cost base	On-going modularizaiton initiatives with top-management focus
Framing new architecture introduction		
Case A	Potential 56% increased standardization in service delivery, supporting a more cost efficient delivery process	Unknown
Case D	Potential to cut in average 2 months of the conceptualization phase and redce investment by 35% for new product introductions	On-going modularizaiton initiatives with top-management focus

As illustrated in Figure 9, the reference model describes how an improved ability to share modules and design principles across an industrial portfolio is linked to the goal-setting of improving the competitiveness of industrial companies. The link is described as the ability to reduce the cost of development and operations through a reduction of direct material cost, direct labor cost, and investments in manufacturing equipment. As described in Table 5, the application of the suggested AME approach and principles for modeling BCDRs indicated an effect on the ability to improve the sharing of design principles and to reduce the number of architectures across an industrial portfolio, with a direct effect on the measurable success criteria. The industrial impact of this research project indicates that approaching modularization as an overarching strategy for design, with a strong top-management commitment and a focus on the communication of critical design decisions on modularization across an industrial portfolio, are key factors in supporting the overall competitiveness of industrial companies through the implementation of modularization principles.

5.5 Research limitations

5.5.1 Problem-based approach

The problem-based approach, using CS and AR as basis for the collection of empirical data, has a number of natural limitations. In this research project four cases (A, B, C, D) were used, in the descriptive stages, to understand the challenges of applying modularization as strategy for development. In three of these studies (A, B, D) prescriptive elements were applied as a basis for developing and testing the suggested design support. Finally one case (D) was used as the primary source for evaluating the suggested principle for BCDR modeling. Further research is needed to be able to claim full transferability of the suggested tools and methods to different contexts. However, due to the timeframe of this project, this was not possible.

5.5.2 Unavoidable subjectivity

The collaboration with industry partners in this research project can be argued to introduce a degree of subjectivity. Several research activities were carried out in action rather than about action as described by Coughlan and Coghlan (2002). The results and conclusions are to some level based on these interactions and it is unavoidable that a subjective influence has been present. However, the applied research approach gave the opportunity to acquire deep knowledge on industrial challenges and test of the suggested methods in a real-life context.

5.5.3 *Evaluation of effects*

The suggested support for argumentation for modularization highlights a financial potential. However, the realization of this potential happens over time. In case B and D, where the AME approach was introduced, significant percentages of the potentials have already been realized, but it has not been possible within the time frame of this project to evaluate the accuracy of the assessment. A number of potential effects are also highlighted in relation to the modeling of BCDRs and these effects will not be measurable until new products or production systems are introduced based on the defined design principles. Further research is needed to assess these effects.

6 Further research suggestions

This chapter highlights suggestions for further research activities

Within the three-year limit of this research project, far from all research opportunities, related to top-down financially driven modularization, have been covered. Areas for further research include those discussed below:

6.1 Evaluation of effects

As mentioned in the research limitations for this project, following the different cases over a longer time period to assess the effects of introducing the suggested support would be an area for further research activity. It would be extremely valuable to further validate the impact of this research. Furthermore, increasing the number of example problems is an area for further research activity.

6.2 Assessment of compliance with a modularization strategy

More generally, it would be interesting to further develop the concept of BCDRs to allow a compliance evaluation with the critical design decisions on modularization based on a number of performance indicators. This could potentially support further operationalization of the approach, which was also highlighted as a desire in Case D. The evaluation of compliance with the BCDRs could, in development projects, be part of gate decisions in the same way that budgets or project progress are evaluated.

6.3 Digitalization

Digitalization is a contemporary trend and highly relevant in relation to modularization. Examples exist of the integration of modular architecture with

Product Lifecycle Management (PLM) systems, and much research exists in the field of product configuration systems. However, many opportunities exist for supporting digital design in relation to modularization. Looking a bit ahead, in having a digitalized modularization strategy, where a level of mixing-and-matching of modules is possible and where critical design rules are clearly defined, intelligent systems might be able to perform much of the configuration or design tasks. This is quite an interesting area where further research could help to clarify the possibilities.

6.4 Organizational aspects

Finally, organizational aspects in relation to modularizations are suggested as an area for further research attention. A common understanding is that when developing modular products, an organization will in time mirror the modular structure of the product, for example, in terms of responsibilities and tasks. However, it would be very interesting to look further into different principles for organizational design, for example, in relation to different modularity maturity levels of companies.

7 Concluding Remarks

This thesis concludes my three-year PhD project. The primary outcome of such a project is to build knowledge. I see this as including both my own knowledge, as building knowledge to able to contribute to the existing knowledgebase on a specific topic, and as communicating findings, results, and challenges to whomever might be interested, in order to build their own knowledge.

The research presented in this thesis is the outcome of an extensive and often difficult process. The time spent from start to finish has, however, led to a giant leap in my understanding of engineering design and product, production, and service development seen both from an academic perspective and from an industrial perspective. It has been extremely interesting to use industry as a testing facility for the evaluation and validation of theories and concepts.

I hope you have enjoyed reading this thesis and have found it (or at least parts of it) useful, interesting, and able to expand your own knowledgebase.

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9 Appended papers

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Assessing the cost saving potential of shared product architectures

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Abstract

This article presents a method for calculating cost savings of shared architectures in industrial companies called Architecture Mapping and Evaluation. The main contribution is an operational method to evaluate the cost potential and evaluate the number of product architectures in an industrial company. Experiences from the case company show it is possible to reduce the number of architectures with 60% which leads to significant reduction in direct material and labor costs. This can be achieved without compromising the market offerings of products. Experiences from the case study indicate cost reductions between 0.5% and 2% of turnover. The main implication is that the method provides a quantitative basis for the discussion on whether or not to implement shared product architectures. This means a more fact-based approach is introduced.

Keywords

product architecture, manufacturing architecture, modularization, concurrent engineering

Introduction

Many industrial companies (developing, producing, and selling physical products) have developed the product portfolio sequentially product by product over a number of years. There can be many good reasons to continue doing so, for example, ability to develop specific products for specific markets and targeting specific low-cost needs and high-end needs. The consequences are, however, often that there exist a large portfolio of products, where there is very limited sharing between the product families, leading to increased complexity cost, several “inventing the wheel” projects and thereby increased time to market and profit for new products (Andreasen, 1980; Hansen, 2015; Harlou, 2006; Levandowsky et al., 2014). A warning signal is often that costs are increasing faster than turnover.

Companies typically have challenges such as the need to reduce cost, increase quality, reduce delivery time, and launch more new innovative products faster. One of the means to address this challenge that is often discussed in both academia and industry is application of modular architectures (Ericsson and Erixon, 1999; Guðlaugsson et al., 2014; Herrmann et al., 2004). The basic idea of modular product architectures is to build up product lines based on a limited well-defined module having well-defined performance steps with clear definition of interfaces (Ericsson and Erixon, 1999). This should lead to the reduction in the number of components, cost reduction in general, and more focused effort on key modules leading to more cost-effective products. The rationalization benefits may be utilized to develop more new innovative products.

In principle, everyone, from board of directors, board of management, and down in an industrial organization, agree on this. But, in practice, there are many uncertainties and many opinions. In our research, we have often come across viewpoints such as “we have exactly the products that we need,” “all products are profitable and needed for our customers and markets,” “we are already modular,” and “if we increase the level of modularity, we will compromise key customer

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requirements and increase cost." All the above viewpoints can often not be proved right or wrong.

Organizational wise, this is a very sensitive topic. Asking the question "could we do better with modular architectures." From research and development (R&D), the reaction is often that they are accused of not having done the perfect job. From sales, the viewpoint will often be that due to the competitive situation and so on, all products are required. In manufacturing, the reaction is very positive—but often more short-term initiatives are in focus such as day-to-day process improvements.

The basic question asked in this article is as follows: how to find out what the financial potential is of shared modular architectures? The target audience is board of management. The intention has been to identify a quantitative method in such a way that discussions are based on facts and not opinions of individuals.

Concerning the link between the number of architectures and concurrent engineering (CE), it is the assumption that when the number of architectures in product and manufacturing is reduced, it will lead to increased efficiency and increased possibilities of achieving concurrent development of product and manufacturing.

The structure of the article is as follows: in section "Research approach," the research method is explained, and section "What is a product architecture and which evaluation parameters to include?" will go through the benefit dimensions and the reasons for including them. Section "State of the art" describes state-of-the-art literature. In section "AME method," the method for calculation of the benefits of shared architectures is presented and section "Application of the AME method" contains experience from application of the method in a large-scale organization. Section "Discussion" contains the conclusion.

Research approach

The suggested method for assessing the potential of shared product architectures has been developed by taking from both the existing literature and some experiences of practitioners. More specifically, the method is based on classical systems' thinking (Andreasen, 1980; Skyttner, 2005), theory of technical systems (Hubka, 1973), and Product Family Master Plan (PFMP) (Harlou, 2006). The work is carried out by three MSc projects and two PhD projects (Bruun, 2015; Hansen, 2015) at the Technical University of Denmark, Department of Mechanical Engineering, Section of Engineering Design and Product Development. The basic assumption is that the competitiveness of a product program cannot be evaluated in itself—only when mapped relative to the market and the internal functions of the company, conclusions can be made. In this study, three aspects are considered: market, product, and manufacturing. The links between these three aspects are the foundations for evaluating the potential of shared architectures. Most approaches in the literature on shared product architectures are concerned with the product aspects in terms of, for example, shared parts. Even though this can be of relevance, it is not sufficient.

A method named Architecture Mapping and Evaluation (AME) method is proposed. The method has been tested in a global company that has approximately 75,000 commercial variants in the market. The company has divided the product portfolio into six product lines. The AME has been tested on all six product lines. This means that in total, six global data sets have been collected and evaluations have been carried out. The main aim of this case study is to test the suggested operational method and receive feedback from the managers in the company.

With regard to internal validity, the research team has full access to detailed data from the company. In order to gather accurate qualitative data, un- and semi-structured interviews are performed with the "key" informants. The research group had semi-structured interviews with the managers, involved in this project, in order to assess the results and receive feedback. The received feedback is valuable for the verification of the results from the analysis and for assessing the proposed method. The studies have been carried out over a time span of 2 years from 2012 to 2014. The next section will discuss the meaning of product architecture and what evaluation parameters to include.

What is a product architecture and which evaluation parameters to include?

Like most phenomena in engineering design, there does not exist a common and agreed way of defining architecture. In this article, a distinction between product structure and product architecture is made (Hansen et al., 2012). Product structure means the way a single product is built up from systems and components. Product architecture means the way a product family or portfolio of products is built up. Traditionally, companies have good control of product structure in, for example, computer-aided design (CAD), enterprise resource planning (ERP), and product data management (PDM) systems. Product architecture is normally very weakly taken care of. Traditionally, responsibility for product structure is well defined, but responsibility of product architecture is ill defined. It is the main assumption in this article that the number of product architectures is a very important fundamental aspect, and that top management and other key persons should consider very carefully. Having too many architectures will lead to high complexity cost and long time to market for product development. The implication of too few architectures can be too high cost for product in, for example, the lower performance areas of the portfolio or simply that the company cannot serve the variety of needs among customers.

In this work, product architecture has the following characteristics:

- Shared core interfaces.
- Core modules/systems exist in balanced performance steps.
- The architecture is explicitly prepared for derivative products and related properties in terms of cost and performances are known.

The above phenomena will briefly be explained.

Shared core interfaces

Only a small fraction of interfaces play an important role, but a few are extremely important for, for example, quality and time to market. An example of a core interface of a truck might be the interface between the cab and the rest of the chassis. If this interface is stable, the cab can be developed without changing the rest of the chassis. The whole product family can be upgraded in one step with one development project.

Core modules exist in well-balanced performance steps

An example of a core module could be the wash-group of a washing machine; some of the performance steps could be 6, 8, 10, and 12 kg. Balanced means that there the number of modules is consciously determined according to market needs and internal complexity within the company, for example, production, service, stock level and development capability. One "ideal" way of balanced performance thinking is "one need—one solution."

Architecture is prepared for future launches

An example could be boggies of a truck. There might exist 21 and 30 ton, but modules are prepared for a 26-ton variant with adding only a few new parts. Another consequence of this is that interfaces have to be stable over time. This is one of the weak parts of architecture work in most companies that we have studied (Bruun et al., 2014; Hvam et al., 2008).

In this article, a product architecture is considered shared when more than 90% of the core interfaces are shared. Then one can ask what a core interface is. This is pragmatic defined among senior market, product, and manufacturing persons. For a car, an example of a core interface is between engine and transmission. For a drilling tool, a core interface will exist between battery and chassis. The basic assumption is that the number of architectures is driving complexity cost; it is driving CAPital Expenditures (CAPEX) in manufacturing and it is often constraining the ability to launch new products and product variants. Then why put the requirement on 90% sharing of core interfaces? This is a pragmatic decision, but due to the size of the test company, the criteria had to be explicitly defined in such a way that each division of the case company could not have individual perceptions.

Having clarified the meaning of architecture, the next question is what evaluation parameters to include. There is in principle an infinite number of evaluation parameters that could be studied. In the literature, roughly two types of evaluations parameters are reported in the literature (Fixson, 2005; Hultink et al., 1997; Krause et al., 2013; Ulrich, 1995) from application of shared architectures. They can be divided into growth parameters and rationalization parameters. Examples of growth parameters could be time to market and ability to make new innovative products. Examples of rationalization parameters could be direct material cost and labor cost. In this article, it has been decided not to include growth parameters, not because it is irrelevant, but because it is difficult to obtain quantifiable data. There are often many opinions but very few facts. On the rationalization side, it has been decided to include data that are available in modern companies with modern information and technology (IT) systems, mainly ERP systems. Again, there are many possibilities, but included are four parameters: direct material cost, direct labor cost in manufacturing and CAPEX on tooling, and number of architectures. The basic assumption is that if benefits can be justified in these dimensions, the rest such as the growth parameters will be additional benefits.

State of the art

The review of the state-of-the-art includes a review of five different groups of supporting methods for the identification of shared architecture benefits for a product program including product lines. The five groups identified are function-based models, matrix-based models, CE, design for manufacture (DFM), and mathematical models.

Function-based models

Methods describing the development of modular product architectures often choose to start with the conscious mapping of functional structures into physical modules (Levandowsky et al., 2014). Functions can be represented in function-based models, for example, functions-and-means trees (Andreasen, 1980), or by schematics of the product including physical elements to a meaningful extent (Stone et al., 2000).

The understanding product functions can be used in different ways to identify possible modules. To improve the identification of modules and make sure that the modular architecture will serve its objectives (Fixson, 2005), define a set of module drivers. The module drivers can support the reasoning behind the module identification by elaborating the justification of the modules' existence, for example, "planned product changes" module, "process" module, "different specification" module, and "technology evolution" module. The module drivers are a part of a comprehensive framework called modular function deployment (MFD), which in analog to the quality function deployment (QFD) method provides support for the linking of relationship between the module drivers and technical solutions.

Matrix-based models

Another approach to identify modules is the application of design structure matrices (DSMs). This approach takes its point of departure in the decomposition of a product into parts and/or subsystems while identifying the relations (and possible future interfaces) among these (Gonzalez-Zugasti et al., 2000; Otto and Wood, 1998). By applying different algorithms and clustering techniques, it is possible to encapsulate functional "chunks" that have the potential of becoming physical modules, due to their functional interrelations. DSM techniques are the subject of many research initiatives and serve as the basis for an array of derived methodologies. An example of this is the multi-domain-matrix (Ulrich, 1995). Alternatively, other design tools focus more on the specific task of examining different functional flows with the aim of identifying modules (Otto and Wood, 1998; Pimmler and Eppinger, 1994). These methods are heuristically based.

Other more general methods focus on the identification of common features in the existing product program in order to point out the basis of the product architecture. By formulating the design task as a quantitative problem, which can be subject to optimization, this method is balancing inputs from requirements and product variants design with data models of performance and costs. By iteration, the optimal product variants are designed and evaluated through quantitative performance metrics.

CE

From the associated area of CE, one can also find research into the concurrent development of product and production architectures, with phrasings such as "methods supporting the development of product platforms." Nevertheless, interesting contributions are submitted within this area. Otto and Wood (1998) introduced a three-dimensional (3D) methodology superimposing the traditional domains of CE, by suggesting the linking of technology, architecture, and focus relations in the process, product, and supply chain domains. Olesen (1992) proposed an important step of operationalization of this 3D-CE approach by developing a multi-dimensional framework that enables comprehensive assessment of alternative product architectures.

The concept of architecture for product family (APF) is introduced as a conceptual structure, proposing logics for the generation of product families (Hultink et al., 1997). The generic product structure (GPS) is then proposed as the platform for tailoring products to individual customer needs. In Andreasen and Olesen (1990), another systematic method for concurrent development of product families is presented, by combining QFD-based methods with quantified DSM techniques and morphology analysis to visualize concepts.

DFM

Original contributions from Olesen (1992) proposed a framework for the concurrent development of manufacturing supported by the theory of dispositions (Andreasen and Olesen, 1990). This is done by proposing a set of models aligning the product design and the product life system phase of manufacturing to create a fit. However, for the case with Design for Assembly (DFA) and DFM methodologies, the main focus is single product development. Herrmann et al. (2004) comment that an extension of the DFM tools to comprise multi-product development will hold the key to achievement of competitiveness.

Mathematical models

Some researchers have undergone the task of developing methods based on mathematical models. Some methods are based on measures of modularity, which act as subjects of optimization using different techniques (Hultink et al., 1997). Others seek to integrate product platform, manufacturing process, and supply chain decisions through the application of mathematical models, thus extending the concept of the generic bills of materials (GBOM) by quantifying relations between decisions from the different domains.

Conclusion

It is evident that the contributions mentioned above can play a role in the identification of program architectures. Situated in this cross-functional research field, it is clear how research centered within either the product or production domain tends to leave out important aspects of the adjacent fields, and considering the identification of program architecture this is a deficiency considering the contributions listed above. Extensive research is also found within the reengineering of business processes and different means of optimization of operations, but these areas exclude necessary details within the field of architectures. They are simply not concrete enough, or deal with sub-optimization of operations and processes leaving out the product domain. The methods do not explain how the modeling and evaluation is carried out for very large product programs with, for example, 70,000 commercial products and 300,000 parts. There is very little support for supporting the very fundamental question: "how many product architectures are right for our company?"

AME method

This section presents a seven-step method to evaluate the benefits of shared modular architectures. These seven steps are as follows:

Step 1: map the market globally and main required properties;
Step 2: map cost/performance for core module areas;
Step 3: map each as-is product architectures;
Step 4: map each as-is manufacturing architectures;
Step 5: identify to-be product architectures and manufacturing architectures;
Step 6: map cycle plan;
Step 7: calculate financial impact.

In the following, each step will be explained.

Step 1: map the market globally and main required properties

In this step, the market and required properties are mapped according to Fixson (2005), Levandowsky et al. (2014), and Meyer and Lehnerd (1997). It means that the market for a product line is grouped into approximately 4–12 categories. There are normally two axes in the mapping (segment and performance levels such as high end and basic), see Figure 1.

For a pump manufacturer, it might segment wise be geographical area (e.g. North America, Europe, Asia pacific) and performance wise, media pressure (up to 2 bar and above). For each group, key properties, for example, energy efficiency and lifting height, are identified. The product line properties are then mapped and competitor product (best in class) is mapped. The result is a number of "spider charts" as shown in Figure 1. Finally trend indicators are identified. It means in

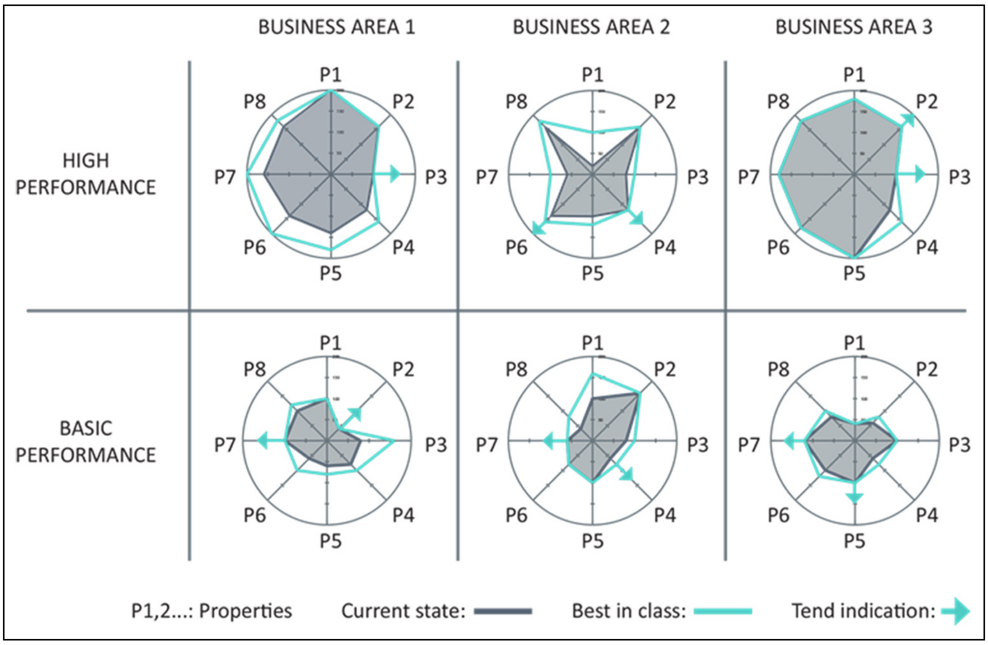


Figure 1. Mapping of market segments and required properties.

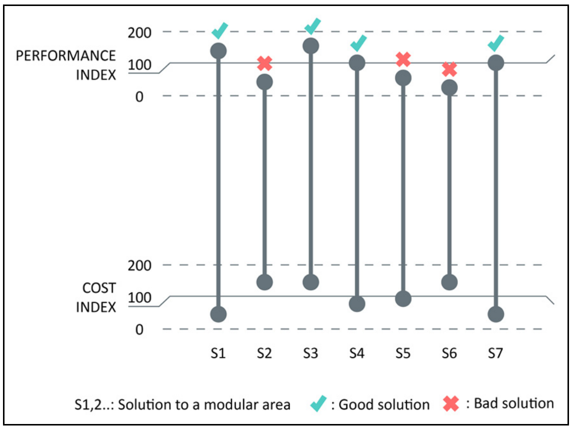


Figure 2. Description of cost/performance for a key module is mapped. Each vertical line represents a module area. The lower dot is the cost and the upper dot is a certain performance of a property.

which directions do the company expect that requirements will change. Concerning the energy efficiency, it is very likely to be reduced in next generation of pumps. Trend indicators are utilized in Step 5. It is very important that the architectures are prepared to deliver the right properties. One CEO explained, "It is important to be prepared for the next war and not the previous one."

Step 2: map cost/performance for core module areas

In this step, the products in a product line are pragmatically divided into a number of module areas that are the carrier of key properties for a product. For a pump, it might be motor, hydraulics, controls, and so on. Then a few key module areas are identified, which are the carrier of major cost and major properties (Huang et al., 2005; Otto and Wood, 1998). The purpose of this step is to map key module areas in a direct material cost and a relevant performance dimension. For a pump manufacturer, it could be the motor and the controls. Often, a few module areas cover the majority of the cost and performance in a product. Then each module area variant is mapped in a cost performance diagram as shown in Figure 2.

This overview is quite important in the method (Guo and Gershenson, 2007). Often, there will be different module areas with very different cost levels but is delivering same performance. In other cases, there will be module areas that have low performance and high cost. In other words, the module area is expensive and can do very little. What should be the immediate reaction to such a module area "is there any good reason for having this module area in the product line." What has been observed in the case project is that there is up to a factor 3 in direct cost differences between module areas that have similar performance. So there are significant direct material cost reduction possibilities by consequently utilizing the most cost-effective modules.

Step 3: map each as-is product architecture

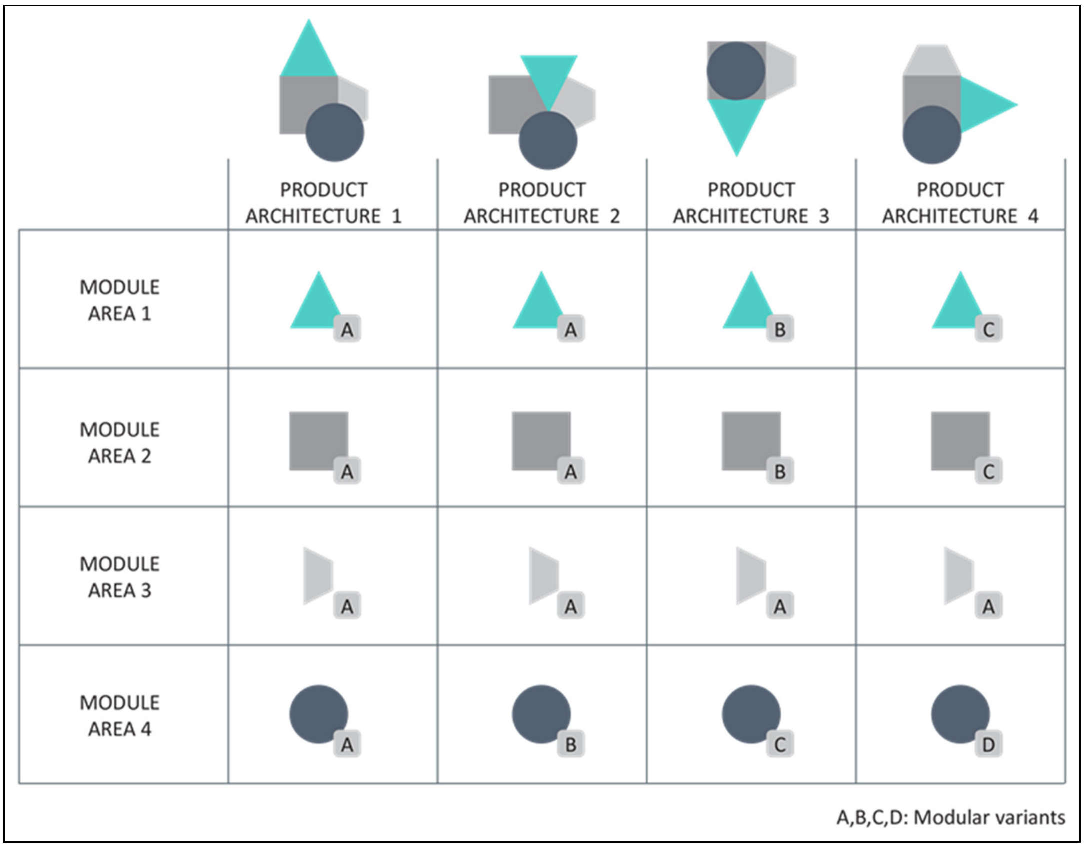
In this step, the number of architectures within a certain product line is identified (Olesen, 1992). The process is that key interfaces are identified. This number has in this research project been 10 or below. Examples on key interfaces in a pump might be between housing and impeller. The interfaces play a crucial role in development for an industrial company. If and only if interfaces are shared, the modules can be shared. Figure 3 shows an example of how the number of architectures is identified. There is a very important link between Step 1 and Step 3. Reasoning from Step 1 to Step 3 should bring forward the question: how many architectures are right for our company in order to deliver good products in the different segments? In the case company, there has been a clear tendency that the companies have more product architectures than can be justified from a market point of view.

Step 4: map each as-is manufacturing architecture

The main purpose of this step is to identify differences in manufacturing properties, that is, labor cost (Andreasen and Olesen, 1990; Stone et al., 2000). Figure 4 shows an example where a product with different architectures is manufactured in different factories in Europe, United States, and China. What is compared are the differences in labor assembly time on subassembly lines and main assembly lines. In the case projects there has been a factor 2 deviation in labor time between the best and worst performing product architecture. This means that the product architecture plays a major role for efficiency in production. In principle, the productivity in the studied factories can be improved with a factor 2 by conscious selection of the best product architectures.

Step 5: identify to-be product architectures and manufacturing architectures

In this step, experienced persons from sales, product development, and manufacturing are taking a top–down look from a market point of view and identify how many architectures and module variants are needed in order to serve the market (Lindemann et al., 2009; Meyer and Lehnerd, 1997). This is really an expert judgment, where the most senior people in the organization have to be involved. In the case project, the reduction possibilities in terms of product



	PRODUCT ARCHITECTURE 1	PRODUCT ARCHITECTURE 2	PRODUCT ARCHITECTURE 3	PRODUCT ARCHITECTURE 4
MODULE AREA 1	A	A	B	C
MODULE AREA 2	A	A	B	C
MODULE AREA 3	A	A	A	A
MODULE AREA 4	A	B	C	D

A,B,C,D: Modular variants

Figure 3. Mapping of current architectures.

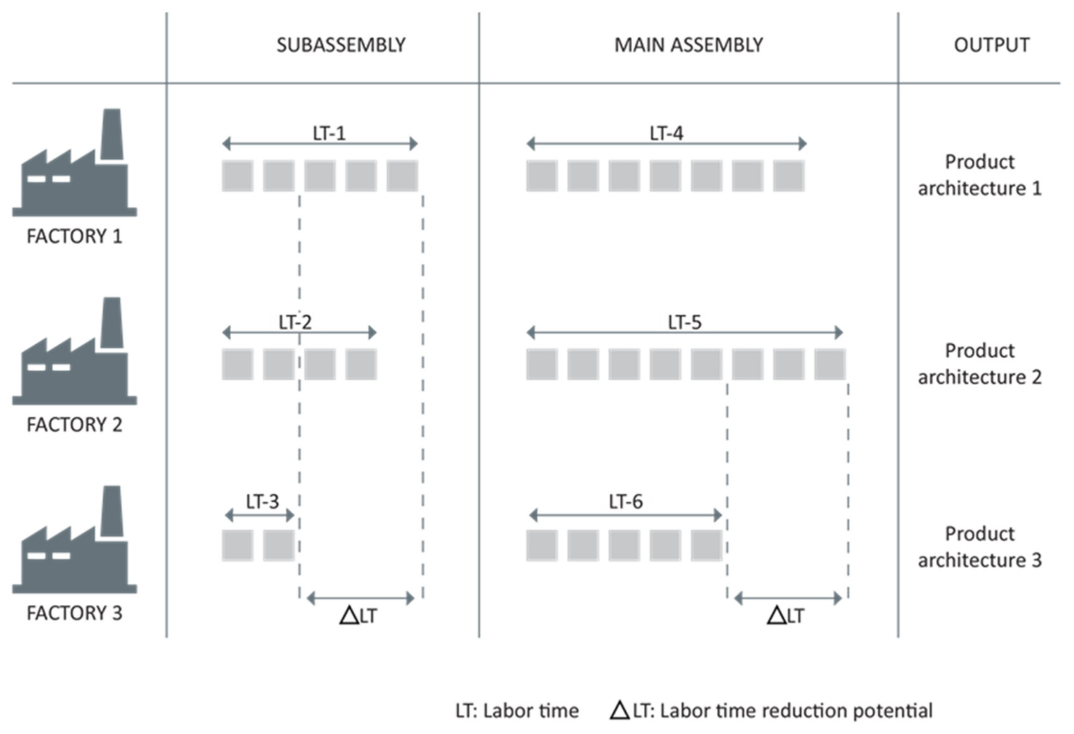


Figure 4. Manufacturing architectures.

architectures, manufacturing architectures, and module variants have been between 5% and 50%. In other words, the company is much more complex than needed.

Step 6: map cycle plan

The starting point in this step is a 5- or 10-year cycle plan, showing when products and product line are expected to be upgraded or relaunched (Krause et al., 2013; Pimmler and Eppinger, 1994). Next, phase out and phase in of architectures are added. It is further assumed that the best modules are consequently utilized across the product lines. Based on the reduction in product and manufacturing architectures, utilizing the most cost-effective module areas, it is possible to estimate direct material savings and direct labor savings.

Step 7: calculate financial impact

In this step, the benefits in terms of direct material cost, direct labor cost, and CAPEX avoidance are summed up (Du et al., 2001; Kester et al., 2013; MacDuffie, 2013). The results are three numbers explaining the financial potential of shared architectures. In the case company, this has been a very important step in order to put shared architectures on the top management agenda. One of the main advantages is that now such an initiative can be compared to other big initiatives such as automation, low-cost country sourcing, and manufacturing footprint location.

Application of the AME method

The method has been tested in a global business to consumer company. The case company has sales companies in 100 + countries and 35 factories in Europe, Asia, North America, and South America. There are six R&D centers that develop six product lines. The company has approximately 75,000 commercial product variants in the market and around 400,000 part numbers. The company has over a longer period been part of several mergers and acquisitions.

For several years, there had been a discussion in the board of management concerning the complexity of the product lines. It has among certain members been the assumption that it should be possible to serve the markets with fewer architectures and parts, but no definitive conclusions could be made. Therefore, the company wanted to test the AME method.

A team of three full-time persons (called the core team) for each product line was appointed. The core team consisted of a researcher, a senior R&D person, and a financial controller. This core team has ad hoc access to senior experts in sales/marketing, R&D, manufacturing, purchase, and financial control. In total, approximately 30 persons for each product line have been active in the work.

The AME work has been carried out during 20 weeks for each product line. The assessment work has been divided into three phases.

Phase 1

This included Steps 1, 2, 3, and 4. The main way of working has been interviews with key persons, site visits to key factories, and data extract from the ERP systems.

Phase 2

In Steps 5 and 6, three workshops with senior market, product, and manufacturing experts were carried out. The work was fundamentally anchored around the number of architectures. The main question asked was as follows: how many architectures do the company need in future? It is an illusion that there will be consensus concerning this. What happened in the workshops is that there were structured discussions and viewpoints were delivered from the experts. After the workshop, the core team made a conclusion concerning the needed number of product architectures, manufacturing architectures, and module area performance steps. This is a very crucial step—and much further detailed work has to be carried out later on in implementation. Table 1 shows a possible reduction in product architectures from 60 to 25. Perhaps, detailed studies will later show that, for example, 30 or 15 product architectures are better. This will, however, not change the main conclusion—that significant cost reductions are possible.

Phase 3

This is calculating (Step 7) the benefits in terms of direct material, direct labor, and CAPEX avoidance

Table 1. List of as-is architectures, to-be architectures, and financial impact.

Product line	As-is product architectures	To-be product architectures	Financial impact (% of turnover)
1	8	4	2.0
2	9	4	0.5
3	12	6	1.2
4	5	3	0.9
5	10	4	2.1
6	16	4	1.0
Total	60	25	

concerning tooling. The main inputs are the cycle plan, number of new architectures, and number of key module areas with "best of breed" cost/performance levels obtained in Step 3. This means that impact calculations are very conservative, that is, it is based on solutions and principles that are already available in the company today. The main results are summarized in Table 1. The work has lead to significant conclusions and discussions in the board of management.

Reduction in the number of product architectures. It is possible to reduce the number of product architectures significantly from 60 to 25 without comprising the number of commercial variants in the market. No one can for sure know whether this is completely true, but it seems that a significant reduction is possible. It has become clear to the board of management that the number of product architectures is strategic decision in the company that has to be anchored on senior vice president level. One vice president explained, "One architecture is very wrong—there will be bad cost/performance compromises. On the other hand 20 architectures is also wrong—this will lead to high complexity on and unfocused R&D effort."

Additional benefits of fewer architectures. It is the assumption that the benefits in Table 1 are only the top of the iceberg. There are additional savings in terms of reduced ware house cost, due to fewer module areas and part number. The efficiency in factories should increase due to fewer change-overs on the assembly lines. It should also be possible to introduce later customer order decoupling points, which should reduce delivery time. Furthermore, it should be possible to increase utilization level in factories, due to fewer parts, modules, and architectures. Furthermore, additional savings can be expected in purchase due to higher purchasing volume.

From an R&D perspective, fewer architectures means that the R&D effort on each architecture could be increased. This should again lead to increased quality, higher level of innovation, and reduction in time to market for new variants.

Product line design principles. During the work, it has been clear that some product lines are fundamentally wrongly designed. The engineering design approach has been wrong. It means that high-end products have been designed first and then the approach has been to "strip" them to reach mid- and low-end markets. The results have been that the costs for mid- and low-end products are too high. One R&D manager explained, "Stripping a Rolls Royce will not lead to a cost effective Polo car." The conclusion is that every module area design should in the future be based on scale up thinking rather than scale down thinking and part of one or more well-defined architectures.

Implementation. Two fundamental implementation alternatives are being considered. The traditional organization could drive implementation according to the approved cycle plans. The implementation time would then be approximately 7 years for all product lines. Another alternative is to establish a separate product and manufacturing architecture organization that has the full responsibility for all product lines and manufacturing. This would reduce implementation time but increase CAPEX. So far, no conclusions have been made. Another concern is the coordination between shared product architectures and increased automation in assembly. These two initiatives naturally have to be coordinated. It would be waste of resources to automate product architectures that will be phased out. Implementing shared architectures and then afterward increased atomization might take too long time.

Discussion

In the state-of-art literature on platforms and engineering design in general, it is often the assumption that concepts for the future product program have to be developed in order to evaluate cost reduction potentials. For practical reasons, this will not be possible in large global companies, so another approach is necessary to evaluate financial impact of shared architectures. The main contribution in this article is a top–down reasoning approach. This means reasoning from what is required in the market and relating this to the number of as-is product architectures. Hereby, the mismatch between market requirement and the current number of product architectures should be recognized and the ideal future number of architectures is identified. Compared to a real conceptualization project, the AME method will not provide financial benefits with the same level of confidence, but still good enough to evaluate whether it is relevant to continue working toward shared and fewer product architectures.

The AME method is very dependent on senior people in an organization, the top–down reasoning from the current state to future state is often difficult and there might be conflicting opinions. The viewpoint of the authors is that even though the "ideal" number of architectures is slightly higher or lower, it will not change the main conclusions. This means that a significant reduction in the number of product architectures is possible without compromising the market coverage.

Concerning application to the AME, the ideal company is mass producing with a history of mergers and acquisitions, distributed R&D, and manufacturing. Due to mergers and acquisitions, there will often be product lines with overlapping products. Due to distributed R&D and manufacturing, there will often be misalignment, that is, reinventing the "wheel" examples.

Conclusion

The article has presented a relatively simple method for calculating the benefits of shared architectures, the so-called AME method. There are three major contributions. The first one is an operational way to describe and count the number of product architectures. Second, the cost performance mapping shows in simple way how the performance steps of modules are realized. Number 3 contribution is top–down reasoning concerning the number of product and production architectures. From a practical point of view, the main contribution is the increased ability to have strategic discussion on the right number of architectures in a company based on facts.

There are many improvement areas in the AME method. One of them is finding out how to reason from requirements in the market, to the number of product architectures, and to the number of manufactured architectures. There must be sound principles for obtaining the right balance between the product and manufacturing architectures. Second, it should also be possible to include other quantifiable benefit dimensions such as time to market, R&D efficiency, and complexity reduction in manufacturing.

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ASSESSING THE FINANCIAL POTENTIAL FOR MODULARIZATION: A CASE STUDY IN A GLOBAL OEM

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Abstract

Assessing the financial potential of implementing a strategy, based on sharing of key modules and interfaces across a portfolio is difficult. However, this is a critical input when deciding strategic direction in industrial organizations. Through a case study, this paper gives an example of how to map and evaluate the architectures in a portfolio to identify the financial potential for implanting a platform-based modularization strategy. The approach has been applied in a global world-leading OEM with 50.000+ product variants and a turnover of USD 3,5b (2015). The results show a potential for reducing the cost-base by up to 15% through systematically sharing of key design principles across 80% of the company's portfolio. This has supported the discussion of adjusting innovation strategy in the organization. The core contribution of the paper is the operational application of the systematic Architecture Mapping and Evaluation approach (AME) and discussion of how it can support strategic decision-making related to modularization. The approach builds on the understanding that a top-down assessment can give a starting point for implementing a level of modularity across a portfolio.

Keywords: Platform strategies, Product architecture, Case study, Decision support

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1 INTRODUCTION

Industrial companies (i.e. a organization developing, manufacturing and distributing physical products) are faced with the challenge of continuously improving their business. Introducing new products to increase turnover and/or reducing the internal cost-base are two ways to achieve this (Dobni et. al. 2015; Kester et. al. 2013). Defining and deciding on a strategic direction for business improvements implies evaluating one strategic initiative against another. In a situation with changing market requirements, increasing global competition and unpredictable technological development this can be a complex task, but non-the less, critical for the success of a business.

This paper presents a case study focused on the application of the Architecture Mapping and Evaluation (AME) approach presented by Mortensen et. al. (2016). The AME approach is meant to support industrial companies in assessing the financial potential of introducing a strategy based on shared modular platforms and architectures, in this paper referred to as a modularization strategy. The approach is based on elements found in existing literature and is a step-based operational method, which is aimed at practitioners working within the field of modularization and strategic decision-making.

The case company is a large and global OEM with operations in Europe, America and Asia. They design and manufacture industrial products and the portfolio includes 50.000+ product variants. Yearly turnover in 2015 was approximately USD 3,5b. Through a systematic application of the AME approach a potential for reducing the company's cost-base was identified. Potentials related to sharing of selected key design principles across 80% of the portfolio. This supported decisions related to changing the innovation strategy in the company. The core contribution in this paper is an example of application and evaluation of the proposed approach. Furthermore, the paper supports an interesting discussion of the financial benefits of introducing modularity in industrial organizations. An area, which is difficult to quantify and has had limited focus in existing literature (Campagnolo and Camuffo, 2010). First, the paper will describe the theoretical basis for the AME and the related research. Next the case study is presented and, finally, results are discussed.

2 RELATED WORK

The AME approach (Mortensen et. al. 2016) draws on classic System Thinking (Klir, 2001), Theory of Technical Systems (Hubka and Eder, 1988) and elements from the Product Family Master Plan (PFMP) (Harlou, 2006), and is primarily a tool to visualize high-level potentials for shared modular architectures. It focuses on the three dimensions: The market, the product and the manufacturing dimension. Industrial insights obtained through research activities and working as professionals in industry, have inspired the tool. Being able to, up front, assess and indicate the financial potential for implementing a platform-based modularization strategy was in several cases identified as a desire in industry. Thus, the approach is thought to act as decision support on a strategic level. The case study will be used to describe the different steps in the AME approach in detail.

The next sections in this paper will briefly describe what is understood as platforms and architectures and show two state-of-the-art examples of existing research related to evaluation of the financial benefits of modularization. When looking at existing research, it is to a large extend focused on situations where companies have already decided to adopt a modularization strategy or elements of one. The result is, that existing methods are technical in nature and not directly operational in the early stages of defining a strategy for modularization. This is why the application of the AME approach provides some interesting input to decision making related to modularization.

2.1 Platforms and architectures in product development

The classic way of developing products, one-at-a-time is costly and can ultimately result in a high number of unique designs. Starting from zero every time a development process is initiated can increase time-to-market and unique designs are seen, where using a standardized solution could have saved resources and significantly reduced developing time (Meyer and Lehnerd, 1997; Harlou, 2006; Simpson et. al. 2014). Product family design, based on modular platforms and architectures, describes a way to organize products as a set of modules that can be designed independently and through combination, can provide a variety of product variants. The method is often seen as a way to enable cost-effective mass-customization as companies can deliver a wide product assortment based on sharing of standardized modules (Jiao et. al. 2007; Gonzalez-Zugasti et. al. 2001; Hvam and Ladeby, 2007). Other benefits are generally recognized as the ability to reduce time-to-market and reduce cost for new product introductions (Harlou, 2006; Simpson et. al. 2014). A modular approach can also be seen applied to the manufacturing domain to achieve similar benefit (Campagnolo and Camuffo, 2010; Sanchez, 2008).

The terms platforms and architectures are often used in different contexts and can be found to have different meanings and interpretations when looking into existing literature (Campagnolo and Camuffo, 2010). The part of the AME approach which focuses on architecture mapping is based on the understanding, that a product or manufacturing architecture describes a structured arrangement of functional elements, the allocation of these functional elements to physical components and the definition of the interfaces between these interacting physical components (Ulrich, 1995; Harlou, 2006). The architecture defines the basis for variant creation towards (1) the market side, to satisfy a variety of customer needs, and (2) the operational side, e.g. technical variants aimed at reducing internal cost or time-to-market (Erens and Verhulst, 1997).

The benefits of platforms and architectures can be said to exist in the dimensions of rationalization and innovation (Mortensen et. al. 2012). Rationalization focuses on benefits related to the optimization of the existing business e.g. increased standardization and effectiveness in production. The innovative dimension focuses on the future of the business, e.g. improved ability to reach out to new markets, rapid new product development based on a reuse of standard designs, and leverage of core technologies in new business areas (Harlou, 2006; Meyer and Lehnerd, 1997). Even as the methodology is well established in research and industry, it can be argued that the understanding of the strategic implications of implementing a modular strategy is still relatively limited (Sanchez, 2013). However, modular architectures and platforms from which several product variants can be developed, can be said to give an organization the foundation to execute multi-product plans focused on strategic market differentiation (Simpson et. al. 2014). The approach presented in this paper includes a market segmentation, which is based on the mapping concept presented by Meyer and Lehnerd (1997), where the market is divided into homogeneous groups of consumer preferences to create a number of market segments. Understanding the market dimension is a fundamental aspect of defining the criteria for development of product platforms and architectures (Hansen et. al, 2012). The AME approach links the architectures to the market segments and includes sales volume to understand how the current portfolio fits the market situation. This overall mapping of the current market, product architectures and manufacturing architectures is considered an important step towards identifying the financial potential for implementing modularity into a portfolio. Jiao et. al. (2007) argues, that future research related to modularization lies in this holistic and system-wide solution-oriented approach. This includes the establishment of a closer relation between the market, product and manufacturing domains. The approach applied in the case study draws on the architecture definition described here and focuses on both rationalization and innovation potentials related to modularization.

2.2 Financial evaluation

Several methods exist to assess the financial value of e.g. a developing project. This includes different variations of assessing Net-Present-Value, Internal Rate of Return, Discounted Cash Flow Analysis or determination of Estimated Commercial Value etc. (Cooper et. al. 2001). These methods give a relative simple indication of the value of a project and can be used to make decisions when planning how to optimize the value of a portfolio. Methods to assess the value of a platform initiative based on sharing of common modules can also be found in the literature. However, research is limited within this area.

Gonzalez-Zugasti et. al. (2001) present an approach to valuation of a platform design for a product family. The method is based on the understanding, that subtracting the needed investments from the sum of benefits related to a modular platform design, can define the value of implementing a platform strategy. They present a two-step model. The first step focuses on the technical design of different platform alternatives for a product family. The second step goes into evaluation and selection of the most valuable/robust product family/platform design. The approach requires a number of alternatives to be evaluated. Thus, the method implies that a company has already committed to the development of these platforms.

Moon and Simpson (Simpson et. al. 2014) introduce a method based on a module instance matrix to valuate modular platforms in product family design. They introduce the expected platform strategy cost function and calculate the expected cost for a specific platform strategy, as the sum of additional design cost per product, plus the expected cost for a given strategy. The strategy cost relate to the cost of redesign of components, creating convenient interfaces and having some components overdesigned so that they can be shared between several variants within the product family. They then valuate a platform design based on the net benefit, related to the volatility rate, the changing demand rate, the cost saving of family design, and the identified additional cost. The approach differs form Gonzalez-Zugasti et. al. (2001) by including a level of risk and uncertainty in the valuation e.g. by taking into account the possibility for market changes. Being able to present the expected cost and a valuation of a platform strategy gives a company the ability to make decisions related to modular family design.

Both approaches compare different platform alternatives or platform strategies to support the selection of the best possible option. This is a valuable input when making decisions regarding modularization. However, they consider different platform alternatives within a product family and they imply that an organization has already, to some degree, committed to designing a level of modularity into their products. Introducing modules, which are shared across one or several product families, can be argued to be seen more as a portfolio management task (Krishnan and Ulrich, 2001) and room exists for an approach to valuate modularization across several product families and the related manufacturing landscape. Furthermore, support related to identifying a holistic strategic direction for modularization within a portfolio is needed.

The approach presented in this paper builds on similar elements as the two existing methods i.e. the possibility of valuating modularization by subtracting needed investments form potential benefits. However, the approach holds two dimensions (1) identifying rationalization potential based on the existing situation in an organization and (2) identifying potentials for platform innovation through windows of opportunity in the company roadmap. The sum of contributions from the two dimensions indicates the financial potential. The AME approach gives a high-level valuation of a platform initiative, which can be used by organizations when making decisions related to defining a strategic direction. The approach is a top-down assessment, which can support identification of areas within a portfolio where the largest benefits can be harvested. This is believed to be an important step before going into the process of designing modularity into a portfolio or a product family.

3 RESEARCH APPROACH

The presented research is the outcome of a comprehensive case study where we had the opportunity to apply the AME approach in a global world-leading OEM. 40 days were spent in the case company, working with the AME as reference model. From August to December 2015 we supported an internal project team in the effort of developing a strategy for modularization. The team consisted of resources from production, R&D and business development. The thoroughness of the study allowed presentation of results consolidated within the company and milestones were presented to top management. The goal of the study was to use the AME approach as tool to define focus areas within the company's portfolio for platform design and to define a financial goal setting for modularization. A high level of uncertainty was identified in the process of assessing the financial potential and the goal was not to provide an exact number and disregard this uncertainty, but as far as possible, to provide a fact-based argumentation for implementing a modular platform-based innovation strategy. The AME approach was introduced through weekly work session and results presented in visual models. Figure 1 and 2 show representations of some of these models. Finally looking at the current situation, the rationalization potentials were assessed across the portfolio, and potentials for platform innovation identified by looking at windows of opportunities. In the end a financial potential based on a holistic portfolio-wide approach was presented. This served as financial goal-setting and starting point for implementing a modularization strategy within the case company.

4 ARCHITECTURE MAPPING AND EVALUATION IN GLOBAL OEM

The AME approach proposes that it is possible to assess the financial potential by applying a holistic and top-down perspective across a portfolio. This includes assessment of the current situation (as-is) in a company and outlining a modular platform-based innovation strategy (to-be). Comparing the two scenarios and taking the sum of all rationalization and innovation potentials and subtracting the investments needed, indicates the financial potential. The approach is relatively simple and is based on the understanding that a new "to-be" scenario can be benchmarked against the current situation to indicate the potential for changing strategic direction. The AME approach should be seen as decision support. It includes a number of steps, which are primarily described through a number of visual models including (1) mapping of the market and global requirements, inspired by Meyer & Lehnerd (1997), (2) the product architecture mapping and (3) manufacturing architecture mapping, inspired by Harlou (2006) and Bruun et. al. (2014), (4) the architecture evaluation, which is a cost/performance evaluation, (5) identification of a "to-be" scenario, (6) a roadmap dimension and (7) the assessment of the financial potential for implementing a modularization strategy. One of the values of this approach is to allow companies to evaluate the impact of modularization relative to other strategic initiatives in the organization e.g. cost reductions through optimization of procurement or a new market entry. The next sections will describe operational examples of the different steps and results from the case study.

4.1 Market segmentation and identification of key design driving properties

The case company designs, manufactures and distributes products, which include an electronic control box (CB). This CB has been the main focus of the study. The core markets are Europe, Americas and China and includes both OEM and wholesale customers. The CB is generally made up by a number of printed circuit boards (PCB) encapsulated in either a composite or metal casing with one or more I/O functions. The CB is responsible for the majority of the total unit cost and is one of the main drivers for product differentiation. The strategy has, historically, been to develop the CB at product family level, with one or more assembly lines dedicated to the specific family. This has resulted in a high level of capital investments and relatively low utilization of the assembly lines. In the first part of the case study the current market situation was mapped and trends and key properties driving CB designs were identified (see Figure 2). The market analysis was the result of a series of semi-structured interviews with key stakeholders in the organization. Several rounds of interviews were held and between these a visual representation of the market segmentation was updated and used as reference for the next round. In collaboration with market and technical specialists the number of key design driving properties was limited to 6. P1: product power requirements, P2: ambient temperature requirements, P3: need for human-machine interface (HMI), P4: serviceability of the product, P5: electromagnetic compatibility (EMC) and P6: The need to live up to international approvals. In Figure 1 these are represented as P1-P6. Each property was evaluated in the segments, creating the profiles seen in the charts. Figure 1 shows an excerpt of the full market segmentation.

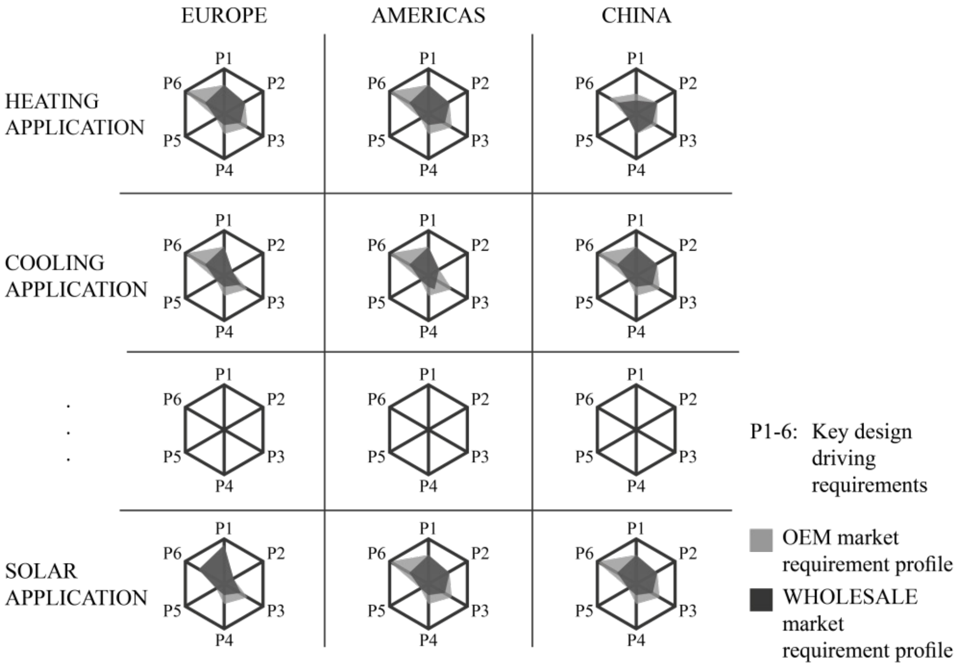

Figure 1. Example of market segmentation and evaluation of key design driving properties

The approach was to focus on the key market segments and key requirements (Mortensen et. al., 2011; Mortensen et. al., 2016). This resulted in a number of segmentations defined by strategic geographical core markets and core application areas. The goal was to show how the existing architectures fit the market and through a top-down reasoning argue for a changed approach if needed. This level of detail gave enough input to show that the existing strategy in the case company resulted in added cost being transferred from low volume segments to the core segments responsible for approx. 90% of the sales volume. The conclusion was, that elements in the current strategy compromised the overall competitiveness of the portfolio.

4.2 Map current architectures

Next, existing architectures were mapped. Identifying the number of architectures in the portfolio, was, to some extend, a pragmatic exercise. As benchmark, an architecture was considered unique if less than 90% of interfaces were shared with other architectures. Software features and minor variance e.g. colouring, was not considered. The 90% benchmark, allowed differentiating product variants. For example, within a certain product family redesign of a single variant had led to a number of interface changes and thus, due to the 90% benchmark, several different architectures were identified within that product family. Through a number of iterations, 24 different product architectures distributed over 8 product families and 20 different manufacturing architectures were identified. The challenge in this process was to be systematic in the identification of the architectures and input from several product and manufacturing specialists was required. The conclusion was, as in average 3 different product architectures existed within each product family, that too many unique architectures existed in the portfolio. Examples of different architectures within the same product family were e.g. different product structures for the American and European markets and different building principles for OEM customers and wholesale customers. At interface level this could be different ways to connect an upper and lower cover of a CB, or different ways to mount a PCB in the lower cover e.g. press-fit, snap-fit or mounting with screws. Only interface variations, which were not directly linked to a customer requirement, were regarded as non-value adding. Cost and sales data for each architecture were analysed i.e. material cost, labour cost, yearly sales volume and full-cost. For the manufacturing architectures each process step was analysed and grouped into three overall categories: Handling, processing and quality control & programming. This indicated core differences between line architectures. Again, core data was identified i.e. cycle time, capacity, investments, footprint and overall equipment effectiveness (OEE). Figure 2 gives a visual representation of the architecture mapping and shows how the production landscape was related to the 24 product architectures.

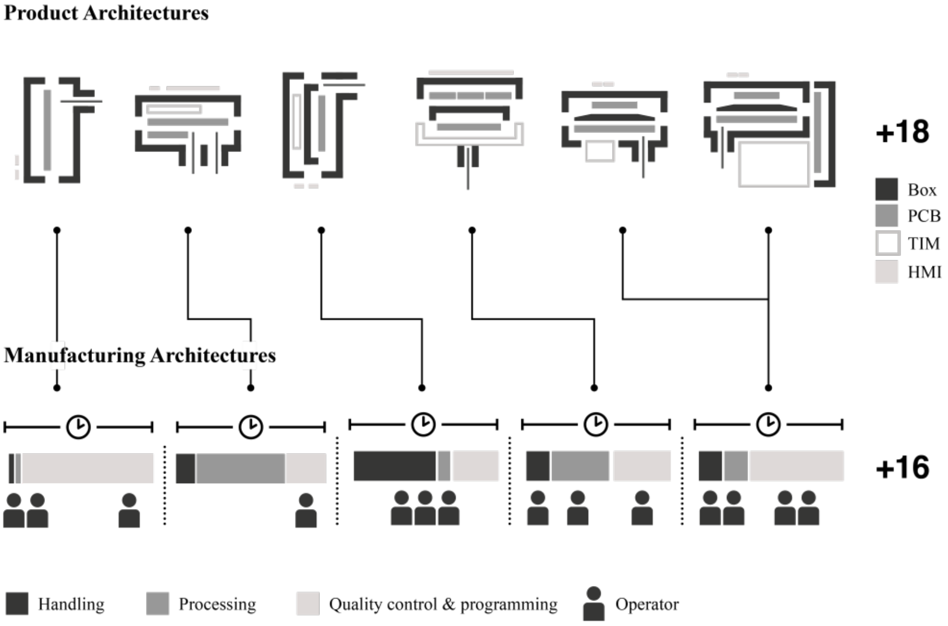

Figure 2. Example of architecture mapping

Differences between product architectures are in figure 2 illustrated by different representation of the main subsystems of the CB i.e.: the encapsulation (box), the printed circuit boards (PCB), the thermal interface material (TIM), which allows transportation of heat away from mainly the power module, and the human machine interface (HMI).

4.3 Evaluate performance across portfolio

Having established an understanding of number of architectures in the portfolio, cost and performance for the individual solutions were evaluated. For example, looking at cooling solutions across the portfolio, it was clear, that several different technologies with different realization and cost structure existed. In a similar way, looking at test and programming equipment across assembly lines, large deviations in cost/performance were identified. The complete evaluation included systematically going through key functional parts of the architectures and comparing cost/performance across the portfolio. The analysis supported the important discussion of which parts of the portfolio should build on in the "to-be" scenario and which parts should be "killed". This type of evaluations was only possible by applying a portfolio-wide perspective and gave the first indications on the rationalization potential. Examples of findings from the evaluation phase were that comparable product solutions differed in cost by up to a factor 2, as different design solutions had been applied to deliver similar product properties. On the manufacturing side, product dedicated test procedures were driving cost. Furthermore, it was observed that copying line designs, or parts of it, provided up to 20% reduction of investments and procurement time.

The 24 unique product architectures and 20 unique manufacturing architectures were related to the market segmentation in Figure 1. This allowed rationalizing across the product, manufacturing and market domains to assess the optimal number of architectures in the portfolio able to cover the market. The assessment showed that roughly half of the existing architectures were enough to cover the market segments. This was an estimation based on the input from the AME approach and conclusions were that the number of current architectures exceeded the optimal. These examples give an idea of the type of top-down reasoning behind the financial estimates presented in this paper.

4.4 Conceptualizing "to-be" scenario and financial assessment

Mapping and evaluating the current market situation and existing product and manufacturing helped to identify a number of potentials for rationalization of the current situation. Next, the roadmap for new product projects were scrutinized to identify windows of opportunity related to modularization. This could e.g. be a new product able to carry a new standardized cooling solution, which then could be implemented across the portfolio for comparable products. Three projects, all in an early development stage, were identified to serve as lead projects. For each project sales forecasts, product, and production concepts were analysed. The "to-be" scenario was conceptualized based on the input from the former four steps in the AME i.e. market segmentation and analysis, architecture mapping of product and manufacturing, evaluation of cost/performance across the portfolio, and the roadmap. The "to-be" scenario formed a holistic picture including a definition of optimal number of architectures to accommodate market demand, modularization of these architectures and the identification of where standardization could be financially beneficial. In collaboration with the specialists involved, the "to-be" scenario was benchmarked against the "as-is" situation and all potentials were summarized. Table 1 shows an excerpt from the total list and illustrates potential finical gain and needed investments for seven rationalization initiatives. Each potential was consolidated and reviewed within the team working with modularization in the organization. The financial numbers are displayed in Mill. USD. The needed investment is indicated with zero, if no or a neglectable direct investment was anticipated to obtain the potential gain.

Table 1. Examples of rationalization potentials

Rationalization potentials		**Investment needed**	**Potential gain**
1	Kill redundant product architecture	0	5
2	Apply best cooling solution for comparable architectures	1,5	3,5
3	Use best solution for quality control	0,3	1
4	Move product from one to another assembly line	3	8,8
5	Implement standard solution for PCB assembly	0	3,2
6	Implement standard solution for box assembly	0	5
7	Run-in of product on existing assembly line	0	2,9
Total		**4,8**	**29,4**

Benchmarking the sum of all financial potentials with the total cost base for the CB (as-is) indicated a potential reduction of material cost by 10%, labour cost by 15% and investments by 35%. In total, the final assessment showed a potential reduction of the total cost base by 15%, by implementing elements of a modular platform-based innovation strategy for the control box. Applying the AME approach helped the case company to define a goal setting for modularization, and the results served as a starting point for realization of a platform-based innovation strategy. Applying the AME and using it as decision support related to modularization, initiated a discussion in the case company to extend the scope and apply the approach to the complete products assortment.

5 DISCUSSION AND FURTURE RESEARCH

So, is it possible to get anything beneficial out of estimating a financial potential based on other estimates of rationalization and innovation potentials at architecture level across a portfolio? As indicated in the case study, putting in the effort, it is possible to get an outcome, which on a high level can indicate if a company can get anything out a modularization initiative. The intention is, that the result of the AME should be used as decision support for top management to answer whether to proceed or not. Based on input from the AME approach the case company has put an effort into pursuing the identified potentials, has initiated similar AME analysis for all product areas, and has put resources into conceptualizing and operationalizing the "to-be" scenario for modularization of the CB. This is considered to validate the value of the approach.

The approach highlights the importance of understanding the current situation before going further into the definition of a platform-based strategy. Specialists in the case company commented in the early phases, that resources was wasted putting so much effort into mapping and detailing the current situation. However, as this mapping served as benchmark for the future modularization efforts, the value became clearer along the process. A fundamental assumption in this paper is that we cannot ignore the current situation. Good product and manufacturing solutions exist across the portfolio, which should be carried into the "to-be" scenario. Very few situations are "green field" and the AME approach seeks to connect future modularization initiatives with the existing portfolio and gives an assessment of how these two situations can be merged in the most optimal way to harvest a financial potential. This is why the AME approach can provide an important input for decision-making regarding modularization in an industrial context. The overall point for this assessment is to bring the discussion of modularization to a strategic level. If we are not able to assess the financial potential, the discussion of platforms and architectures is believed to often remain an R&D task, and be constrained to specific project contexts. The top-down approach presented in the AME showed a positive result and has brought the discussion of modularity to a new level in the case company. A major challenge related to the approach applied in the case study, is the collection of data. Collection of data e.g. cost data, market data and production data, must be performed so stakeholders are confident, that correct conclusions are drawn based on the AME approach. Extensive effort was put into validating data study and several iterations of mapping cost structures of the existing architectures were needed. As each company context is different, research effort should be put into systemizing the data collection process related to the AME approach. This could strengthen the approach and improve the operational use.

As seen in related methods to valuate modularity in product families (Simpson et. al., 2014), a high level of uncertainty exists in this type of assessment e.g. in market changes and internal cost variations. The uncertainty presents a fundamental challenge for the AME approach. However, and as the case study showed, the AME approach should indicate if a financial potential for modularization exists and in which range this potential should be expected. Not to give an exact number. It is up to management, with input from the AME to dictate the strategy for modularization in the organization.

For future research activities related to decision support in the early stages of developing modularization and platform strategies, focus should be on how to systematically approach the data collection to the extend it is possible. A more systematic overview of data needed to execute an assessment based on the AME approach would be valuable. This could improve the operationalization of the approach. One of the main challenges is that every company context is considered to be different. Further research activity should also be put into how the "to-be" scenario for modularization is defined. In the current application of the AME approach, this scenario is developed, adjusted and verified in collaboration with specialists from the case company. An overview of dimensions to be covered in this scenario could also increase the operational use of the approach.

6 CONCLUDING REMARKS

In the paper we show how the AME method has been applied in a large global organization to assess the potential for introducing a modular platform-based strategy across several product families. The results show a significant potential for rationalizing across the existing portfolio, and when looking into the roadmap and identifying windows of opportunity, also for a standardization of new product and manufacturing solutions. The main contribution of this paper is the example of application of the AME approach, which can give input to practitioners and serve as inspiration for executives who want to investigate the potentials of applying a platform-based strategy across a portfolio. The top-down and holistic approach presented in the paper allowed generating results within the case company in a relatively short time frame and at a level of quality able to support strategic decision-making concerning modularization. Results from the case study are believed to indicate the validity of the approach, in spite of a high level of uncertainty associated with the assessment.

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Using Business Critical Design Rules to Frame New Architecture Introduction in Multi-Architecture Portfolios

When introducing new architectures to an industrial portfolio, counting multiple existing product and manufacturing solutions, time-to-market and investments in manufacturing equipment can be significantly reduced if new concepts are aligned with the existing portfolio. This can be done through component sharing, or sharing critical design principles. This alignment is not trivial, as extensive design knowledge is needed to overview a portfolio with many, often highly different products and manufacturing lines. In this paper, we suggest establishing a frame of reference for new-product introduction based on several 'game rules', or Business Critical Design Rules (BCDRs), which denote the most critical features of the product and manufacturing architectures, and should be considered an obligatory reference for design when introducing new architectures. BCDRs are derived from the portfolio, architecture and module levels, including modelling of the most critical links between the product and manufacturing domains. The suggested modelling principle has been tested as a frame for new-architecture introduction, capturing critical modularisation principles in a large and global OEM. Application of the suggested method revealed a potential for reducing time-to-market and potentially cutting 35% off investments in new manufacturing equipment when introducing new products in the portfolio.

Keywords: product platform, portfolio management, cost improvement, new-product development, architecture introduction, design rules

1. Introduction

In a competitive global market dominated by heterogeneous customer demands and short product-life cycles, industrial organisations are seen developing product families based on shared platforms and architectures (Simpson et al. 2014). This potentially can elicit fast and cost-efficient introduction of new products, as development need not start from zero every time a project is launched (Meyer and Lehnerd 1997). Embedding a level of modularity into the architecture of a system is generally accepted as a way to reduce time-to-market and increase flexibility toward variant creation (Mikkola 2006). The approach focuses on minimising dependencies within systems to allow for parallel development facilitated through interface standardisation and reuse of design principles (Baldwin and Clark 1997). Much research effort has been focused on supporting organisations in designing modular product architectures and platforms. This includes design support across the life cycle of the product and across domains, i.e., market, product, manufacturing and supply chain (Fixson 2005; Carrillo and Franza 2006; Kubota, Hsuan and Cauchick-Miguel 2016). However, sharing architectural characteristics, common platforms and modularisation principles across an industrial portfolio demands a level of governance to successfully harvest the benefits, and organisations have failed at such efforts (Sanchez 2013). This is especially difficult with industrial portfolios containing multiple product and manufacturing architectures, as extensive design knowledge is needed to fully understand the implications of introducing new products or product variants (Schuh et al. 2016). Creating an overview of existing architectures across an industrial portfolio, as a reference for concept development can be beneficial by allowing for assessment of concept compliance with existing architectures, strategic decisions related to modularisation, and the use of platforms (Jiao, Simpson and Siddique 2007; Gudlagsson et al. 2016). However, modelling characteristics for multiple architectures have had limited focus, and operational methods that can describe high-level and critical architectural characteristics across product lines, architectures and domains are lacking. In this paper, we propose the mapping of Business Critical Design Rules (BCDRs) to encapsulate these critical characteristics. The proposed framework adds to literature on how to model and operationally describe the most important characteristics of product and manufacturing architecture. This makes it considerably easier to communicate important decisions on modularisation and improve the ability to make decisions at the portfolio level. The case study indicates that identification and modelling of BCDRs lead to improved decision making when designing products and factories, which, in turn, can lead to significant improvements in manufacturing-capacity utilisation, resulting in potential investment reductions of up to 35%.

The following sections describe the basis for the suggested framework. First, the concepts and characteristics of architectures and platforms are introduced, followed by a description of how links are established across domains. Finally, existing methods for describing and modelling multi-architectures are discussed before introducing the suggested principle for modelling BCDRs.

1.1. Product architectures and platforms

A product architecture is a carrier of structural and functional design decisions (Fixson 2005; Gudlaugsson et al. 2014) and is an essential enabler for modularisation and platform application (Simpson et al. 2014). Ulrich (1995) generally defines a product architecture as the arrangement of functional elements, the mapping from functional elements to physical components and the specification of the interfaces among interacting physical components. Sharing product architectures and standardisation of interfaces can be seen as the basis for product-family design, i.e., products with similar structures and a level of commonality between variants (Harlou 2006). While the architecture represents the structural and functional decomposition of a product, a product platform can describe the collection of modules, or parts, from which specific products can be derived and efficiently launched (Meyer and Lehnerd 1997). Robertson and Ulrich (1998) expand this definition to describe a collection of components, processes, knowledge and people and relationships shared by a set of products. Modelling BCDRs is based on the understanding that a product architecture defines the basis for product family design and can be seen as a rule-based scheme capturing the most important design knowledge. The platform can be seen as a collection of critical assets shared across product families or product variants (Ostrosi et al. 2014; Parslov and Mortensen 2015).

1.2. Manufacturing architectures and platforms

Like the product domain, a manufacturing system can be seen as a structural combination of subsystems, together performing a complex function (Mesa et al. 2014; Jepsen 2014; Gudlaugsson et al. 2016). Both systems exhibit characteristics as a result of design choices, and the value-adding processes performed by the manufacturing system can be seen as corresponding to the functions of a product (Claesson 2006). As in the product domain, it is possible to describe and model a manufacturing architecture capable of capturing critical structural and functional design knowledge. Furthermore, it is possible to embed modular characteristics by decoupling dependencies between subsystems (Jiao, Simpson and Siddique 2007; Mesa et al. 2014). Building modularity into the architecture of a manufacturing system generally has been found to enable reduction of setup and lead time, increased system flexibility, cost reductions, easy replacement of defective modules and quality improvements (Rogers and Bottachi 1997; Piran et. al. 2016). In this paper, we build on the understanding that manufacturing architectures and product architectures can be represented in similar ways that capture important design knowledge.

1.3. Linking architectures across domains

Product architectures and related manufacturing architectures can be, more or less, closely linked (Carrillo and Franza 2006). Designing modularity into a product architecture for easy assembly creates an intuitive link between the two domains, and the level of modularity embedded in a product architecture can be seen as affecting the modularity of the manufacturing system, such as in relation to outsourcing decisions, production layout and product-variant creation (ElMaraghy and AlGeddawy 2014). Designing modularity into a manufacturing architecture can affect the product architecture, e.g., through co-design efforts with suppliers or through standardisation of value-adding processes (Kubota, Hsuan and Cauchick-Miguel 2016). Understanding links across the two domains is important for efficient and fast introduction of new products (Carrillo and Franza 2006). ElMaraghy and AlGeddawy (2014) describe how the product, manufacturing and market domains interact and develop over time as a biological co-evolution. In their Associated Product Family Design (APFD) model, they relate requirements and constraints at the architectural level and across market, product and process domains to support the design of modules, platforms and process plans. The APFD can be used to link the product's architectural characteristics to the 'master assembly process plan' for all variants in a product family, as well as to the physical layout of assembly processes. Jiao, Zhang and Pokharel (2007) introduce the Generic Product and Process Structure (GPPS) as a tool for coordinating product and process variety. The GPPS can be seen as a meta-structure and reference, from which several product and process variants can be derived. Material requirements link the process and product domains. Also, Design Structure Matrices (DSMs) and variants of these (Eppinger and Browning 2012) are used to establish relationships between domains and highlight important architectural characteristics (Baldwin and Clark 2000; Browning 2016). DSM terminology has been applied to link product domains to several associated domains, including manufacturing, through what Danilovic and Browning (2007) define as a Domain Mapping matrix (DMM). Modelling critical architectural relationships across the product and manufacturing domain is considered a key element of the proposed framework. The modelling principle applied is based on the understanding that product and manufacturing architectures can be described in similar ways, and links can be established across functional and structural elements in the two domains.

1.4. Describing characteristics of multiple architectures

Leveraging from modular architectures and platforms as a strategy for new-product development demands managing design knowledge on the standardisation of interfaces, platform assets and strategic drivers (Campagnolo and Camuffo 2010; Simpson et al. 2014).

Even with the potential to largely impact portfolio management (Mikkola 2001), capturing this knowledge across a portfolio containing multiple product and manufacturing architectures has received little research attention. Assessments related to the introduction of new architectures into a portfolio focus mainly on optimisation of portfolio profitability (Cooper, Edgett and Kleinschmidt 2001), resources (Danilovic and Browning 2007; Dash, Gajanand and Narendran 2017) or market-strategic drivers and constraints (Ghaemzadeh and Archer 2000). The level of commonality among product variants also can be used as an evaluation metric in deciding product launches (Tucker and Kim 2009). Some contributions seek to expand the perspective of modularisation and platform development, to become a guiding factor in portfolio management by, for example, introducing the concept of Design Bandwidth (DB), which relates to a platform's ability to accommodate existing or future product designs in terms of functionality, performance and variants. DB can be expressed in relation to functional requirements, design solutions and constraints (Berglun and Claesson 2005; Michaelis and Levandowski 2013). High bandwidth means that a platform has a high flexibility to accommodate various new products. Defining DB enables continuous evaluation of new concepts against the platform. Baldwin and Clark (2000) introduce what they call hidden and visible design rules to capture high-level decisions related to a modularisation strategy. The rules are hierarchical design parameters relating to system architecture and are a way of capturing strategic decisions and supporting modular development. The application of Modular Function Deployment's (MFD) module drivers (Östgren 1994; Erixon 1998) is another approach to linking business-strategy aspects to product architecture and to modularisation efforts. Module drivers include 12 perspectives and can allow for embedding strategic considerations related to definition, application and life-cycle aspects of modules in product architectures (Lange and Imsdahl 2014). A Module Indication Matrix (MIM) can be used to link a modularisation strategy, based on the module drivers, to specific components or subsystems of a product architecture. The PKT-Approach (Krause, Eilmus and Jonas 2013), which includes a perspective on the product program, embeds product family development in a corporate strategy. The Product Structuring Model (PSM) divides the product portfolio into five levels: product program, production program, product lines, product families and products. Combined with the Carryover Assignment Plan (CAP), sharing and carryover potentials across the product program and generations of product families can be visualised. Borjesson and Hölttä-Otto (2014) present an algorithm based on integration of a DSM and MFD/MIM, allowing for a strategy for product commonality to be balanced with module independence. The approach is a way to integrate strategic portfolio drivers and capture company component sharing or modularisation strategies in the development of modular product architectures. DSM-based approaches are widely used for mapping system relations and relations across domains. However, a challenge is that when looking across multiple architectures and multiple domains the complexity of the matrices grows to a level where they become difficult to handle, and difficult to use as basis for communicating key architectural characteristics in daily design processes. Generally, several aspects of multi-architecture modelling are supported by existing methods, including sharing of platform assets and the integration of strategic drivers. Support is, however, limited when it comes to capturing characteristics across multiple architectures and operationally communicating these.

1.5. Summary and research opportunities

Several review papers on the topic of modularisation as a strategy created the basis for our understanding of challenges related to operationalization of the concept. Relevant contributions are summarised in Table 1.

Table 1. Overview of review papers

Reviews of related literature	Research focus	Relevant conclusions
Jiao et al. (2007)	Review of product family and platform-based product development. (Based on 246 references)	• Need for holistic and system-wide solutions in relation to product family design. • Need for coherent framwork including front-end issues: Customer integration, market segmentation and economic evaluation, and back-end issues: Manufacturing and supply chain considerations.
Campagnolo and Camuffo (2010)	Review of modularity in management studies. (Based on 125 references.)	• Need for all-around framework bringing light to relatioships between product, production and organisational modularisation • Need for studying cost of developing modular product architectures
Bonvoisin et al. (2016)	Review of modular product design. (Based on 163 references)	• Need to define modularisation metrics to achieve a level of definition that is practical enough for engineers. • Research is needed to embed principles of modularisation in day-to-day design activities.
Piran et al. (2016)	Review of modularisation strategy in production and operations management. (Based on 81 references.)	• Need for studying background for modularity in production • Need for quantifying effects of modularisation
ElMaraghy et al. (2013)	Review of product variety management. (Based on 224 references)	• Need to improve communication among stakeholders in the product life cycle to link commonality assessment to the structure of the product architecture. • Need for integrating "design for variety" with manufacturing system synthesis and design.

Common elements were identified as: (1) a need to improve the understanding of relationships between product architecture and manufacturing architecture, and (2) a need to improve communication of architectural characteristics and relationships, to better support embedding modularisation principles in the development of new products and manufacturing systems. Practical screening of literature from the review papers and a backward reference search led to several papers focusing on definitions and modelling principles of architecture characteristics. These create the theoretical basis for the proposed framework for modelling BCDRs. Table 2 provides an overview of key literature and constructs linked to modelling principles.

Table 2. List of relevant papers describing architecture characteristics

Relevant papers:	Main focus on product architecture characteristics	Main focus on manufacturing architecture characteristics	Perspectives of product family design	Cross-portfolio perspectives applied
Albers et al. (2015)	x		x	
Baldwin & Clark (1997)	x		x	
Baldwin & Clark (2000)	x	x	x	
Berglund & Claesson (2005)	x		x	x
Borjesson & Hölttä-Otto (2014)	x		x	x
Bruun et al. (2014)	x		x	
Claesson (2006)	x	x	x	x
Danilovic & Browning (2007)	x		x	
ElMaraghy & AlGeddawy (2014)	x	x	x	
Eppinger & Browning (2012)	x		x	
Erixon (1998)	x		x	
Fixson (2005)	x	x	x	x
Gudlaugsson et al. (2014)	x		x	
Gudlaugsson et al. (2016)	x	x	x	
Harlou (2006)	x		x	
Hsuan & Hansen (2007)	x			x
Jepsen (2014)		x	x	
Jiao et al (2007)	x	x	x	
Koren et al. (1999)		x	x	
Krause et al. (2013)	x		x	x
Kubta et al. (2017)	x	x	x	
Lange & Imsdahl (2014)	x		x	
Liang & Huang (2002)	x		x	
Markworth et al. (2017)	x		x	
Mesa et al. (2015)	x	x	x	
Mesa et al. (2014)	x	x	x	
Meyer & Lehnerd (1997)	x		x	x
Michaelis & Levandowski (2013)	x	x	x	x
Mikkola (2006)	x		x	
Mortensen & Løkkegaard (2017)	x		x	x
Östgren (1994)	x	x	x	
Parslov & Mortensen (2015)	x		x	
Robertson & Ulrich (1998)	x		x	
Rogers & Bottachi (1997)		x	x	
Sanchez (2013)	x	x	x	
Shuch et al. (2016)	x		x	x
Ulrich & Eppinger (1995)	x		x	

Existing methods, tools and definitions mainly focus on product family design and provide limited support for mapping multiple architectures and explicit relations across domains, which can allow engineers and project managers to understand critical design decisions made across architectures in a large multi-architecture portfolio. In this paper, we want to improve the understanding that these most important characteristics can be encapsulated across an industrial portfolio using the defined BCDRs, establishing a frame for new architecture introduction.

2. Modelling Business-Critical Design Rules

This section describes the modelling principle for BCDRs and uses a manufacturer of white goods as an example. Industrial multi-architecture portfolios generally can be divided into several subcategories, e.g., part features, parts/components, part families, product modules/sub-assemblies, products, product families, product platforms and product portfolios (ElMaraghy et al. 2013) or, as defined by Krause, Eilmus and Jonas (2013): product programs, production programs, product lines, product families and products. When modelling BCDRs, we suggest applying a top-down focus across the portfolio and to put equal focus on the product and manufacturing domains. Thus, we suggest establishing BCDRs at the portfolio, architecture and module levels (Figure 1).

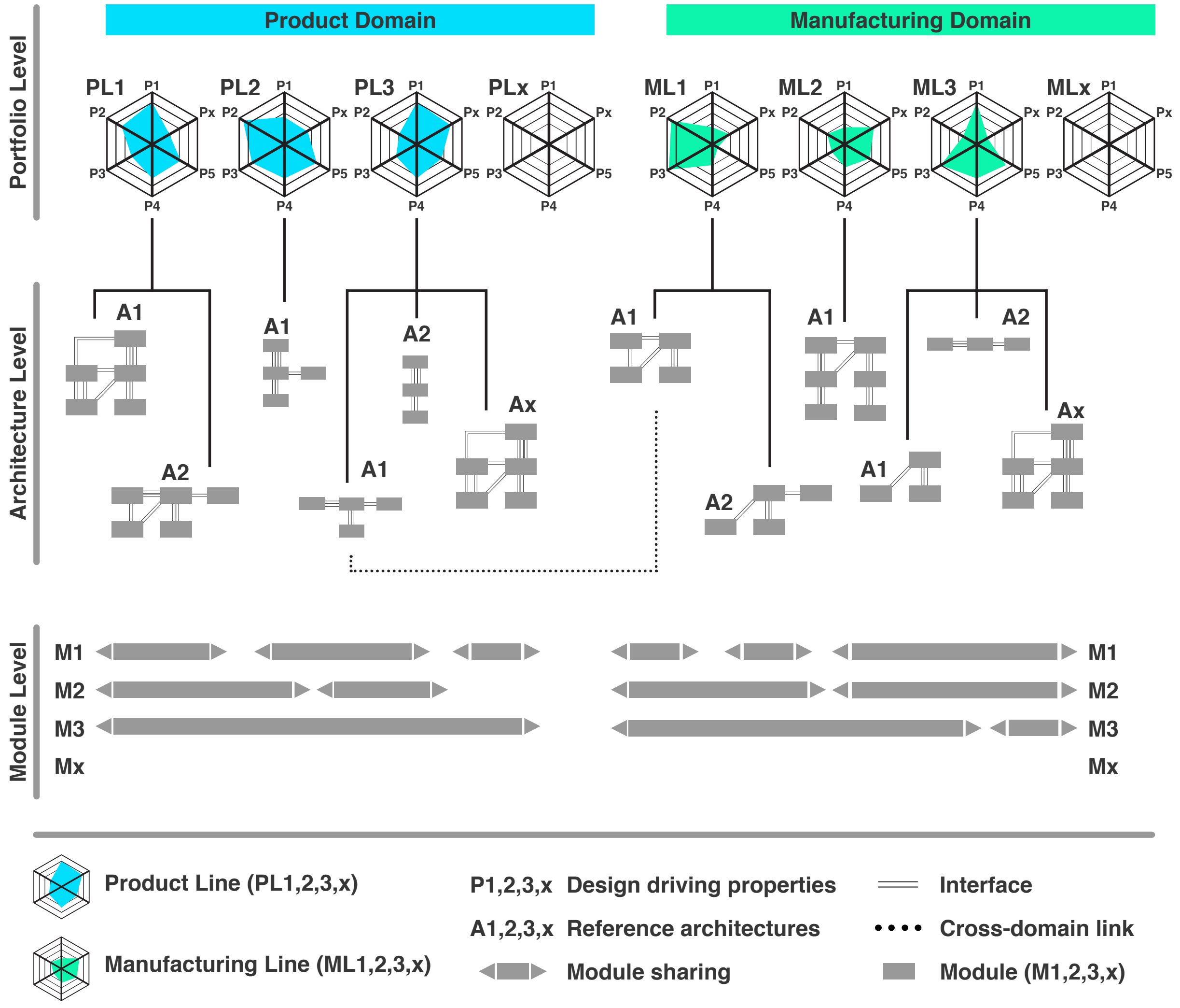


Figure 1. Visualisation of the Portfolio, Architecture and Module Level

2.1. Portfolio level

At the portfolio level, we define several product lines (PL1,PL2,…,PLx) and manufacturing lines (ML1, ML2,…,MLx), which are groups of systems with similar characteristics (Krause, Eilmus and Jonas 2013; Mesa et al. 2015). Using a white-goods manufacturer as an example, different product lines could include washing machines, dishwashers and refrigerators. In the manufacturing domain, examples could be dedicated manufacturing systems (DMS), flexible manufacturing systems (FMS) or reconfigurable manufacturing systems (RMS) (Koren et al. 1999). Building on the concept of design bandwidth, several key properties (P1,P2,…,Px) are defined, spanning the solution space for a line of products or manufacturing systems (Berglun and Claesson 2005; Schuh et al. 2016). The properties can be market-driven, as well as technically and strategically driven, and we argue that identifying these is a somewhat pragmatic exercise. The assumption is that a relatively limited number of decisions dictate most critical design decisions for a line of product or manufacturing systems. These are illustrated using radar plots (Figure 1), indicating the capabilities and limitations of existing product and manufacturing solutions in the portfolio.

2.2. Architecture level

At the architecture level, reference architectures are defined (A1, A2,…,Ax), describing key structural and functional principles for product families within a product line. Several reference architectures can exist within the same line of product or manufacturing systems. Within a line of washing machines, this could be reference architectures for the American or European markets. In the manufacturing domain, it could be reference architecture for automated or manual systems. At the architecture level, BCDRs refer to critical interface decisions in and across reference architectures. The term *reference architecture* describes a somewhat incomplete schematic of the system architecture, only capturing the key elements of the design and highlights in which BCDRs are defined. This resembles the GPPS (Jiao, Zhang and Pokharel 2007) and the Interface Diagram presented by Bruun, Mortensen and Harlou (2014), and it builds on what Parslov and Mortensen (2015) define as A-interfaces, which are considered interfaces with strategic importance, in which a management decision is needed to make design changes. When modelling BCDRs, it is assumed that a limited number of links across domains is critical for new architecture introduction. Building on existing literature, links are considered strategic or constraint-driven. An example could be the outer dimensions of a washing-machine chassis. If the dimensions of a new architecture exceed what is defined in the reference architecture, process equipment cannot handle the component, leading to increased investment, development time and introduction of risk. Defining reference architectures, and the links across these, illustrate where design freedom exists and where top-down and strategic decisions related to interface standardisation and sharing of design principles limit this freedom.

2.3. Module level

At the module level, key modules (M1, M2,..,Mx) are described, and sharing across the portfolio and product and manufacturing lines is visualised. Modules subject to BCDRs are considered off-line modules, which are physical, predefined building blocks shared across reference architectures. Applying off-line modules is in line with what Liang and Huang (2002) define as 'design with modules', in which products are configured out of existing modules or with a design based on a 'construction kit', a collection of predefined elements that define the reference for design (Albers et al. 2015). We argue that it can be essential for efficient new-architecture introduction to define the most critical modules decoupled from other development activities, with the ability to apply these as off-the-shelf solutions. For example, if an organisation allots 24 months from conceptual design to launch for a new product, and process equipment has a lead-time of 18 months, it simply would not be feasible to launch the product in time. Critical modules must be decoupled and developed separately to allow for fast product introduction.

2.4. Visualising BCDRs at portfolio, architecture and module levels: Example

Figure 2 presents an overview of how BCDRs are modelled at the portfolio, architecture and module levels to establish a frame for new-architecture introduction. A company designing and manufacturing washing machines is used as an example. Generally, the product and manufacturing domains are related using a matrix, in which A, B, C, D and x represent segments in which reference architectures exist for both product and manufacturing, and new designs must comply with BCDRs. If a new architecture concept is outside the defined segments in the matrix, it means 'untested' ground and that no direct effects from existing platform efforts should be expected. A segment in the matrix contains a description of the BCDRs at the portfolio, architecture and module levels.

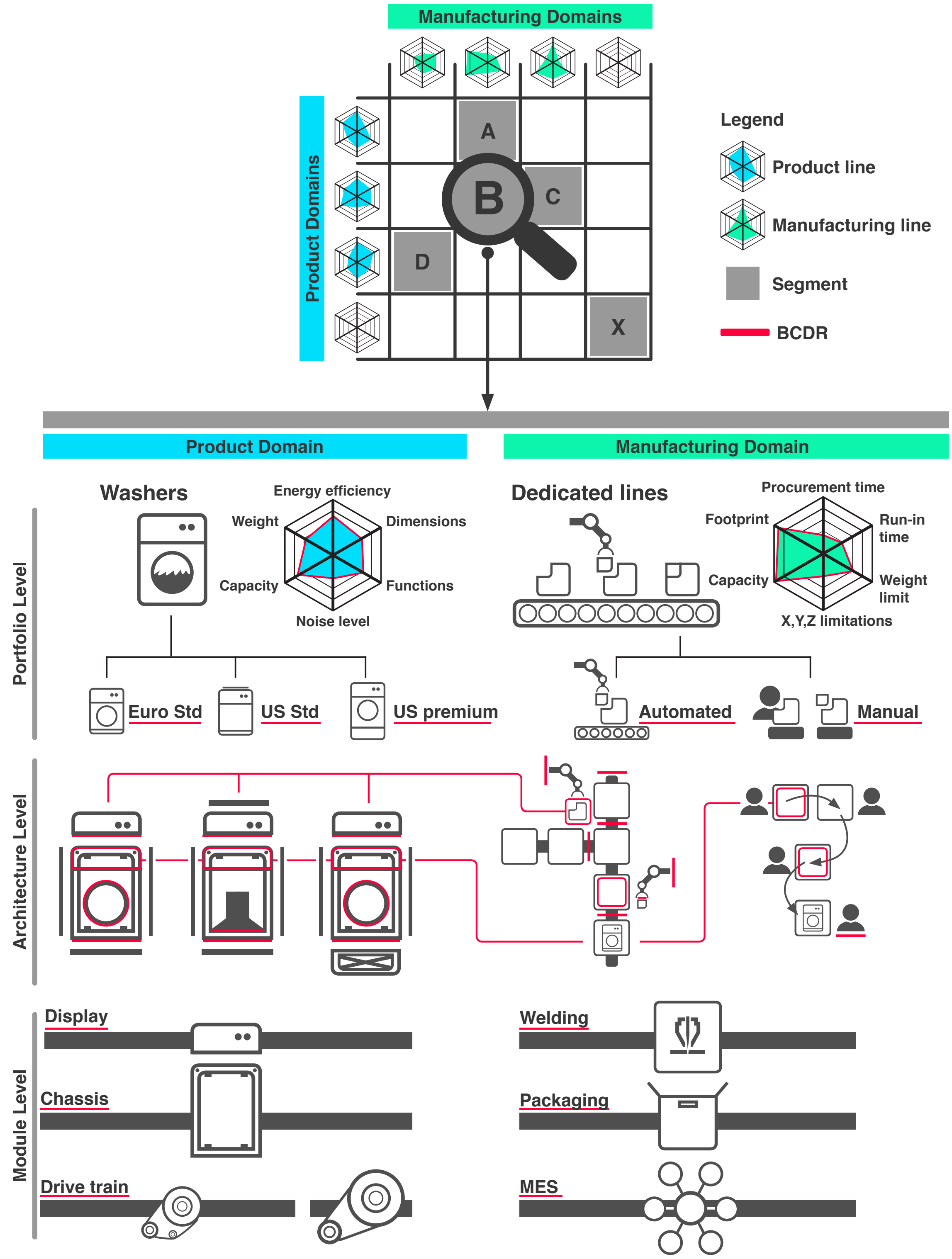


Figure 2. Visualisation of Business-Critical Design Rules

In the example, three reference architectures for product design are defined at the portfolio level: the standard European model, the standard U.S. model and the premium U.S. model. On the manufacturing side, two reference architectures exist: an automated manufacturing system, designed for countries with high labour costs, and a manual and distributed system for assembly in low-cost countries. The main design-driving properties are identified for each domain at the portfolio level (energy efficiency, noise level, capacity, run-in time, etc.). This is illustrated using radar plots. BCDRs denote number of variants and specifications on key design-driving parameters, e.g., a maximum wash capacity and maximum x,y,z limitations of the manufacturing system. At the architecture level, structural and functional decomposition of the systems is described, along with critical interfaces and links across the product and manufacturing domains. For example, standardisation of the interface between the chassis and the display is subject to a BCDR, as this is critical for application of a standard display module and defines a link to the manufacturing domain, enabling late product customisation. Finally, on the module level, three modules on the product and manufacturing sides are defined and considered off-the-shelf building blocks. Considering risk, investments and time-to-market, these modules must be applied when introducing new architectures within the specific segment, e.g., the display, the chassis and the drive train. In the manufacturing domain, the examples cited are the welding cell, packaging cell and manufacturing execution system (MES).

3. Research approach

The suggested modelling principle builds on elements from existing theory within the field of architecture and platform modelling, and has been tested and evaluated in a case study. The study was mainly a prescriptive study (Blessing and Chakrabarti 2009) in which, as researchers, we introduced the suggested modelling principle as support for a modularisation effort at the case company. The primary data-collection methods used were observations, interviews, workshops and internal company documentation, i.e., CAD drawings, bills of material, factory plans, and market data. Visualisation, mainly in the form of visual posters, was used as a communication approach between team members, researchers and managers in which representations of the portfolio could be displayed and used as boundary objects across professional disciplines (Carlile 2002). The generation of BCDRs was a combination of data-driven efforts and input from domain experts. Cost drivers and drivers for time-to-market were identified by going through company data (bills of material, project data, drawings, etc.). Findings were analysed in collaboration with domain experts in a workshop format, including experts from the business, product and manufacturing domains. Outlining a holistic modularisation strategy and establishing BCDR were initiated in August 2015, running over a period of 12 months. During this period, the research team spent more than 100 days on site, engaging with a team of 20 specialists, engineers and managers. The first six months focused on identifying the potential and scope for modularisation at the portfolio level, and the final six months were focused on identifying and formulating BCDRs.

In the product domain, while considering impacts across the portfolio, reference architectures for future products were synthesised, i.e., it was decided which sub-systems should be decoupled to support a strategy of reducing time-to-market. Manufacturing reference architectures were synthesised in a similar way and mapped. However, in the manufacturing domain, optimisation potentials across factories were the main driver for establishing future reference architectures. The strategy was to decouple system dependencies to optimise capacity utilisation through increased flexibility and reuse of equipment. This should reduce investments and development time. The company roadmap played a significant role in the process of identifying BCDRs. The study ended with a consolidated list of critical features to be considered as an obligatory reference for new-architecture introduction.

4. Establishing BCDRs for development of electrical control units

The case company was a large and global OEM designing, manufacturing and delivering approximately 4.5 million electrical control units per year, with an annual turnover of approximately USD 3.5 billion. Throughout the latest product cycles, the company focused extensively on product family design and increasing commonality between variants. However, modularisation efforts had varying effects, as short-term goals often were prioritised at the expense of compliance with overall modularisation strategies. Furthermore, efforts were focused on single product families, with a very limited focus on manufacturing considerations. Product updates, new-product introductions and a focus on time-to-market reduction were the drivers for a new and portfolio-wide perspective on modularisation in the organisation. Historically, major development projects, on average, have a 46-month lead-time from concept phase to product launch, and the new target set by top management was 24 months. This put enormous pressure on the development departments to ensure efficient introduction of new architectures. One way to achieve this was believed to be a strengthening of platform and modularisation efforts. The following sections describe how BCDRs were defined at the portfolio (Figure 3), architecture (Figure 4) and module levels (Figure 5).

4.1. Portfolio level

We have chosen to focus on BCDRs, defined in the core segment of the case company's portfolio, which includes "low-power" electronic control units for heating applications. The products were manufactured for a variety of manufacturing systems, ranging from manual to fully automatic. Approximately 80% of the annual production volume was generated in this segment. Key properties driving product-design decisions were identified combining a baseline analysis of existing product and manufacturing lines with input from domain experts on current and dominating trends. The properties were identified as: (1) power level; (2) need for inputs and outputs, i.e., types and numbers; (3) level of accessibility needed, e.g., the possibility of servicing the product; (4) need for human-machine interfaces (HMI), e.g., LCD display, LEDs, navigation, buttons, etc.; and (5) ambient temperature requirements, defined by operating conditions. In the manufacturing domain design drivers were identified as: (1) test concept, mainly defined by the product power level and test principles; (2) process equipment x,y,z limitations; (3) equipment-weight limitations related to inter-process transportation; (4) automation levels; and (5) annual capacity. A total of six product lines and three manufacturing lines were defined at the portfolio level; they were related through a matrix structure with six segments (A,B,C,D,E and F), in which BCDRs were defined as references for new-architecture introduction (Figure 3).

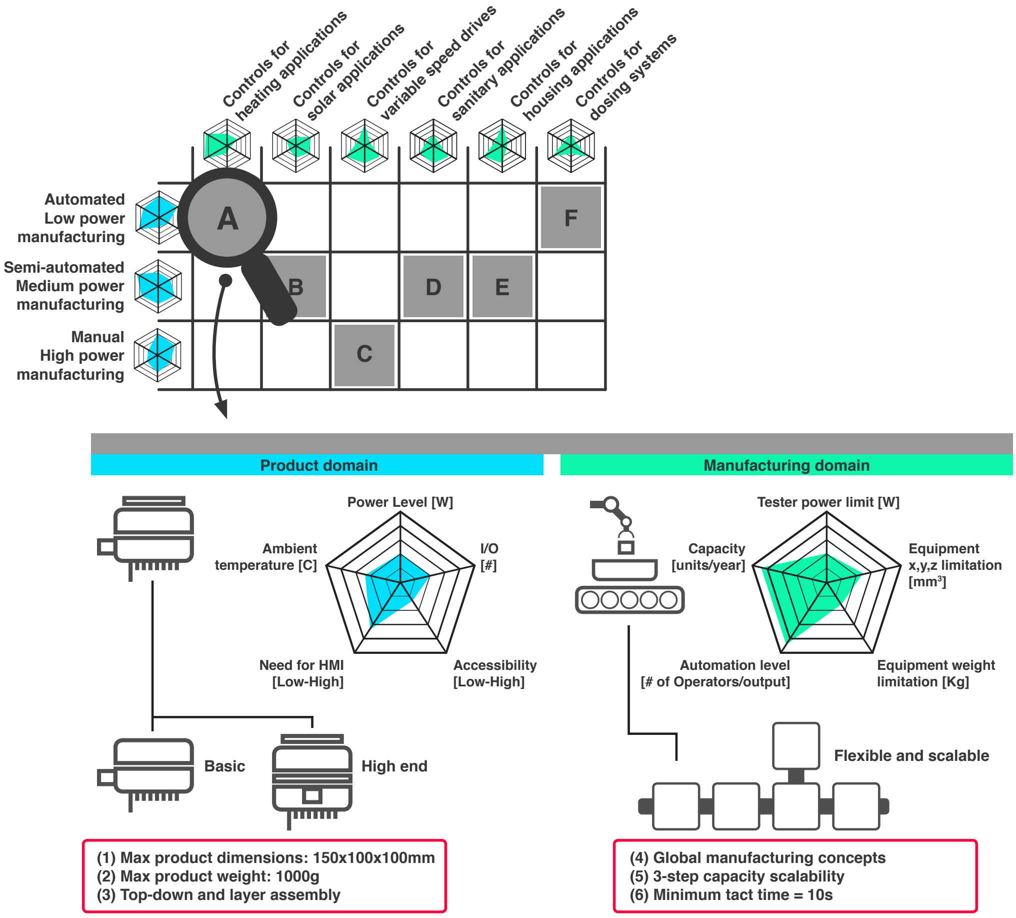


Figure 3. Portfolio level BCDRs in Segment A

In Segment A, constituting the core segment, six critical design rules were defined at the portfolio level (Figure 3): (1) top-down and layer-by-layer assembly of the product, implicating that no side assemblies et al. would be allowed; (2) Manufacturing capacity scalability in three steps. Process equipment should be the same in each step, while the level of automation and the need for automated inter-process transportation and automatic feeding increased; (3) no tact times below 10 seconds; anything below that required radical changes to the reference architecture; (4) clearly defined maximum dimensions and weight limits, allowing for a level of standardisation to be built into grippers, fixtures and pallets (size and support points); (5) single-test concept, as the tester was identified as the main driver for cost and time-to-market aspects; (6) global manufacturing solutions, indicating that no matter where in the world a new manufacturing system was to be built, it would be based on the same reference architecture.

4.2. Architecture level

At the architecture level, reference architectures describing the structural and functional references for designs were defined. In Segment A, this included two product-reference architectures and one manufacturing-reference architecture. At this level, eight BCDRs relating to critical interfaces and links across domains were mapped (figure 4).

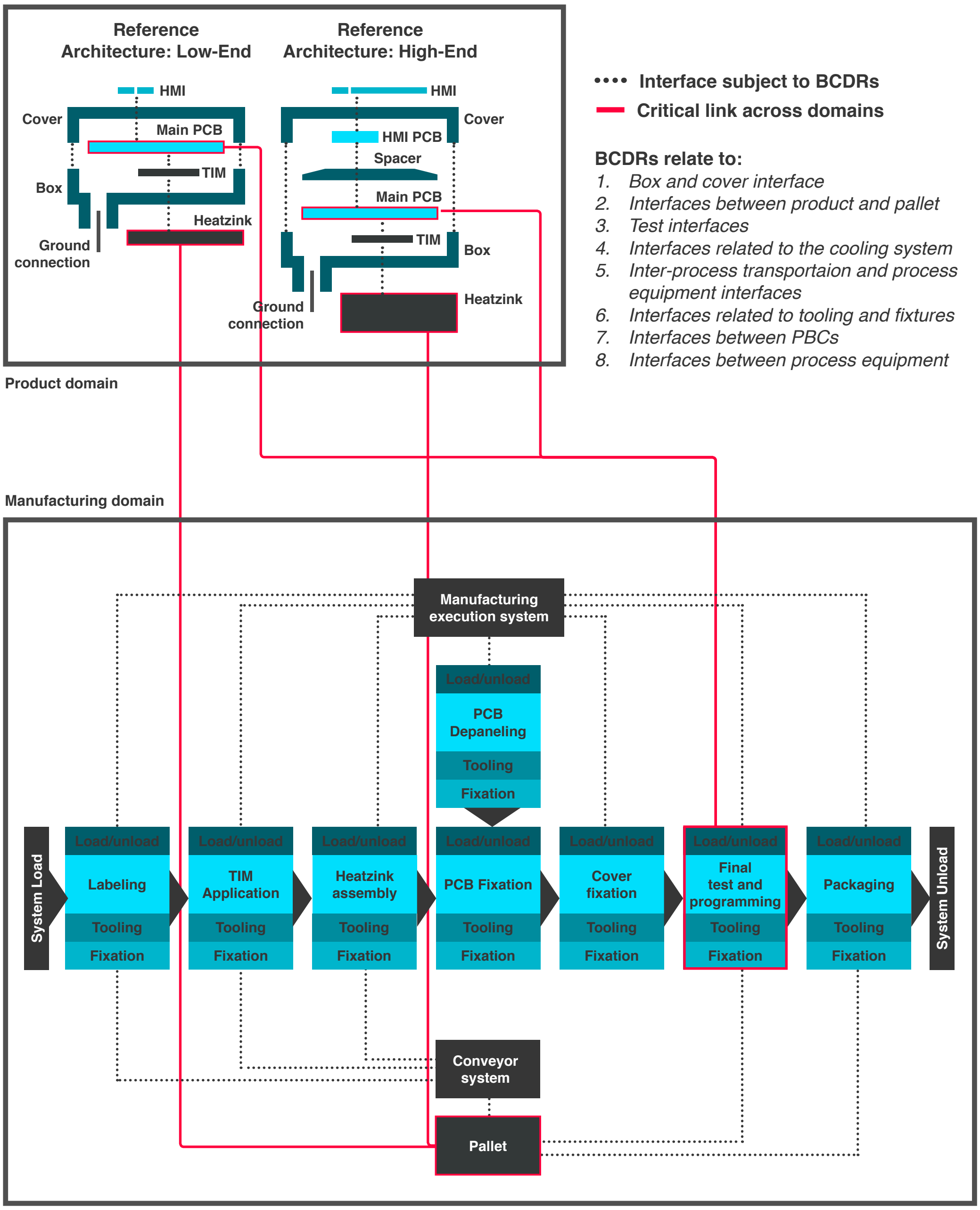


Figure 4. Critical interfaces in and across the product and manufacturing architectures

BCDRs defined at architecture level: (1) The interface between cover and box of the control unit; (2) interfaces from the pallet to the conveyor system and from pallet to the product, e.g., support points and orientation, defining a critical cross-domain link; (3) interfaces and cross-domain links related to the test concept; (4) the thermal interface material in terms of application in the product and manufacturing process; (5) interfaces between the conveyor system, process equipment and system load/unload; (6) interfaces related to tool and fixture changing in the process equipment; (7) interfaces between PCBs; and (8) interface with MES system. Each interface subject to a BCDR was specified and documented to allow compliance evaluation when introducing new architectures.

4.3. Module Level

At this level, a module should be seen as something that can be taken down from the 'shelf' and directly applied in a development project. Critical modules were identified as: (1) test module; (2) cooling module; (3) HMI module; and (4) pallet module (figure 5).

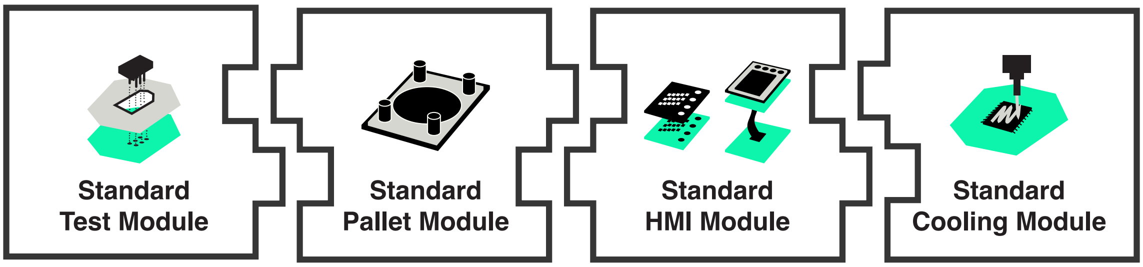
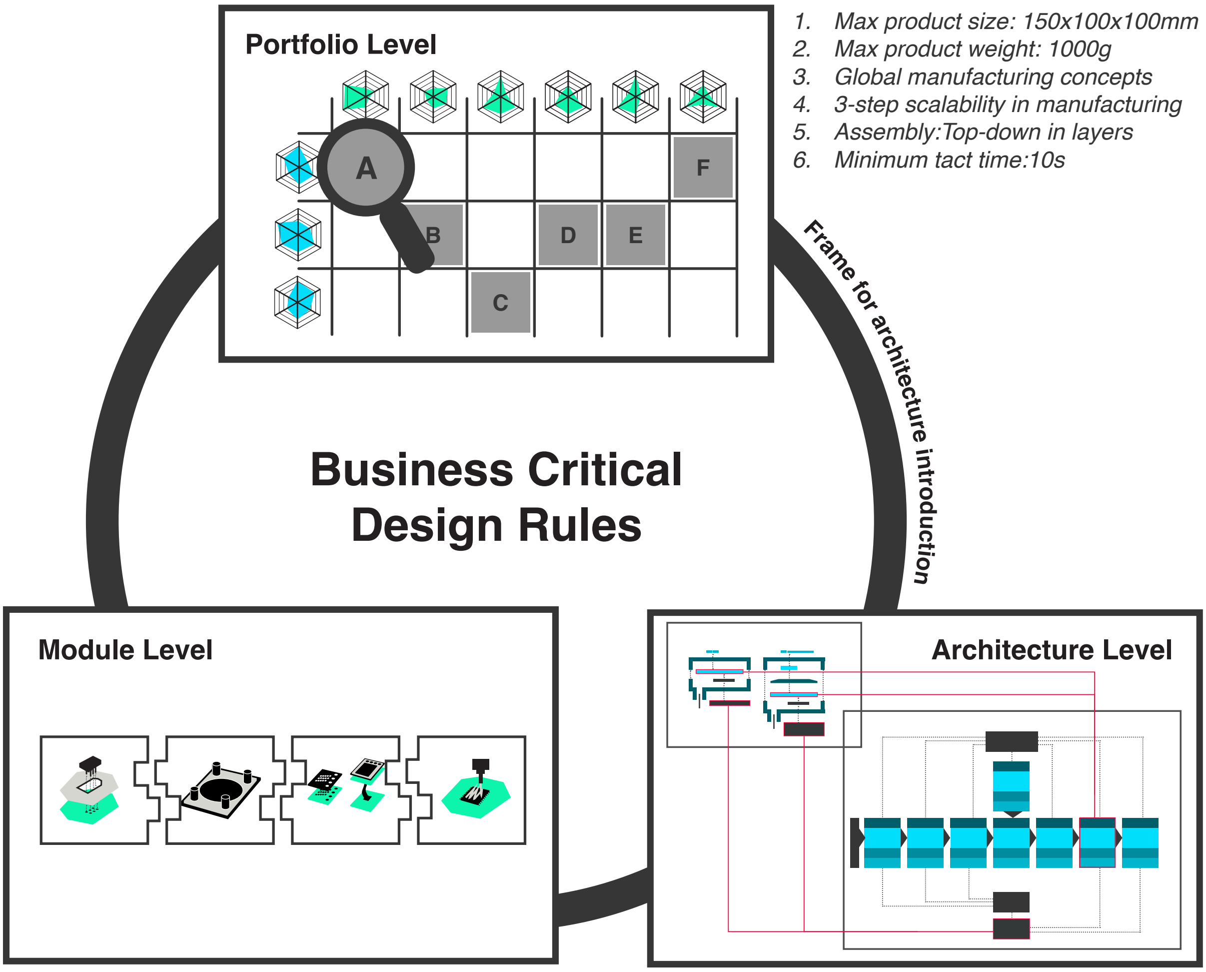


Figure 5. Modules subject to BCDRs

Some modules are relevant for either the product or manufacturing domain; however, some cross over. For example, the test module was defined as a building block in the manufacturing system, but also as a critical driver for the product solution, i.e., by dictating the test interface, distance from entry point to test array and the maximum power level of the product.

4.4. Establishing frame for introduction of new-product and manufacturing architectures

Having defined BCDRs at the portfolio, architecture and module levels helped establish a frame for new-architecture introduction in the organisation, capturing the strategy for sharing platform assets and key design principles. Input from the company roadmap was scrutinised, and implementation was planned based on identified windows of opportunity, i.e., projects were selected to be carriers for development of off-line modules and subject to BCDRs. Figure 6 summarises how the frame for design was established in the core segment of the company's portfolio.



1. *Max product size: 150x100x100mm*
2. *Max product weight: 1000g*
3. *Global manufacturing concepts*
4. *3-step scalability in manufacturing*
5. *Assembly:Top-down in layers*
6. *Minimum tact time:10s*

1. *Standard test module*
2. *Standard cooling module*
3. *Standard HMI module*
4. *Standard pallet module*

1. *Box and cover interface*
2. *Pallet interfaces*
3. *Tester interfaces*
4. *Interfaces related to cooling system*
5. *Conveyor interfaces to process equipment*
6. *Tool change interface*
7. *Interfaces of fixtures*
8. *Interfaces between PCBs*

Figure 6. Overview of BCDRs identified in the case study

BCDRs were defined as guidelines for how new products and manufacturing systems should be designed to ensure alignment with the overall strategy for time-to-market reductions. The production manager and key stakeholders said defining and agreeing on the basic rules for design would allow for an average of two months to be cut from the concept phase for all new product introductions. Encapsulating structural and functional design rules, critical for the execution of modularisation as a strategy, helped create this frame, enabling designers to become familiar with the playing field, thereby improving capabilities for introducing new innovations. Furthermore, the approach revealed a potential for reducing investments in new manufacturing equipment. Traditionally, dedicated lines were built when introducing a new product architecture. However, knowing the capabilities of the existing manufacturing lines, support was created for new architectures to be a run-in on existing equipment, potentially reducing investments in manufacturing. Integrating newly planned manufacturing lines, existing lines and roadmap considerations highlighted a potential for a 35% reduction in investment through optimisation of equipment utilisation.

5. Discussion

Designing product and manufacturing systems with an embedded level of modularisation can be challenging, and governance is needed to realise the benefits of interface standardisation and application of standard platform assets. Effects are realised over time, thus, stability related to critical design decisions is important. Modelling BCDRs provides a way to communicate important design knowledge and a way to guide designs from a top-down perspective, with an emphasis on a company’s strategic aims for modularisation.

As indicated in the review of literature, description and development of modular architectures and platforms are relatively well-supported. However, when introducing new architectures in a multi-architecture portfolio, support is limited for communicating strategic-design decisions on modularisation, platforms, and relations between product and manufacturing architectures. The strength of modelling BCDRs is, on a managerial level, the ability to clearly communicate strategic directions on modularisation to project teams and engineers. This provides a frame for development by clearly illustrating existing solutions, their capabilities and obligatory design rules to follow when introducing new-product or manufacturing architectures in the portfolio.

Based on the analysis of related literature (Table 2), Table 3 provides an overview of the identified methods and tools supporting a level of cross-portfolio thinking in relation to modularisations. The table illustrates how the suggested framework for mapping BCDRs contributes to this knowledge base.

Table 3. Relevant papers applying a cross-portfolio perspective to modularisation

Support for:	Module sharing across product architecutes	Describing product architecture characteristics	Module sharing across manufacturing architecture	Describing manufacturing architecture characteristics	Describing critical links across product and manufacturing architectures	Using existing design knowledge as reference for product introductions	Portfolio level considerations on number of architectures/ platforms
Cleasson (2006) - CC	x	x	x	x	x		
Meyer & Lehnerd (1997) - PPP	x	x	x	(x)			(x)
Karuse et al. (2013) - PKT	x	x	(x)	(x)	(x)		x
Michaelis & Levandowski (2013) - SBCE/CC	x	(x)	x	(x)	x	x	
Mortensen & Løkkegaard (2017) - ADP	(x)	(x)			(x)		(x)
Borjesson & Hölltä-Otto (2014) DSM/MFD	(x)	x	(x)				
Fixson (2005) - PAF		x		(x)	(x)	x	
Berglund & Cleasson (2005) - DB/CC	(x)	(x)				x	
Baldwin & Clark (2000) - DR	x	x				(x)	
Lange & Imsdahl (2014) - MFD	x	x		(x)			
Husan & Hansen (2007) - PPM	(x)	x					(x)
Shuch et al. (2016) - MSCA	(x)						(x)
Modelling BCDRs	(x)	(x)	(x)	(x)	x	x	x

x - Modelling principle, method, defintion
(x) - Addressed
▨ Main contribution

CC - Configurable component framework
PPP - Power of product platforms
PKT - PKT Approach
SBCE - Set-based concurrent engineering
ADP - Architecture Design Principles
DSM - Design Structure Matrix

MFD - Module Function Deployment
PAF - Product Architecture Framework
DB - Design bandwidth
DR - Design Rules
PPM - Platform Portfolio Matrix
MSCA - Multidimensional scaling and cluster analysis

The suggested framework stands out as it supports capturing critical links across product and manufacturing architectures, supports using this design knowledge to frame new architecture introduction in multi-architecture portfolios and, from a top-down perspective, allows industrial organisations to consider the number of existing architectures and platforms across a large portfolio. Mapping BCDRs allows, in an operational way, to communicate this important design knowledge. The benefit is that design decisions related to modularisation efforts and application of platform assets can be effectively governed across an ever-evolving multi-architecture portfolio, to increase the chances for harvesting related effects of standardisation.

In the manufacturing domain, defining BCDRs generally can affect several aspects of performance, e.g., investments, utilisation, scaling, delivery performance, quality, etc. This is considered highly dependent on the specific company context. As seen in the case study, establishing a frame for new-architecture introduction, based on several defined BCDRs, has the potential to optimise manufacturing-capacity utilisation by improving the ability to run-in new architectures on existing equipment. This was the result of improved communication of manufacturing capabilities across the portfolio and deciding on several critical design principles.

Managing relationships across product and manufacturing architectures generally is recognised as important for efficient new-product launches and time-to-market aspects (Carrillo and Franza 2006; ElMaraghy and AlGeddawy 2014; Gudlaugsson et al. 2016). At the portfolio level, segmentation based on the matrix (Figure 2) provides an overview of existing product and manufacturing lines, their main design-driving characteristics and how the domain relates. This allows designers to assess which product or manufacturing line a new concept is compliant with and which BCDRs to follow. At the architecture level, links across domains are related to critical interfaces. As demonstrated in the case study, the test interface was an important driver for investments and time-to-market, and thereby elevated to a BCDR. Practically speaking, this meant that new designs all should allow top-down testing through a standardised opening in the product, have a maximum distance to the PCB of 8mm and have standardised test software preloaded on the PCB prior to testing. Changing any of these parameters would require significant investments in manufacturing and influence time-to-market negatively. These factors make the test interface an excellent example of what, at the architecture level, should be defined as a BCDR.

Validation of the suggested modelling principle for BCDRs has been limited to a single case study. The case company was a large industrial OEM with a portfolio counting multiple product families and related manufacturing solutions. The desire to reduce time-to-market was the main driver for modelling BCDRs in the case company. However, at the current state, it is not possible to quantify a direct effect. We can support the evaluation through qualitative statements from the case company, in which an agreement was established on the validity of the approach. Top management's increasing involvement throughout the process was seen as an indicator of the approach, providing new value related to executing modularisation as a strategy in the organisation. Toward the end, the head of development elevated the defined BCDRs as a reference for all new development projects in the organisation. Future research activities will be focused on applying the concept in different contexts to further validate and generalise the modelling principle. This includes application in smaller organisations. Furthermore, with the possibility to assess effects over time, future research efforts will be focused on quantifying the direct effects of modelling BCDRs.

Top management commitment has been stated as a critical factor for succeeding in modularization efforts (Sanchez, 2013). We believe that modelling BCDRs provides an important contribution in relation to existing challenges. In a relatively simple and pragmatic way, it forces organisations to formulate their strategies by directly linking them to critical design decisions across the portfolio. An area for future research opportunities includes developing quantitative performance indicators to support the use of BCDRs as a guiding factor for new-architecture introduction. Meaning that, for example, in a stage-gate process, compliance with BCDRs could potentially be evaluated as a prerequisite for gate passages. However, a framework is needed for this type of evaluation. Finally, the suggested modelling principle has been limited to a product and manufacturing focus. It could be interesting to expand the scope and include an explicit focus on supply chain considerations (Sawik, 2017) and market domains when modelling BCDRs.

6. Conclusions

The main contribution of this work is the introduction of a modelling principle for BCDRs at the portfolio, architecture and module levels. It has been possible to establish BCDRs for a large industrial OEM to support a corporate modularisation strategy focused on time-to-market reductions. Modelling BCDRs has provided a frame for new-product introduction and has served as a starting point for defining a modularisation strategy at the portfolio level.

We conclude that it is beneficial to govern new architecture introduction based on several design rules related to product and manufacturing design. Focusing only on a limited number of critical decisions allows the task to be manageable and communicated within a large organisation. Key stakeholders at the case company commented that agreeing on key elements in and across domains (e.g., pallet size, IT system interfaces and line-reference architectures) could cut, on average, two months of development time at the concept phase. Adding the effect of parallel development possibilities and application of standardised off-line modules, the approach is believed to be able to support organisations in improving time-to-market for new-product introductions.

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GOOD PRODUCT LINE ARCHITECTURE DESIGN PRINCIPLES

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Abstract

Based on existing research concerning product architectures Du et al. (2001), Ericsson and Erixon (1999), Levandowski et al.(2014), Bruun et al. (2015) and studies of more than 200 product architecture projects across a variety of industries, this paper defines ten central principles for design of product line architectures. The first and most important principle is to identify the right number of product architectures to cover a particular market. Having too few or too many architectures can be extremely damaging to profitability and time to market for new products. Despite the importance of having the right set of product architectures, important architecture decisions are often made in individual projects. This is a risky approach, since the total market coverage is not considered, implying that product architectures may overlap or there are areas between product architectures which are not covered. Furthermore, the full benefits of synergies in terms of e.g. increased module/part production volume, increased purchase volume and reduced CAPEX (CAPital EXpenditures) are not harvested.

Keywords: Platform strategies, Product architecture, Product families

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1 INTRODUCTION

The role of product architectures (describing how product lines are built up in terms of key modules, key performance steps and interfaces) has during the last ten years received increased attention by academia and the industry, Gonzalez-Zugasti et al. (2000), Hansen (2015), Harlou (1996). It is evident that if architectures are designed right, significant benefits in terms of shorter time to market, cost reductions and improved quality can be achieved, Hultink et al (1997), Jia and Tseng (1999), Krause et al (2013) and Meyer & Lehnerd (1997). Ultimately a certain profit is the goal, but the balance between e.g. cost and time to market is very company specific and product line specific. In the low end, product line architecture is often cost driven and in the high end time to market may be the driving factor.

Based on studies of more than 200 company projects the picture is that many companies have product architectures that have evolved slightly uncontrolled for many years with very little top management attention. The consequences are often that companies have more product architectures than what can be justified from a market point of view. Implications are too high cost and too much complexity in almost every part of the company. Other companies have too few product architectures, which often imply that products are "average", i.e. having too high cost in the low-end segments and not being able to perform in the high-end segments.

In more than 50% of the companies studied, turnover was growing, but the costs were increasing faster than turnover. Among the reasons are: increased number of components, increased stock levels, increased number of new products in the portfolio, etc. In the long run, such a situation is not financially sustainable. One way to address this issue is to introduce new ways of developing products. This paper argues that careful consideration of design principles for product line architectures is of critical importance.

The discussions above can be illustrated by an example from one of the cases studied. A manufacturer of water boiling equipment is producing more than 5.000.000 units per year. In this company, two large development projects were initiated. One project focused on creating a product line for "small" boilers and the other project on creating a product line to cover "large" boilers. Two projects had the task to develop approximately 100 new products (commercial variants) and five new automatic or semi-automatic assembly lines. The results were two individual product architectures and two individual manufacturing architectures. These two product architectures technically covered the market from small to large products, but were problematic from a cost point of view, since costs in the mid-area between small and large boilers were too high. The main reason was that the mid-area boilers were built on a 'scale down' from large boilers. The right principle would have been a scale up from approach from the small products. As the example illustrates, it is important to bring product architecture decisions outside individual projects, since it is not possible to make the right trade off decisions within individual product development projects.

To address such issues, this paper describes ten important design principles to support the design of product line architectures and illustrates these with examples.

Our product development research group at the Technical University of Denmark has during the last seven years been a part of industrial projects in terms of Bachelor, Master, PhD and consultancy projects. The product types that have been studied include power plants (19 studies), white goods (18 studies), consumer electronics (15 studies), toys (17 studies), pumps (12 studies), sensors (13 studies), wind turbines (7 studies), special machinery (30 studies), cell phones (3 studies), control systems (11 studies), boilers (3 studies), filters (4 studies), measurement equipment (11), building equipment (20), and construction equipment (28 studies). 48% of the companies have below 250 employees and the rest ranging from 300 to 80.000 employees. Several of these studies have been published in journals, conferences and in books, Hansen (2015), Harlou (2006), Hansen et al. (2012), Hvam and Mortensen (2007). The data collected in the studies were analysed to derive more general conclusions related to product line architecture design principles. The study of the mentioned case studies of a company's software aspects were not included. This delimitation was introduced to have a clear focus of the research.

2 RELATED WORK

The review of the state-of-the-art literature includes five different groups of literature providing insights into product architectures for product lines Hansen (2015). The five groups identified are: function-based methods, matrix-based models, concurrent engineering, design for manufacturing (DFM), and mathematical models.

Function-based methods: Methods describing the development of modular product architectures often start with the conscious mapping of functional structures into physical modules, Levandowski et al (2014). Functions can be represented in function-based models, e.g. functions-means trees Andreasen (1980), or by schematics of the product including physical elements to a meaningful extent Ulrich (1995).The understanding of product functions can be used in different ways to identify possible modules. To improve the identification of modules and make sure that the modular architecture will serve its objectives Ericsson and Erixon (1990) define a set of module drivers. The module drivers can support the reasoning behind the module identification by elaborating the justification of the modules' existence, e.g. 'planned product changes' module, 'process' module, 'different specification' module, 'technology evolution' module etc. The module drivers are a part of a comprehensive framework called modular function deployment (MFD), which is an analogue to the quality function deployment (QFD) method that provides support for the linking of relationship between the module drivers and technical solutions.

Matrix-based models: Another approach to identify modules is the application of design structure matrices (DSM). This approach takes its point of departure in the decomposition of a product into parts and/or subsystems while identifying the relations (and possible future interfaces) among these Stone et al. (2000). By applying different algorithms and clustering techniques, it is possible to encapsulate functional 'chunks' that have the potential of becoming physical modules, due to their functional interrelations. DSM techniques are the subject of many research initiatives and serve as the basis for an array of derived methodologies. An example of this is the multi domain matrix, Lindemann et al (2009). Alternatively, other design tools focus more on the specific task of examining different functional flows with the aim of identifying modules Otto et al (1998), Stone et al. (2000). These methods are heuristically based. Other more general methods focus on the identification of common features in the existing product program in order to point out the basis of the product architecture. By formulating the design task as a quantitative problem, which can be subject to optimization, this method is balancing inputs from requirements and product variants design with data models of performance and costs. Through iterations, the optimal product variants are designed and evaluated using quantitative performance metrics.

Concurrent engineering: The areas associated with concurrent engineering include research in the concurrent development of product and production architectures, with phrasings such as 'methods supporting the development of product platforms'. In this context, Olesen (1992) introduced a three dimensional methodology superimposing the traditional domains of concurrent engineering, by suggesting the linking of technology, architecture and focus relations in the process, product and supply chain domains. Krause et al (2013) proposed an important step of operationalization of this 3D concurrent engineering approach (3D-CE) by developing a multi-dimensional framework that enables comprehensive assessment of alternative product architectures.

The concept of architecture for product family (APF) is introduced as a conceptual structure, proposing logics for the generation of product families Du et al (2001). The Generic Product Structure (GPS) is then proposed as the platform for tailoring products to individual customer needs. Ko and Kuo (2010) presented another systematic method for concurrent development of product families, involving combination of QFD-based methods with quantified DSM-techniques and morphology analysis to visualize concepts.

Design-for-manufacture (DFM): Olesen (1992) proposed a framework for the concurrent development of manufacturing supported by the Theory of Dispositions. This was done by proposing a set of models aligning the product design and the product life system phase of manufacturing to create a fit. However, the case with DFA and DFM methodologies is that the main focus is single product development. On this basis, Herrmann et al. (2004) argue that an extension of the DFM tools to comprise multi-product development will hold the key to achievement of competitiveness.

Mathematical models: Some researchers have undergone the task of developing methods based on mathematical models. Some methods are based on measures of modularity, which act as subjects of optimization using different techniques Jiao and Tseng (1999). Others seek to integrate product platform, manufacturing process and supply chain decisions through the application of mathematical models, thus extending the concept of the Generic Bills of Materials (GBOM) by quantifying relations between decisions from the different domains.

Conclusion: The above state of the art literature all point in the direction of reducing complexity in products by stabilizing interfaces and reducing the critical interactions between key modules and systems. The concept of functional independence is of importance and is strongly supported by the function models, matrix and mathematical models. What are not explicitly explained in the literature are the more "down to earth" design principles. It is the intension that the design principles defined by this paper should be utilized in the early phases of product architecture projects outside individual projects. Matrix methods and mathematical models are well suited for the later more detailed clarification of product architectures. In other words "do the right things" before "do the right way".

3 PRODUCT LINE ARCHITECTURE DESIGN PRINCIPLES

Based on analysis of the case studies carried out, this paper proposes the 10 following product line architecture design principles, which subsequently are further explained.

1. Determine the right number of product architectures which can be justified from a market point of view.
2. Isolate low volume selling features and options from the core product architecture.
3. Decompose the product architectures in to key module areas based on stable and non-stable key properties.
4. Identify key interfaces that shall be stable over time.
5. Identify right product architecture detail level – ranging from e.g. flow diagram to physical components.
6. Design product architectures to be upwards scalable from low performance to high performance – never from high performance to low performance.
7. Design each key module area to have balanced performance steps aligned between properties in the market and cost in production, supply and delivery. There are discrete performance steps and continuous performance steps.
8. Ensure that product architectures are stable from a production volume point of view.
9. Establish clear link between product architecture and production/supply/delivery architecture, e.g. late customer order decoupling points.
10. Be explicitly prepared for next product launches, e.g. by establishing roadmaps on module level.

3.1 Determine the right number of product architectures which can be justified from a market point of view.

Having the right number of architectures is crucial for all companies, see Figure 1. In this work, product architectures have the following three characteristics: (1) shared core interfaces, (2) core modules/systems exist in balanced performance steps, and (3) architecture(s) prepared for a number of future development projects.

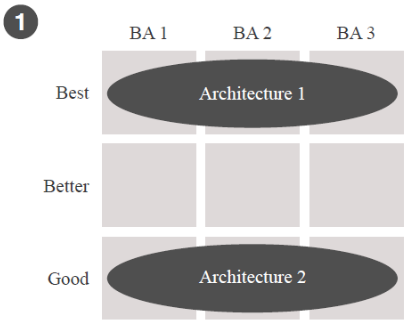

Figure 1. Two product architectures serving "best" and "good" market (BA: business area).

Example from the case studies: In a company manufacturing automotive components four architectures could be justified from a market point of view but eight product architectures existed. This means that this company's product architectures are way too complex and that there are significant cost optimization possibilities in terms of lower purchasing cost due to volume increase of shared components. Too many solutions are covering the same need/function in the product lines and are therefore non-value adding R&D effort is carried out. This means that when the architectures are reduced from eight to four, it should be possible to reduce time to market significantly and increase number of new products with the same R&D organization. As a vice president stated, “We are the biggest company in our industry – but we do not have the biggest barging power toward our suppliers because of too many product architectures”. "Furthermore automatization cannot be increased further".

3.2 Isolate low volume selling features and options from the core product architecture.

The main idea of product architectures is to harvest synergies in a variety of ways. It is therefore important that product architectures are spot on, cost and performance wise for products with high sales volumes and “trade-offs” can be accepted for lower sales volumes, see Figure 2.

Example from case studies: In a company manufacturing advanced motors with integrated controls, it was decided to integrate the electronics for control of the motor and the display electronics of motor performance due to lower material cost for one complete printed circuit board. Only five percent of the motors are delivered with a display panel. This means that 95% of the motors have cost that are not necessary. Therefore, the right approach would have been to separate electronics into two modules; one module for control of the motor and one module for display of the motor performance.

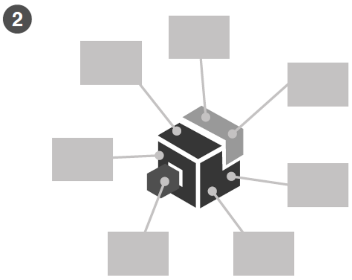

Figure 2. Features (grey boxes) with low sales volumes shall be separated from the core architecture

3.3 Decompose the product architectures in to key module areas based on stable and non-stable key properties.

One very important aspect of product architecture design is to enable explicit preparedness for future product launches Meyer and Lehnerd (1997). In more than two third of the studies cost rationalization has been the main focus. This is all right if the products are stable during the coming years, but can be a disaster if new properties and features have to be introduced, see Figure 3. In some companies significant rationalization has been achieved, but it has not been possible to phase out old products, because the new products are offering the same performance and features as the old products. This means that such companies will have even higher complexity and higher costs when the new product architecture in introduced. As a vice president explained it, “we do not want to be prepared for the previous war but the next war”

Example from case studies: A manufacturer of electric door locks has an architecture where changes of colour (a non-stable property that will be changed due to request from customers) are influencing the moveable mechanics. This means that something relative simple as changing colour will lead to significant utilization of R&D resources and new tool investments. There should have been a clear distinction between the visible and non-visible part of the door lock.

Figure 3. Separate modules according to stable and non-stable properties.

3.4 Identify key interfaces that shall be stable over time

Interfaces are a key concept in all practice and theory on product architectures Erissson and Erixon (1999), Guo et al (2007) and Lindemann et al. (2009). It is clear that interfaces preferably should be stable over time, but in practice this is rarely the case, Mortensen et al. (2016). Among the reasons for this is that decisions in product development in most cases are based on variable cost (direct material and direct labour in manufacturing), see Figure 4. As a senior designer explained, “If decisions are based on variable costs, the answer will always be a new part or new module, it can in most cases be improved – but from a total cost perspective this is not necessary the right answer.” In some companies senior engineers that have been in the same job for many years ensure that this is happening. One company introduced the rule that key interfaces can only be changed if the request is accepted in the board of management.

Example from case studies: An automotive manufacturer has for fifteen years had a stable interface between the gearbox and chassis. This means that when a new gearbox family is developed, it can be applied across all products within the product line. The alternative would have been to execute R&D projects for building the new gearbox into each and every product. The consequence would have been longer time to market and higher R&D effort.

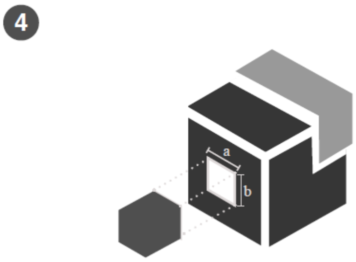

Figure 4. Stable key interfaces over time

3.5 Identify the right product architecture detail level – ranging from e.g. flow diagram to physical components

In literature there is no accepted classification of product architectures. The needs across companies and product lines are very different and therefore the content should most likely be different. An automotive company manufacturing millions of cars and a wind farm company delivering a wind farm every third year will have different architecture needs, implying that the ways synergies should be utilized in such companies differ. One aspect is the level of details. The automotive company would need a detailed architecture on part and module level, while the wind farm company would need a more high level “system” architecture, see Figure 5.

Example from case studies: An Oil & Gas company has implemented product architectures based on modular flow diagrams. This ensures that functionality and key components are the same in each project, while it also promotes flexibility in terms of changing the physical structure for each customer project. The benefits are reduction of engineering hours and increased quality. Such a company would most likely not benefit much from detailed product architecture on the physical part level, because each customer project is highly different and sales volumes are relatively low.

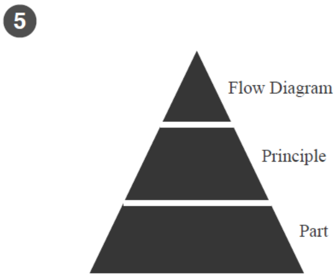

Figure 5. Different product architecture levels

3.6 Design product architectures to be upwards scalable from low performance to high performance – never from high performance to low performance.

There seems to be a tendency that companies start with the most difficult application areas and products. This will however most likely be damaging the profitability of products with lower performance. In the companies studied there were no examples in which a scale-down architecture for physical products was successful, see Figure 6.

Example from case studies: A manufacturer of equipment for analysis of a certain liquid has two product lines: a large one for laboratories where the number of samples are high and a small one for doctor clinics where the number of samples are low. The company decided to develop the architecture for the large product first (laboratory) and then later aimed to down grade it for the small products (doctors clinics). The small products failed to meet the cost target, since it was not possible remove functionality and key components from the large product architecture. As a senior vice president explained, “it is not possible to strip a Rolls Royce and then get a Polo”

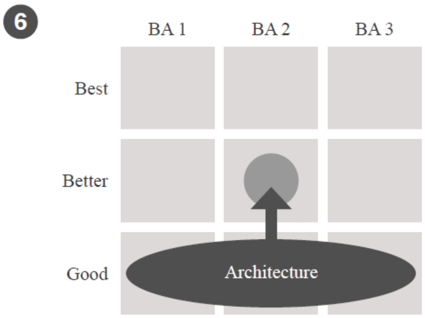

Figure 6. Product architecture shall be scalable upwards

3.7 Design each key module area to have balanced performance steps aligned between properties in the market and cost in production, supply and delivery. There are discrete performance steps and continuous performance steps

In the literature Huang et al (2005), Krause et al (2013), discussions about product architectures containing discrete modules can be found. In many cases, this is a relevant issue, but there are also cases where integration and continuous performance are the right solutions, see Figure 7.

Example from case studies: A wind turbine manufacturer concluded that for wind turbines the different module areas need to allow both discrete and continuous performance steps. An area where continuous performance steps are relevant is the steel tower. Due to the cost of a steel each tower, it shall be optimized according to the load conditions in each position. An example of discrete performance steps is a control system that can be built with modules having discrete performance steps depending on e.g. the power rating and temperature requirements.

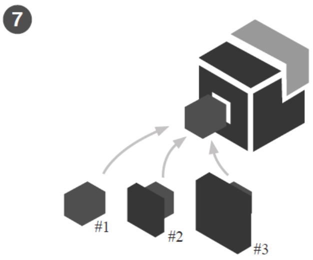

Figure 7. Three different modules with different performance steps

3.8 Ensure that product architectures are stable from a production volume point of view

It is often very difficult to forecast production volume. One way to address this is to build in volume flexibility in a manner allowing increased production volumes to be handled efficiently, see Figure 8.

As a vice president stated, “Product architectures that are designed for automation are also good for manual assembly”.

Example from case studies: A toy manufacturer has been working on product architectures of plastic injection moulds in such a way that e.g. exhaust and cooling functions are established in well-defined modules with well-defined performance steps. The elements that determine the shape of parts are designed individually in each project. In this company it is difficult to make precise forecast on which products will sell in which volumes. Now the company is much more flexible to handle variation in production volume. All the modules, such as the exhaust and cooling modules can now be shared across products. This implies a much faster reaction to changes in production volumes is possible.

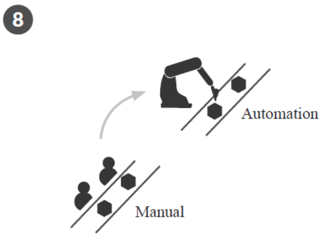

Figure 8. Production volume scalability of a product architecture

3.9 Establish clear link between product architecture and production/supply/delivery architecture, e.g. late customer order decoupling points

Traditional companies are organized according to responsibilities for sales, manufacturing and delivery/supply. The horizontal responsibility definitions across the above areas are therefore often relatively weak, see Figure 9. Significant benefits can however only be obtained if the product architecture work is considered end to end. As a CEO explained, “in our company the work on product architectures has been an exercise in moving cost from one area to another”

Example from case studies: A pressure transmitter manufacturer has worked intensively in automation across many factories. After detailed investigation it was concluded that if the existing product architectures were to be automatized, it would lead to different automation setup in each factory. As a result the number of product architectures were harmonized and reduced with approximately 50%. The benefits were, that the similar factory line architecture could be shared across factories. The consequences are lower investment and increased flexibility, i.e. more products can be produced in several factories.

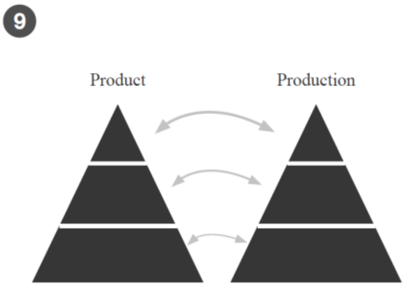

Figure 9. Clear link between product and production architecture

3.10 Be explicitly prepared for next product launches, e.g. by establishing roadmaps on module level.

In most companies, road mapping on product level are introduced, but seldom road maps exist on lover levels such as systems and modules. Working with lower level roads maps is one of the leavers for successful implementation of product architectures, see Figure 10.

Example from case studies: A pump manufacturer has a launch pattern for new products that involved a first launch serving Europe, followed by a US launch, and finally a launch of OEM (Original Equipment Manufacturer) products. A module road map has been introduced in such a way that region (e.g. frequency, UL approvals) and customer specific (colour, size) requirements are isolated in the product architecture. In parallel with development of the European product line explicit product architectures for the US and the OEM are taken care of. This has led to a significant faster time to market for the US and OEM variants.

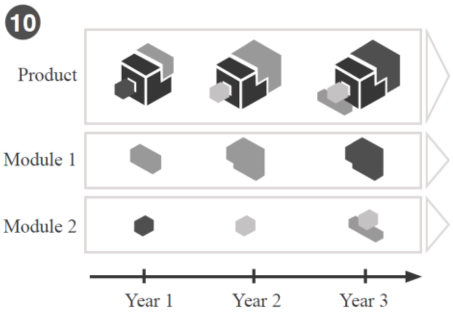

Figure 10. Road maps on both product and module level.

4 CONCLUSIONS

Despite that all the companies studied have had some kind of product planning and road mapping in place, all of them are non-compliant with the first principle, i.e. having the right number of product architectures. The consequences can be quite severe in terms of increased cost and increased time to market. Situations observed in the cases studied include:

- Product architectures are taken into market areas where they technical can cover but have very bad cost/performance. This will lead to low margins.
- Product architectures are too many and overlapping. This means that there are multiple ways of serving the same customers or segments. This again will lead to increased complexity in engineering, production, quality, purchase etc.
- Product architectures are not covering “the middle” areas”. In some of the observed companies this has been important due to unexpected high sales volumes in the middle area between two product architectures.

The first analysis of the data presented in this paper indicates that companies generally have too many product architectures. This has a significant negative impact on financial and innovative performance. The above challenges cannot be handled in individual projects but has to be clarified upfront. Product architecture responsibility is in principle being taking care of by e.g. a program management department, but on the concrete level that is not sufficiently concrete to guide the individual product projects. In one of the companies the cost of “wrong and too many product architectures were quantified”. The cost base was roughly 5% too high measured on direct material and direct labour in production. On top of this there were complexity costs, such are long change-over times on assembly lines, low purchase volumes, high investments in tooling, etc.

Our future research will therefore focus on studies of procedures to identify of the optimal number of product architectures. Such procedures need to include calculations of complexity costs and end-to-end thinking to avoid sub-optimization.

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ORIGINAL PAPER

Towards a framework for modular service design synthesis

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Abstract This paper seeks to improve the understanding of how service-based companies can benefit from developing and delivering service offerings from a standardised core of service modules, which are organised through a service architecture. Research within the field is relatively sparse, and there is scope for an explicit definition of elements related to the development of modular service platforms and architectures. A study of the existing literature, combined with a comprehensive case study in a global engineering consultancy, has created the basis for development and evaluation of the conceptual model for modular service design synthesis presented in this paper. The case study is based on internal documentation and a high level of interview data. Inductive research methods have been used for the analysis. The presented conceptual model defines three suggested dimensions (Market Segmentation, Service Roadmap and Service Architecture Layout) to be included in development of modular service platforms and architectures. Testing indicates a significant standardisation potential for service configuration across service families. Our understanding is that the approach can increase strategic flexibility and adaptability to changes in a quick evolving service market. The empirical part of this paper is exploratory in nature and is limited to one provider of high-end engineering consultancy services. Thus, further research will be needed to verify the aspects of the presented methodology to allow a further generalisation of our findings. Nevertheless, this paper contributes to the emerging literature on service modularity by presenting a specific operational approach for description and utilisation of modular service platforms and architectures.

Keywords Service design synthesis · Service modularity · Modular platforms and architectures · Strategic service development · Application of service platforms

1 Introduction

The ever accelerating evolution of technology, changing market structures and financial challenges over the past few years have made it increasingly important for service-based companies to be able to effectively manage innovation and service delivery (Chae 2012). To sustain a competitive edge, in a market where competitors are quick to copy successes and with short life cycles, service businesses have no time to rest (Chesbrough 2011). Companies often struggle to adapt quickly to market changes and to align service offerings to constantly evolving customer needs (Menor et al. 2002). To stay competitive, companies must be evolutionary and able to operate with an effective and holistic strategy, from both a short-term and a long-term perspective, which is not an easy task. This paper suggests that the key to obtaining the level of flexibility and competitiveness needed for success in service-based companies can be found in the methodology of modular platforms and architectures.

The core concept of modular product platforms and architectures, based on reuse of standard designs and commonality across product families, is well established in the production industry. A broad base of the recognised literature supports the methodology, and new research is

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constantly driving it forward. A number of pioneers exist in the field, e.g. Collier (1981); Meyer and Utterback (1993); Robertson and Ulrich (1998). The concept has evolved over the past three decades, and today some of the recognised benefits of the methodology include decreased time to market, decreased production cost, faster introduction of new technologies into existing production lines (Meyer and Lehnerd 1997; Harlou 2006; Bask et al. 2010; Simpson et al. 2014). However, it must be pointed out that no universal consensus exists regarding a conclusive definition of how modular product platforms and architectures should be perceived, nor what defines the related benefits (Bask et al. 2010). It is rare to see the potential of the methodology utilised for service delivery (Voss and Hsuan 2009), and research in the area of service platform architecture is generally limited (Bask et al. 2010).

Development of an understanding of the concept has been defined as one of the challenges for service innovation and service science (Menor et al. 2002). Pekkarinen and Ulkuniemi (2008) emphasise the importance of standardisation of services and processes, due to the potential efficiency gains and point out that the conceptual benefits are the reasons why modularity related to service innovation and delivery deserves further research attention. Through the presentation of a suggested conceptual model, including elements entitled Service Architecture Layout; Market Segmentation; and Service Roadmap, this paper seeks to improve the understanding of how platforms and architectures based on standardised service modules can support new service innovation and effective service delivery.

Firstly, the relevant literature is reviewed to create the foundation for the presented approach and a model for modular service design synthesis. Then, we define a number of criteria for successful service platform and architecture development, before continuing to present the conceptual model. Finally, a case study is presented in which the conceptual model has been applied. The case study is used as a basis for discussion and evaluation of the applicability of the model.

2 Research approach

Our research generally has an exploratory and qualitative nature. We have strived to apply a synthesis focus, where methodology known from the manufacturing industry, combined with the non-technical elements of services, defines the basis for our research contribution (Carlborg et al. 2014). Industrial insights obtained through engagement with service-based companies created the starting point for our interest in the field of service modularity. We saw a need for structuring and standardising service delivery and innovation to increase competitiveness. Based on our knowledge in the field of product modularity, we started looking into the existing literature within the field of service platforms and architectures. Building on the existing research and gaps identified within the field, we started working on a conceptual model for modular service design synthesis. The elements in the model were then tested and evaluated through a comprehensive case study.

The empirical evaluation is based on semi-structured interviews and workshops in a global high-end engineering consultancy, with more than 500 employees. The activities related to introducing and testing our suggested model ran over a period of 6 months. During this period, we spent more than 40 days physically located in the company, working alongside the technical consultants, observing and getting to know the company from the inside. The objective was to obtain a necessary level of insight, making it possible through the theoretical lens of platform and architecture methodology, to define a structural and functional description of how modular service design synthesis could support operations in the company. Interviews were held with both junior and senior consultants related to 11 specific projects. Workshops were held with senior management to continuously evaluate the conceptual model. Furthermore, historical project data from the past 5 years were studied and evaluated, in order to create a holistic picture of the service delivery process, i.e. timeframes, margins, tasks, service variations, etc., and to built an understanding of the different market segment in which the company offered its services. We also identified trends in service innovation and delivery within the company. This allowed us to develop and present a conceptual model, consolidated within the company context. We were furthermore able to evaluate our initial conceptual model and discuss the potential for support service-based companies in structuring and standardising service offerings.

3 Review of the existing literature

Looking at the existing literature framed our work towards presenting a conceptual model for modular service design synthesis. The following chapter of this paper highlights elements, which created the basis for the model.

3.1 Product platforms and architectures

A product architecture can be seen as a building principle or blueprint for a product and can be considered as the arrangement of a product's functional elements into a number of physical building blocks. The product architecture also includes a definition of the interfaces between interacting physical elements (Voss and Hsuan 2009). In classic production-based companies, developing single products one at a time is costly and ultimately results in a very high number of unique designs. Starting from zero every time that a development process is initiated can increase time to market, and unique designs can often be seen in products, where using a standardised solution could have saved resources and significantly reduced development time (Simpson et al. 2014; Harlou 2006; Meyer and Lehnerd 1997).

Designing and leveraging from robust product platforms, from which several product variants can be developed, will give an organisation the foundation to execute multi-product plans, focused on strategic market differentiation (Simpson et al. 2014). It can potentially reduce time to market, by supporting rapid product and production development (Meyer and Lehnerd 1997). Generally, the benefits of product platforms and architectures can be found in the dimensions of rationalisation and innovation. Rationalisation focuses on benefits related to the optimisation of the existing business, e.g. increased standardisation and effectiveness in production. The innovative dimension focuses on the future of the business, e.g. improved ability to reach out to new markets, rapid new product development based on a reuse of standard designs and leverage of core technologies in new business areas (Meyer and Lehnerd 1997).

3.2 A service business must be agile, flexible and prepared for growth

The service sector is growing, with global predictions that the 21st century will see both economic and job growth being dominated by this sector (Chae 2012; Chesbrough 2011; Menor et al. 2002). This predicted growth makes it interesting to investigate how service organisations can leverage from the concept of modular platforms and service architectures to effectively handle innovation and service delivery, without being inhibited by increasing portfolio complexity. However, despite its importance, research in the field of alignment between service innovation and service strategy for service-based companies is relatively sparse (Lightfoot and Gebauer 2011). Implementation of a modular approach to service innovation is assumed to support this alignment and help service-based companies to succeed in effective service innovation.

Voss and Hsuan (2009) argue that the dynamics of the service market generally make it difficult for companies to sustain a competitive advantage. Thus, a service-based company must be agile, flexible and ready to handle growth to become and stay successful and at the same time be able to deliver cost-effective services, without compromising quality and consistency (Menor et al. 2002; Nijssen et al. 2006). This defines the challenge for service businesses to manage both customisation and standardisation (Birkinshaw and Gibson 2004; Chesbrough 2011; Kostopoulos et al. 2012). We argue that service-based companies, maybe even more than production-based companies, must be ready to implement radical changes with high frequency and short lead time in order to sustain success. We believe that by leveraging from modular service platforms, based on a high level of standardisation, it is possible for service-based companies to move forward at a high pace and obtain the flexibility and scalability needed for success in the service market.

3.3 Services as a heterogeneous combination of elements

In contrast to physical products, services are generally intangible in nature and can be defined as activities produced by people, processes and/or systems (Meyer and DeTore 2001). Services can be seen as heterogeneous constellations with the characteristics of being produced and consumed at the same time and having a process-like nature, which unfolds over a period of time in a specific context (Perrey and Lycett 2003; Vargo and Lusch 2011; Bask et al. 2010; Voss and Hsuan 2009). As an example, a professional consultancy service can be seen as a series of events, occurring between business partners, agreements, deadlines and deliverables. The service has a defined timeframe, with a logical initiation and completion, and the service will only create value when delivered in a well-defined context. One aspect that clearly distinguishes services from physical products is the role and influence that people have in the delivery process (Voss and Hsuan 2009). A service is a co-creation between customer and service provider and generally exists in the boundary between the customer value proposition and implementation (Perrey and Lycett 2003). As a result of the nature of services, a model for modular service design synthesis must be able to handle this heterogeneity.

The intangible and co-creative nature of services means that a high level of customisation is often part of the service delivery process. This can result in difficulties in standardising service offerings without compromising the ability to satisfy customer needs (Anderson et al. 1997). This presents a challenge for how to approach modularisation without compromising the competitiveness of a service-based company. The nature of services also makes it relatively difficult to define service variants and to specifically identify the building blocks of a service. However, it is possible to identify an understanding that a service can be divided into smaller entities, from which it is possible to define service modules with individual functionalities (Pekkarinen and Ulkuniemi 2008; Voss and Hsuan 2009). In this paper, we consider service elements as the smallest entities into which a service can be divided and the combination of these elements into functional units as the basis for modular service development.

Service and product innovation hold many similar characteristics (Nijssen et al. 2006). We argue that translating parts of the methodology for product platform and architecture development to fit service innovation is possible. However, fundamental characteristics of services define a need for adapting the methodology to the service domain. We identify differences in the definition of interfaces and modules. Furthermore, the characteristics of services present a challenge in maintaining stability of potential standardised service offerings. When considering products, modules and related physical interfaces can be defined by a clear specification of functionality, dimensions, material, frequency, etc. Service interfaces and service modules may generally have a more heterogeneous nature. The conceptual model presented in this paper will strive to improve the understanding of how service interfaces and modules can be constructed and visualised, to support modular service design synthesis.

3.4 Service platforms and architectures

Research in the field of service modularity and service architecture development is generally limited (Pekkarinen and Ulkuniemi 2008; Bask et al. 2010). Sundbo (1994) was one of the first to investigate how modularisation can support service innovation, since then publications concerning similar fields of research have followed. Notable publications include Menor et al. (2002), Meyer and DeTore (1999, 2001), Pekkarinen and Ulkuniemi (2008), Voss and Hsuan (2009) and Bask et al. (2010). More than 10 years ago, Menor et al. (2002) defined the field as an important area for service innovation. Integrating modularity and architectural thinking into service innovation and delivery has since been gaining increased attention (Voss and Hsuan 2009).

Voss and Hsuan (2009) define areas within the framework of service architecture and modularity that can support the competitiveness of service-based companies. They argue that applying a modular structure to service innovation and delivery will make it difficult for competitors to copy service offerings and that the ability to leverage from modularity, through reuse, will reduce time to market, support customisation and help service-based companies to sustain competitive advantages. Generally, the ability to leverage from existing assets to fast and efficiently deliver and launch new service offerings is seen as one of the strongest benefits related to service modularity (Crawford et al. 2005; Meyer and DeTore 2001; Voss and Hsuan 2009).

Tuunanen et al. (2012) define three concepts of service modularisation. They argue that for service-based companies to benefit from modularity and standardisation, they have to work within the dimensions of service modules, service architecture and service experience. The service modules make up the service architecture and together they constitute the service experience. Looking at service modularity, Pekkarinen and Ulkuniemi (2008) generally describe a service module as an integration of various functions within a company, and Homann et al. (2004) adds that each service module should hold a high degree of autonomy. Blok et al. (2010) provide a description of three kinds of service modules: basic modules, common to all services; modules that can be configured to accommodate specific needs; and modules used for customisation of the individual services. It is, however, still unclear how service modules are designed. The general understanding of this paper is that it is possible to identify service building blocks, i.e. service elements, which can be combined into subsystems, each holding a specific functionality and which, when put together, constitute the service (Bask et al. 2010). One of the requisites for working with modularisation and standardisation is the ability to define stable modular interfaces. However, it is generally difficult to find a unified view of dimensions included in modular service interfaces. As similar to product modularity, interfaces are generally considered of high importance for the success of a modular service architecture (Voss and Hsuan 2009). As Lin et al. (2015) highlight, the definition and application of interfaces within the domain of service dominant logic, holds a potential for optimising business operations. They define three different types of interfaces: design-; process-; and information interfaces. Voss and Hsuan (2009) describe interfaces between subsystems in a service architectures, as containing the dimensions of people, information and rules, which governs the flow of information. It is also possible to distinguish between modular interfaces and customer interfaces (Bask et al. 2010). Generally, we see interfaces within the domain of services holding different dimensions with a heterogeneous nature.

Meyer and DeTore (1999) and Pekkarinen and Ulkuniemi (2008) have presented models with similarities to the conceptual model (Fig. 2). Meyer and DeTore (1999) apply a product development framework to service development and define a model consisting of three dimensions: the market segmentation grid; production platform; and core competencies. They emphasise the importance of integrating market considerations related to modular service development, to define market segmentations and clearly focus service development. The production platform includes modules or subsystems connected by interfaces, which by mix and matching can accommodate the identified customer needs. The final dimension focuses on the core competences within the company and how these can be developed to support the modular production platform. Pekkarinen and Ulkuniemi (2008) go deeper into the development of the modular service platform and define three levels of modularity: modular service offerings; modular organisation; and modular processes, where interfaces exist between the different levels of modularity. With respect to these two rather similar models, it appears that there is room for improvement regarding the understanding of how to design service platforms to support clear strategic service delivery and innovation.

The existing literature in the field of service modularity and architecture development generally agrees that benefits exist similar to what is seen for product modularity and architecture development, i.e. reduction in cost and time to market for new service innovations and increased flexibility. However, the literature leaves room for improvement regarding the understanding of how to approach modular service development. Generally, the process of service innovation can be said to be rapid and dominantly incremental in nature (Hipp and Grupp 2005), which makes it interesting to improve the understanding of how a service company can leverage from modular development through strategic planning and define a healthy balance between service standardisation and customisation. Based on the review of the literature it is proposed that aspects concerning definition of elements and key interfaces in a service architecture leave room for further improvement. This creates the basis for introducing a model for modular service design synthesis, as is proposed in this paper. Due to the heterogeneous and intangible nature of services, an important function of the presented model is to give a simple and visual representation of how modules can be deployed to support modular service offerings (Mortensen et al. 2008).

3.5 Criteria for service platform development

Criteria for successful service innovation can be found in the literature. Tan et al. (2009) define a number of steps that a company should consider to successfully integrate services into their portfolio. One is being able to design a well-defined service platform that can secure effective delivery of services and improve productivity by automation, standardisation or delegation of activities and responsibilities. Lightfoot and Gebauer (2011) and Droege et al. (2009) agree that successful service innovation for business practice must include dimensions of service, market and strategy-related factors. Furthermore, Droege et al. (2009) define the need for active management of human resources, if a service-based company is to succeed in radical service innovation.

As identified, a critical aspect for service modularisation is to be able to align activities and decisions across different domains, i.e. market-related decisions, decisions related to human resources and strategy for innovation. We believe this is possible by addressing the overall dimensions of flexibility, scalability, standardisation and competitiveness. To support these aspects, the conceptual model should be able to accommodate a number or criteria displayed in the specification seen in Fig. 1. The specification is summarised from the findings in the literature and the needs identified in industry.

4 Conceptual model

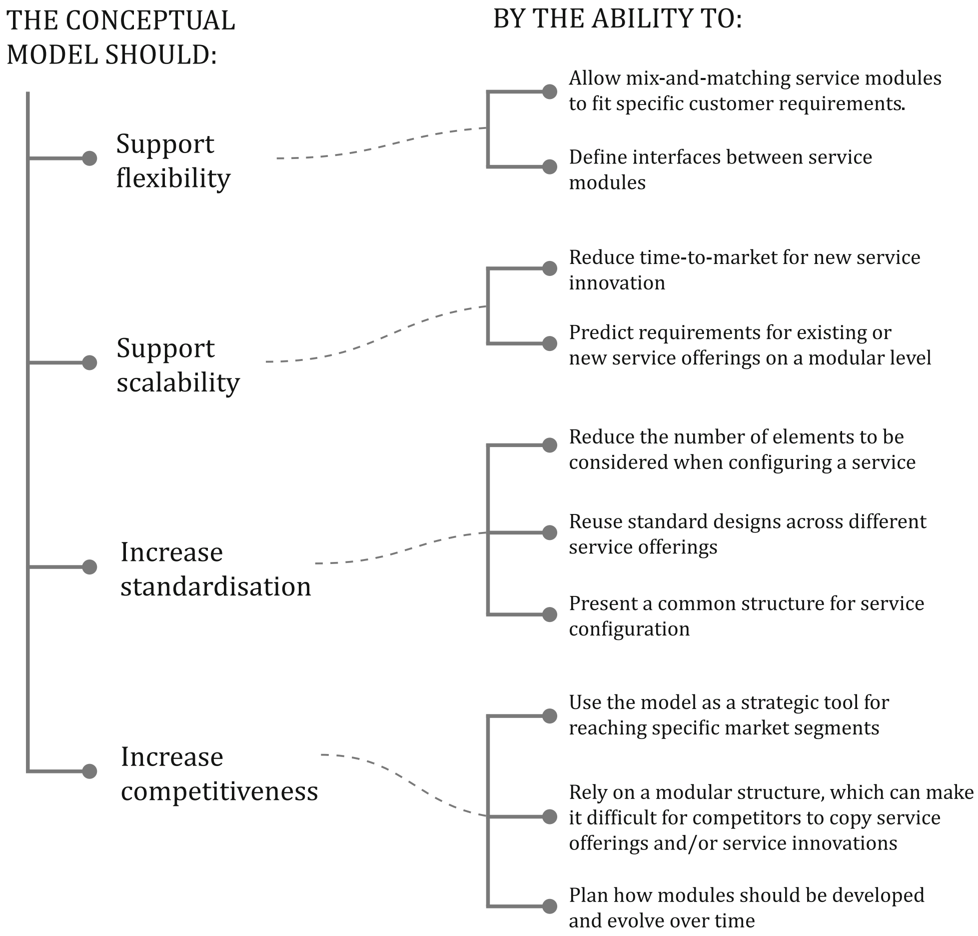
The following describes our proposed conceptual model for service platform and architecture development. The model is presented in a number of figures, which capture the concept. We highlight the importance of defining a clear strategy for modular service design synthesis, which we suggest should include market considerations, a service architecture structure and a planning dimension, i.e. road mapping. The concept outline of our model presented in Fig. 2 visualises how these dimensions are integrated to form the frame for developing modular service platforms, including the Market Segmentation, the Service Roadmap and the Service Architecture Layout.

The existing literature has created the basis for the model (Meyer and Lehnerd 1997; Meyer and DeTore 1999; Harlou 2006; Pekkarinen and Ulkuniemi 2008). We add to the current understanding of modular service design synthesis by connecting these elements and introducing the Service Architecture Layout. This will allow alignment between modular service delivery and innovation, which we consider one of the keys to succeed with modular service development.

4.1 The Market Segmentation

The Market Segmentation is considered an essential dimension for modular service delivery and innovation. It allows identifying focus for service platform development as it helps to strategically aim service offerings. The presented model (Fig. 3) is deduced from the power tower and market segmentation grid presented by Meyer and Lehnerd (1997). Meyer and Lehnerd (1997) present the power tower in the context of product platform and architecture development, in order to show how platform development can be used as a strategic tool. Later, they apply the same approach to services and argue that they are able to translate the methodology from products to services (Meyer and DeTore 1999). Pekkarinen and Ulkuniemi (2008) also introduce Market Segmentation in their conceptual model for modular service development. We believe that this approach is essential for applying service

Fig. 1 Specification for conceptual model



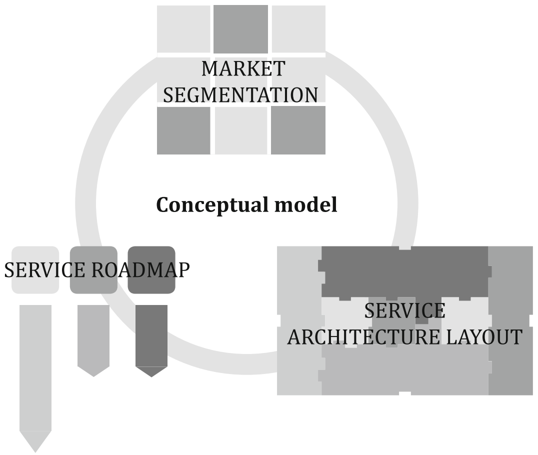


Fig. 2 Dimensions of the conceptual model

modularity to strengthen competitiveness for service-based companies and to allow strategic decisions related to defining core business areas, potential extensions and new market entries. We propose an evaluation of each market segment based on attractiveness, competition and predicted market development. Figure 3 shows a generic representation of a Market Segmentation where different market segments A, B and C are found on the horizontal axis, each representing different customer demands. On the vertical axis, different performance levels are found, e.g. low-end, mid-range and high-end segments. Focusing on performance scaling gives service-based companies the possibility to define standardised off-the-shelf service solutions focused on performance level 1 and then scaling up performance through integration of additional features. We argue that this type of segmentation will give a strong foundation for the definition of a strategic focus for a service platform.

4.2 Service roadmap

Strategy related to approaching different market segments is closely connected to the roadmap dimension. The Service Roadmap indicates how to approach new market segments by upgrading or introducing new modules into a service platform. We base our understanding of how to model and visualise the Service Roadmap on the examples found in Harlou (2006). The ability to clearly define a roadmap with focus on modular development is one of the

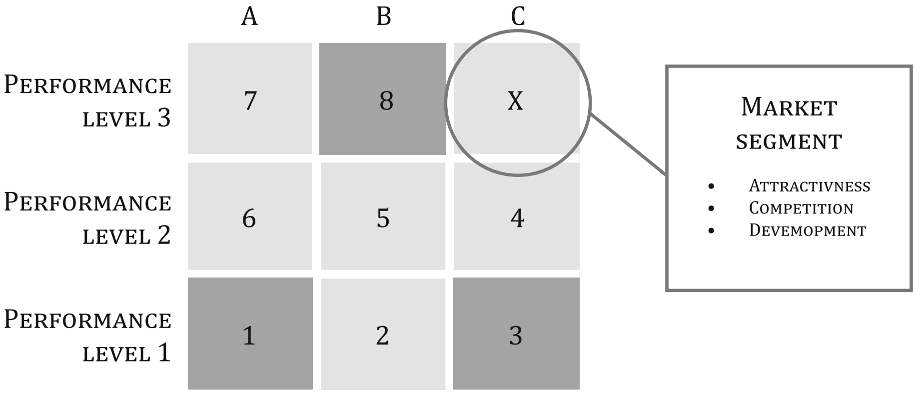


Fig. 3 Market Segmentation

major benefits of modular service development. The roadmap dimension allows a definition of how each subsystem can gradually be improved and how integration of new innovations and technology can be handled. The stability of the interfaces between each subsystem in the Service Architecture Layout is of high importance and allows the modules to be upgraded or replaced, without affecting other parts of the service architecture. This allows managing each service module individually and increases flexibility and adaptability of a service-based company. Figure 4 shows an example of how development of the individual subsystems can be managed to reach new benchmarks, e.g. service upgrade to version 2.0 or preparing to enter a new market segment.

4.3 The service architecture layout

The architecture layout describes our proposed principle for structuring services and defines the basis for modular service development and delivery. It includes description of service modules, interfaces and add-ons. Existing research within functional modelling (Harlou 2006) has inspired the representation of the Service Architecture Layout. The purpose of the model is to present the functional elements/modules needed to constitute a service and the interrelations/interfaces between these modules. In the Service Architecture Layout, the functional modules are represented as boxes with an attached attribute; for example Execution or Planning and interfaces are represented as ‘plugs and sockets’ between these boxes.

4.3.1 Modules

Seven generic subsystems: offering; planning; equipment; human resources; execution; quality assurance; and completion, each with a specific functionality, constitute the Service Architecture Layout (Fig. 5). The modules are generic representations and must be designed to specifically fit the service context in which the model is implemented. Each module in the Service Architecture Layout holds a functionality, and when combined, they constitute the service offering. Each module can have a number of standard designs. It is these standard designs that constitute the service platform. As example, difference instances of

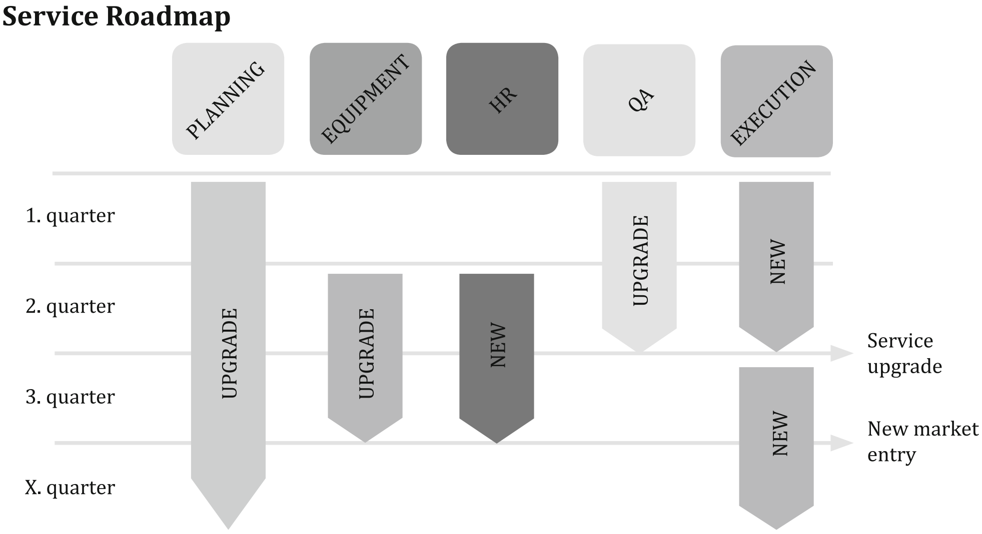


Fig. 4 Example of Service Roadmap

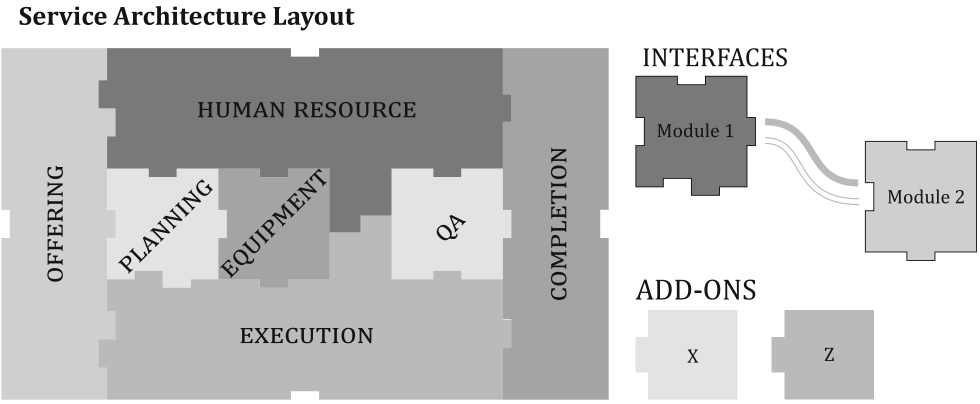


Fig. 5 Service Architecture Layout

the module Human Resources could be, e.g. junior consultant, senior consultant and chief consultant and describe the specific competencies for each performance step. When configuring a service and determining the requirements for a specific service offering, the best-suited standard design for Human Resources can be selected. The required input for selection is provided through the interfaces between the Human Resource module and the other modules in the Service Architecture Layout.

4.3.2 Interfaces

As identified in the existing literature, interfaces related to service modularity are described with a heterogeneous nature. We have translated this into an interface definition in the dimensions of dependencies and artefacts. The artefact dimension describes tangible elements needed for two modules to interconnect, e.g. reports, plans/guidelines or instruments/tools. The dependencies describe the demands and requirements of an interconnection between two modules, e.g. demand for specific human resources, capabilities or other modular characteristics.

4.3.3 Add-ons

Add-on features are individual autonomous entities with separate specification. Each has an external interface, which allows connection to the core of the architecture framework. The autonomous add-on features are considered necessary to increase flexibility and accommodate customisation in a service platform.

5 Example of application

To give an example of how the suggested model can be applied, we imagine the fictive service-based company ‘Cleaning Inc.’. Based on the ‘Cleaning Platform 1’, Cleaning Inc. provides services for the different market segments illustrated in Fig. 6.

Scaling of performance allows vertical leverage of the service platform to reach both the mid-range and high-end market segments. When looking ahead, Cleaning Platform 1 can be extended horizontally to reach out to new market segments (Meyer and Lehnerd 1997). In Fig. 6, Segment A defines the core focus for Cleaning Platform 1 and the B segments illustrate market opportunities, thought to be reachable through update of the existing platform. Segment C illustrates a potential market, reachable through major updates or introduction of a new service platform. Figure 7 shows how the Service Architecture Layout is used to structure standard designs from the Cleaning Platform 1 into modular service offerings.

As indicated in Fig. 6, Cleaning Inc. desires to focus on two new market segments (B segments). In this example, an update and extension of the Cleaning Platform 1 is expected to enable this. On a modular level, the Service Roadmap (Fig. 4) defines how each module should be upgraded to reach out to the new segments and when introduction of new subsystems is necessary.

To evaluate the model against the specification (Fig. 1), we applied it in a context where service delivery and innovation were not based on a modular strategy.

6 Empirical study of service delivery and innovation based on the conceptual model

A case study in a leading global high-end engineering consultancy has created the basis for evaluation of our suggested model for modular service design synthesis. The case company mainly operates with service offerings in the maritime and energy sectors and was, at the time for our study, facing challenges related to profitability and consistency in their service delivery process. Furthermore, the company had experienced difficulties in leveraging core

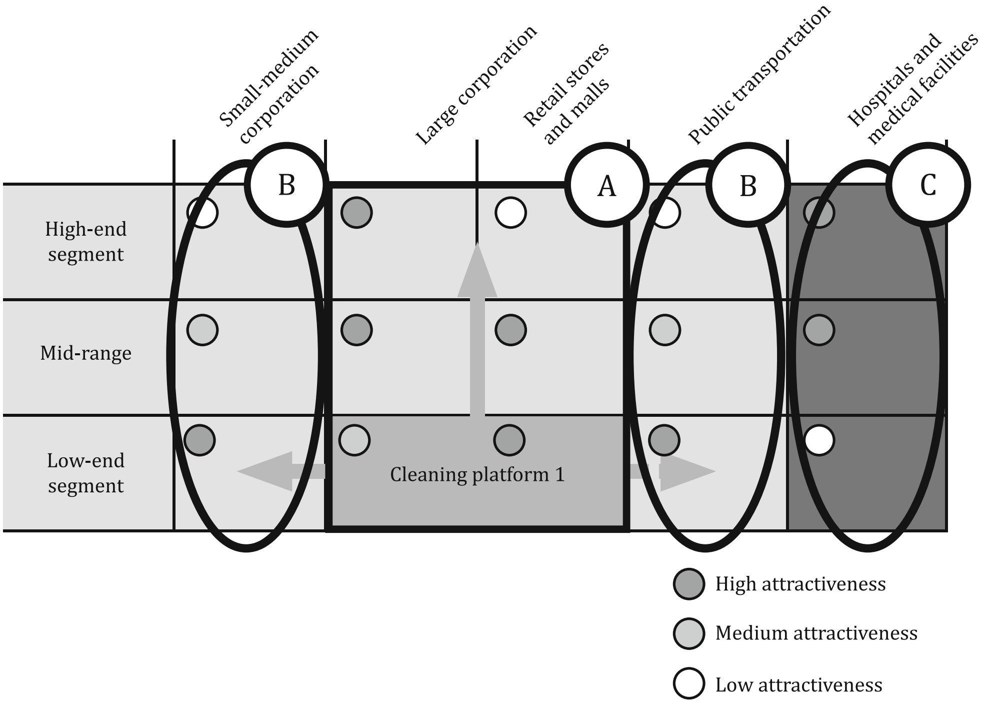


Fig. 6 Market Segmentation for Cleaning Inc

technologies from one business area to another, hereby losing potential highly valuable business opportunities. This created the basis for an operational test of the model in an effort to increase consistency in the service delivery process and increase organisational flexibility.

The scope for platform development was limited to a single service family, which allowed presenting a specific design within a relative short timeframe. As no previous experience with modular service delivery existed within the company, it was considered of high importance to limit the scope and present a simple and tangible modular design. Focus was placed on services related to commissioning of new or revamped compressors installed in oil and gas facilities. This service family had historically presented a number of challenges, which made them difficult to handle and made it difficult to maintain consistency in the service delivery process. Eleven historical projects were selected in collaboration with the case company, and these served as basis for understanding the service delivery process. The projects were analysed to identify commonality across services, which created the basis for combining service elements into service modules. From decomposition of services and integration of service elements, it was possible to define modules, add-ons and key interfaces and to present the Performance Platform. This platform was focused on service delivery at three performance levels. Examples of service elements combined to form modules were tools, analysis methods, measurements methods and technical capabilities.

It was possible to identify a positive market development in the segment of commissioning, as investments in the energy sector and rising global energy demands were expected to generate new business opportunities related to construction of new oil and gas installations. This trend made it interesting to define a platform, where leveraging from modular standard designs could support service delivery. The Market Segmentation was used to visualise this trend and to identify the core focus for the Performance Platform and identify where market development was expected. Through the Service Roadmap, we were able to indicate which modules should be updated over a period of four years to accommodate the evolving customer needs. The identification of commonality between services allowed definition of standard designs. Together with market alignment and a plan for service updates, it was possible to present a modular approach to service delivery and innovation.

6.1 Introducing the Performance Platform

The Performance Platform included 22 different standards designs and 25 add-on features. Through mix and matching of these modules and add-ons, a high number of service variants were supported at three performance levels. Performance level 1 focused on off-the-shelf service delivery and was considered the smallest saleable unit of commissioning. The scope of a service included structural assessment of the compressor and the services required limited

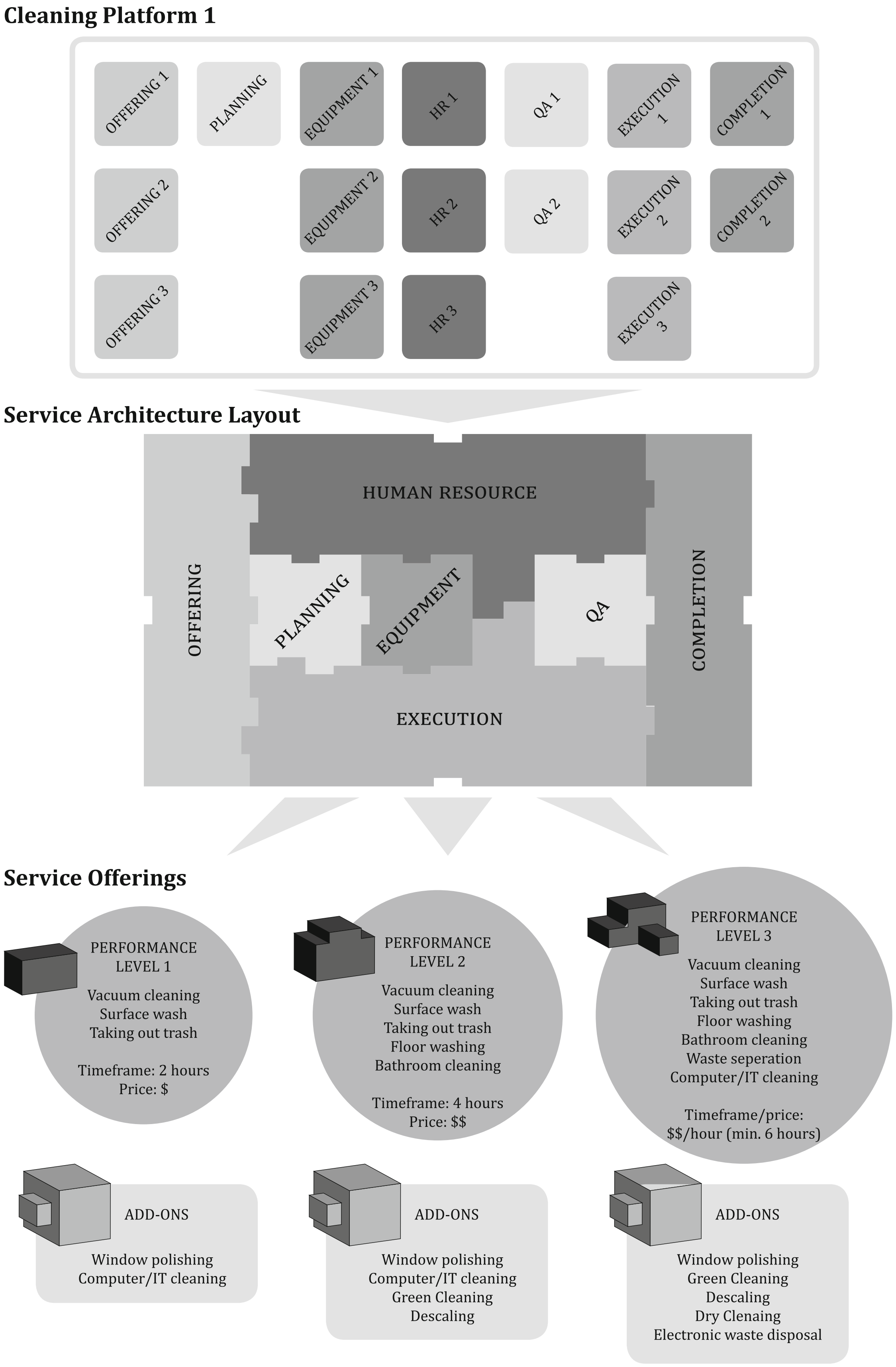


Fig. 7 Service delivery based on Cleaning Platform 1

instruments, experience and hours on-site. The service was design so that an inexperienced consultant with limited capabilities could perform it. The possibility for customisation at performance level 1 was relatively limited. On top of the structural assessment, service delivery at performance level 2 included a contextual assessment, e.g. influence of foundation, other machinery linked to the compressor and compressor casing. Service delivery at performance level 2 had higher requirements to the involved consultants, as integration of external instruments to perform measurements was needed. The last performance level represented the most comprehensive packages and included the scope of services at both performance level 1 and 2 and furthermore focused on the process within the compressor, e.g. temperature, mass flow and pressure. Assessing the internal processes in a compressor requires experience and extensive capabilities from the involved consultants. At levels 2 and 3, the possibility for customisation through additional standard designs and integration of add-ons increased.

An example of a standard design, included in the Performance Platform, is the execution module aimed at the basic low-end segment. This included definition of an approach for Base Line Vibration Measurements on the compressor train. As seen in the Service Architecture Layout, this module interfaced with the human resource and planning modules. The interface between execution and human resources defined a need for specific competences and a timeframe for execution. The planning interface defined a need for tools, measurement plan and definition of service context, e.g. onshore or offshore service delivery. Add-ons were defined, where low commonality existed between services. As example, an add-on for Valve Response Time verification was defined, including description of tasks to be performed, timeframe and cost. It interfaced with the execution module by defining competence requirements and tools needed.

Introducing the Performance Platform allowed for standardised subsystems to be reused for several service offerings related to the service family of commissioning. To evaluate service standardisation we compared the original number of elements included in the 11 service offerings we analysed, with the number of defined modules in the Performance Platform. By doing this, we are able to argue that instead of starting from zero every time a service should be configured and with high degree of freedom in the configuration process. We were now able to present a limited number of standard designs and add-on features, which could be reused and combined into service offerings, while serving the same market segments. This allowed increasing standardisation of service offerings by as much as 56 %. With the design of the Performance Platform, it became possible to change focus from individual service development to service development on a modular level. Market predictions made it possible to strategically plan future upgrades and integration of new standard designs to reach new market segments. The ability to mix-and-match standard designs supported the ability to leverage from core technologies and competences in one area to another; for example measurements, analysis and approach for verifying structural vibrations in a compressor could be translated to fit verification of vibrations in safety structures in high-speed trains. Finally, the standardised backend was believed to support an improved cost efficiency for service delivery. In the configuration process, mix-and-matching services based on the Performance Platform would indicate the needed timeframe and competence level for a service, thus enabling a standardised cost structure for all services. As we saw in the case company, this could remove the challenge for cost estimation of a customised service offering, where the individual service provider, with a very high degree of freedom and in a co-creative environment, had to evaluate the price setting.

7 Evaluation of the conceptual model

Developing a service platform based on the conceptual model and introducing it in the case company have shown potential for supporting the service delivery and innovation process. Potentials can be found in both the dimension of rationalisation of the existing service portfolio and in the dimension of improved innovative potential. The conceptual model was based on a synthesis focus, where methodology from the world of physical product development was combined and altered with the unique characteristics of services to fit a service context. This is seen in the definition of service modules and interfaces, e.g. by defining interfaces in the intangible dimension of dependencies and the physical dimension of artefacts. The findings that we present indicate that the conceptual model is able to live up to the specification defined in Fig. 1 and that a potential exists for working towards a holistic framework for modular service design synthesis.

The nature of services makes it difficult to identify and distinguish commercial variants, and due to the high level of co-creation it can be argued that close to infinite service variants exist. Blok et al. (2010) argue that this can limit the possibility for repetitive execution of service components and might limit the possibility for advantages in efficiency. This defines a fundamental challenging for modular service development. The conceptual model can potentially support service-based companies in defining this difficult trade-off between standardisation.

The Market Segmentation and Service Roadmap are elements with similarities to what have see in existing research (Meyer and DeTore 1999; Harlou 2006; Pekkarinen and Ulkuniemi 2008). Inclusion of these two elements in the conceptual model supports the critical alignment of strategy, execution and innovation in service operations. We believe this is key to strengthening competitiveness and to achieving the identified potential benefits related to service modularity. The Service Architecture Layout represents a supposed generic building principle for modular services. This principle allows a service-based company to identify standard designs and interfaces for each module and is key to the process of standardising service offerings. The proposed structure of the Service Architecture Layout was successfully able to accommodate service offerings and the configuration process in the case company. As this has only been verified in one case, other ways may exist to represent this structure, e.g. by adding or changing modules and/or interfaces. However, we consider the definition of a common service architecture as the starting point for service standardisation. The ability to built service offerings based on a standardised structure is the basis for increasing flexibility by allowing a level of mix-and-matching the standard design and add-on features.

As the goal for our research has been to present and test a conceptual model for modular service design synthesis, we have not addressed the dimension of governance and organisation of modular service delivery and innovation. Further research should be put into this aspect to investigate how service modularity should be controlled and maintained. The evaluation of the conceptual model is based on a single case study, and further research should focus on a validation of the presented approach and a broader generalisation of our findings. Challenges related to definition of service variants and in securing stability and robustness of a service architecture have been identified. Our findings related to the development and introduction of the Performance Platform in the case company are highly qualitative. We see a large potential in focusing further research on quantifying these findings and give a specific answer to e.g. decrease in time to market and increase in innovative potential.

8 Concluding remarks

The presented case study showed how an engineering consultancy, through reuse of well-defined standardised subsystems, i.e. service modules, could potentially improve their service delivery process. Furthermore, through definition of the Performance Platform, the presented model enables working with service design synthesis and updates on a modular level, thus simplifying the process of adjusting the service portfolio. With a clear focus for platform development including the elements presented in the conceptual model, it was possible to define functional units within service families and identify a level of commonality between service variants, thus developing service modules aimed at strategic market segments.

The conceptual model defines a holistic approach to modular service development and includes the three dimensions of Market Segmentation, Service Architecture Layout and strategic planning through Road Mapping. We believe that developing a robust platform as foundation for service innovation and delivery can be a key for service-based companies to increase flexibility and enable efficient strategic execution of service delivery and innovation. Generally, the identified potential benefits of service delivery and innovation based on modular service platforms, i.e. increased flexibility; cost efficiency; service consistency; and reduction in time to market, align well with the challenges identified for service-based companies today, i.e. changing market structures; short service life cycles; and increasing competition.

We believe that the conceptual model presented in this paper provides a meaningful contribution to the understanding of how service-based companies could approach modular service delivery and innovation. We hope that the research in this paper will contribute to push forward the emerging topic of service modularity.

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ASSESSING INCREASED PRODUCT LINE COMMONALITY'S EFFECT ON ASSEMBLY PRODUCTIVITY AND PRODUCT QUALITY

M. Løkkegaard, N.H. Mortensen, L.S. Jensen and C.K.F. Christensen

Abstract

We present results of an experiment focused on quantifying effects on assembly productivity and product quality by introducing a product platform and increasing commonality between variants in a product family. The experiment was set up with 50 engineering students, who over three rounds produced a family of LEGO car models. Over the rounds a product platform was introduced and the Commonality Index was increased from 47,8% to 88,4%. Compared to productivity and quality results show an increased output of 118% and a decrease in product defects by 31% when applying a platform-based approach.

Keywords: Product platforms, commonality, experimental, product families

1. Introduction

Developing families of products, based on shared and standardized platforms assets and with high commonality between variants is an approach utilized by industrial companies to offer product variance to heterogeneous markets while limiting internal complexity, cost and time-to-market (Ulrich and Eppinger 1995; Harlou 2006; Simpson et al. 2014). The approach has been applied in a range of industries from automotive to design of electronics (ElMaraghy et al. 2013; Sanchez 2004; Simpson et al. 2001; Baldwin and Clark 2000). Research exists on the benefits and drawbacks of product platforms and design of product families, generally concerning cost optimization (Meyer and Lehnerd 1997; Park and Simpson 2008) and reduced development time (Thomas et al. 2014). Cameron and Crawley (2014) summarize commonality benefits as related to Strategy, Design, Manufacturing, Testing and Commissioning, and Operation. They present a list of potential benefits of increased commonality in a product family but state that the benefits are not causal or assured but should rather be seen as potentials, which have been indicated in existing research. Studies generally report of successful development and application of product platforms, however, current research is dominated by empirical studies or examples. The need to better understand the effects is highlighted in several studies of existing literature (Piran et al. 2016; Campagnolo and Camuffo 2010; Jiao et al. 2007). One reason that effects are difficult to measure is that they are seen over time, when the platform is utilized to launch a family of products or as platform assets are reused to launch new product variants.

Little understanding of the effects of increasing commonality and utilizing product platforms often results in an intuition-based approach, when companies are deciding to allocate investments to platform and standardization efforts. Ultimately, even as companies claim to apply concepts of product platforms, initiatives risk receiving low priority and potential benefits are lost (Sanchez 2013).

When assessing the effects of increased commonality an experimental setup allows filtering out the "noise" created from external factors supporting a better understanding of the direct effects. In a company context, this noise can be created by other optimization initiatives in the organization, market fluctuations and organizational changes etc. This is why this paper provides a valuable contribution to the understanding of effects related to increasing commonality within a product family. The following parts will describe the method used, results and finally discuss if the findings can be used to reflect platform effects in a real-life context.

2. Method

The presented experiment was set up with a group of 50 engineering students at the Technical University of Denmark. In a game setting the students competed in manufacturing most cars made from LEGO bricks and with minimum defects over three rounds of 22 minutes. The students were divided into 6 groups of 7-9 persons and given instructions to the game. Initially the rounds were explained, however, product variants to be produced were not disclosed until 5 minutes before the beginning of each round, where each team was given a set of master cars as reference for designs. Before the beginning of each round the teams had five minutes to get organized and assign roles as team manager, supplier, quality inspector, runner and operators. A "customer" was assigned to each team. The customer's job was to check the finished cars for quality and to buy them, if they were correctly assembled. Customers were beforehand instructed to go into detail and if the smallest mistake was made i.e. misalignment of bricks, loose bricks or application of wrong bricks, they should consider the car as defect. In case of a defect the team would have to pay a penalty. This ensured that defects had a large impact on the team performance and should make sure they were not taken lightly. A currency was used in the game allowing teams to buy parts from the supplier and the customer to purchase the finished products. The winning condition in each round was to have most cash in hand when the 22 minutes were up. The overall winning team was the one that had accumulated most cash over the three rounds.

Figure 1 illustrates how each team was suggested to organize. Having a supplier, runner, team manager and quality inspector was obligatory. The rest of the team would be in charge of assembling cars. However, teams could decide for themselves if they e.g. wanted to have more than one person checking for quality or more than one runner.

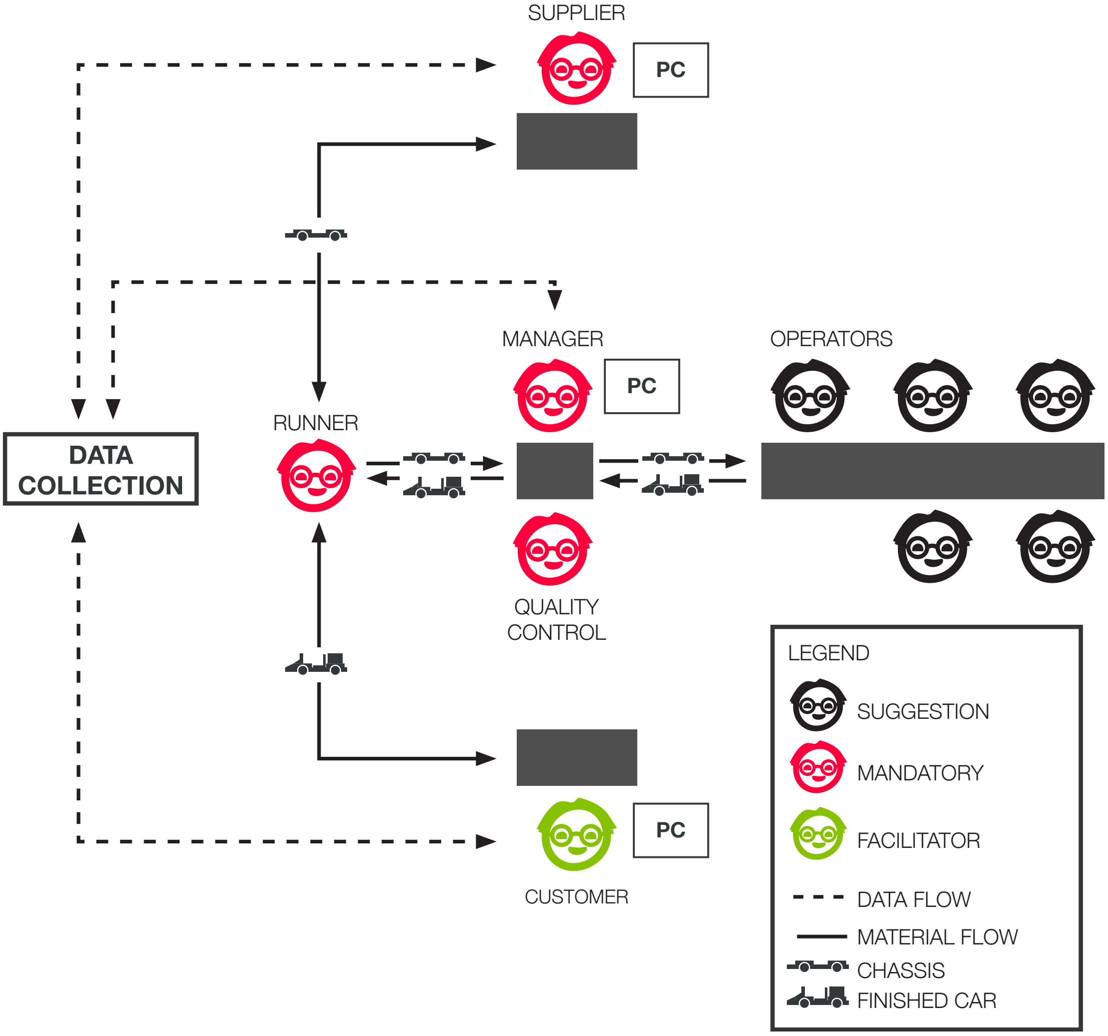


Figure 1. Suggested team organization

2.1. The three rounds

In the first round each team was given a single car variant, which they had to mass-produce. Apart from the chassis, teams were provided with all bricks needed to produce the car. Round one was designed to serve as reference for round two and three, enabling a comparison of the outcome of the following rounds with the number of cars produced when mass producing a single variant. Furthermore, round one should allow the teams to familiarize with the game, minimizing effects of team experience on the productivity.

In the second round the challenge was to assemble a family of three car variants with relatively low commonality and no intended product platform characteristics. Each variant had specific characteristics e.g. the ability to carry several passengers or carrying a "tool box". If teams sold cars in families of three including one of each variant, selling prices would be doubled. This should ensure an incentive for the teams to produce all car variants. Round two focused on the effects of introducing variance in the "factory".

In the third round teams were to produce the same three variants as in round 2. But cars had been redesigned and a product platform was introduced significantly increasing the commonality between product variants. The individual properties of the different variants were still present and differentiating parts were still used, only non-value adding variety had been eliminated. The third round focused on the effects of platform based production. An overview of the conditions in the three rounds is presented in Table 1.

Table 1. Detailing of rounds

Round	Duration	Product variants	Cash-in-hand at beginning of round	Parts bought at supplier	Price for parts bought at supplier	Selling price at customer for perfect product	Penalt for defect
1	22 min	1	200	Chassis A	10	50 (from 0-500s) 40 (from 501-1000s) 30 (from 1001-1320s)	50
2	22 min	3	200	Chassis A Chassis B Chassis C	10 10 10	25/product for single product 50/product for a family of products	50
3	22 min	3	200	Chassis A	10	25/product for single product 50/product for a family of products	50

Figure 2 illustrates the different product variants in each round of the experiment and highlights the changes made to the designs between rounds. Each product variant is broken down to the main functional units allowing a comparison across all variants.

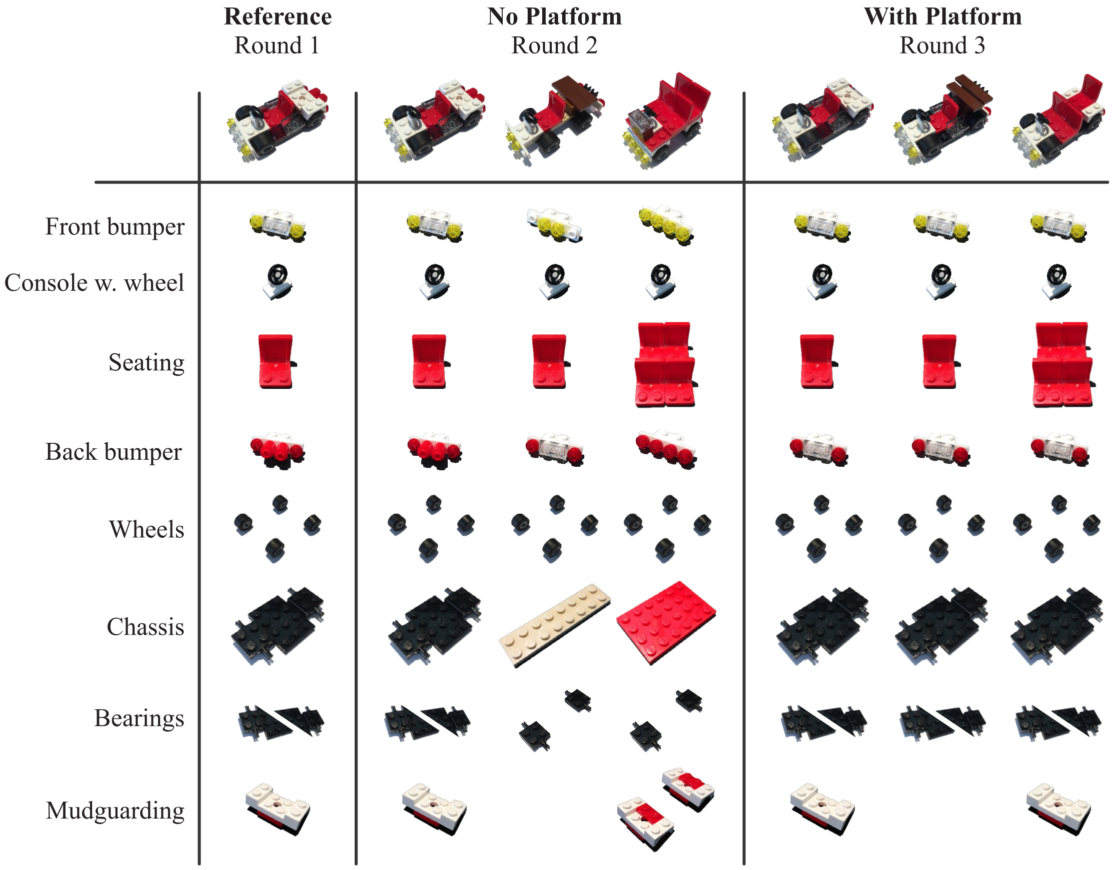
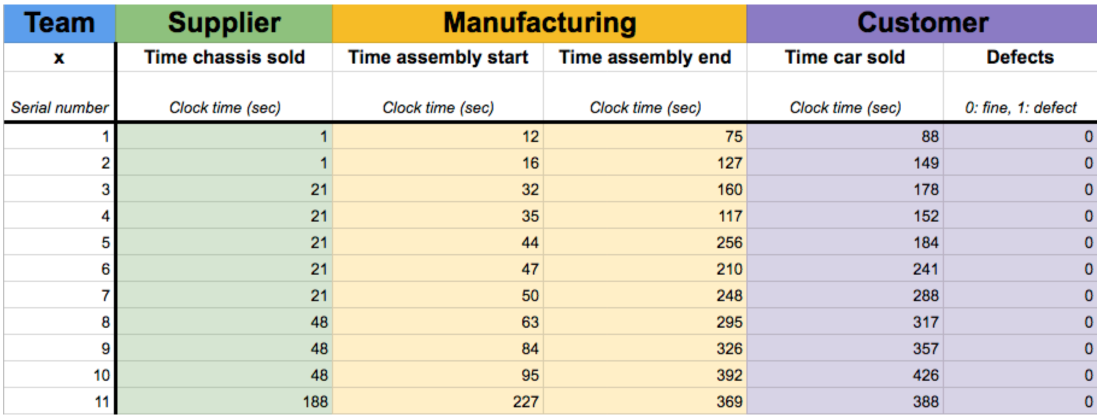


Figure 2. Product variants, main functional units and variations in each round

2.2. Data collection

Collection of data on number of cars produced and defects was collected using Google Sheets. Each team was provided with a link to a sheet where the team supplier, the team customer and the team manager were all logged in. At the supplier each chassis was given a serial number and a time stamp was entered in the sheet when a chassis was sold, when received at the "factory" the team manger entered another time stamp to the serial number and when the car was sold, the customer entered a final time stamp and a 0 for a perfect delivery and 1 for a defect (see figure 3). This allowed accurately capturing data in real time from the experiment and afterwards to see the number of cars produced in each round by each team.



Team	Supplier	Manufacturing		Customer	
x	Time chassis sold	Time assembly start	Time assembly end	Time car sold	Defects
Serial number	*Clock time (sec)*	*Clock time (sec)*	*Clock time (sec)*	*Clock time (sec)*	*0: fine, 1: defect*
1	1	12	75	88	0
2	1	16	127	149	0
3	21	32	160	178	0
4	21	35	117	152	0
5	21	44	256	184	0
6	21	47	210	241	0
7	21	50	248	288	0
8	48	63	295	317	0
9	48	84	326	357	0
10	48	95	392	426	0
11	188	227	369	388	0

Figure 3. Example from data collection

As part of the experiment the serial number and data entered by the team manager should all be completed in order to sell the car, this was set in place to simulate a real world context, where not only the production is a challenge, but also maintaining an overview of associated data. Uncertainties related to data collection relate to the manual entering of time stamps and defects to the correct serial numbers.

2.3. The product platform

Commonality increase in the final round was the result of redesign of the three car variants and introduction of a product platform (figure 4). The base of the car, including the chassis, wheels, front bumper, back bumper and the steering console constituted the core platform.

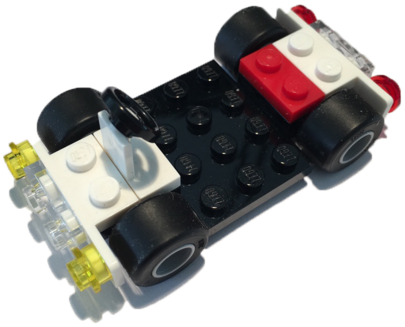


Figure 4. The product platform introduced in round 3

Figure 4 displays the platform, which was 100% common for all product variants. Utilizing the platform the teams were able to reorganize their assembly process and postpone the variant creation to boost productivity and improve the quality of the assembly process.

2.4. Product line commonality index

Different ways exist to assess commonality between product variants in a product family, examples being calculations of: Commonality Index (CI), Percent Commonality Index (%C), Component Part Commonality Index ($CI^{(c)}$) and the Product Line Commonality Index (PCI) (Simpson et al. 2006). The methods focus on different aspects of commonality e.g. number of common components (CI), common connections and assembly (%C), cost of components ($CI^{(C)}$) and non-differentiating components (PCI). The PCI is selected as the best metric to evaluate commonality of the product family used in the experiment. The index includes considerations related to components, manufacturing and assembly and as it excludes unique components and functional units from the equation, it provides a good overview of the actual impact of introducing a product platform. The PCI is calculated as:

$$PCI = \frac{\sum_{i=1}^{P} n_i \cdot f_{1i} \cdot f_{2i} \cdot f_{3i}}{\sum_{i=1}^{P} n_i - \sum_{i=1}^{P} \frac{1}{n_i^2}} \cdot 100 \qquad (1)$$

Where P is total number of non-differentiating components, n is number of products in the product family that have the component, f1 is part size and shape factor, f2 is material and manufacturing factor, f3 is part assembly and fastening scheme factor, PCI is expressed from $0 \leq PCI \leq 100$. The three main factors (f1, f2, f3) are evaluated based on the designs of the product variants. If a functional unit e.g. the Front bumper is the exact same across variants it scores 1 in all factors. If, for example, the assembly orientation is different for one product variant, f3 will score 0,66. Variants between round 2 and 3 (f1, f2, f3) and calculation of PCI were based on data from Table 2.

Table 2. Data for PCI calculation for round 2 and 3

	No	Functional Unit	n	1/n^2	f1	f2	f3	n*f1*f2*f3
Round 2	1	Console w. Wheel	3	0,11	1	1	1	3
	2	Chassis	3	0,11	0,33	1	0,33	0,33
	3	Front bumper	3	0,11	1	1	0,33	1
	4	Back bumper	3	0,11	1	1	0,66	2
	5	Drivers seat	3	0,11	1	1	0,66	2
	6	Mudguarding	2	0,25	1	1	0,33	0,66
	7	Bearings	3	0,11	1	1	0,33	1
	8	Wheels	3	0,11	1	1	0,66	2

	No	Functional Unit	n	1/n^2	f1	f2	f3	n*f1*f2*f3
Round 3	1	Console w. Wheel	3	0,11	1	1	1	3
	2	Chassis	3	0,11	1	1	1	3
	3	Front bumper	3	0,11	1	1	1	3
	4	Back bumper	3	0,11	1	1	1	3
	5	Drivers seat	3	0,11	1	1	0,66	2
	6	Mudguarding	2	0,25	1	1	0,66	1,33
	7	Bearings	3	0,11	1	1	1	3
	8	Wheels	3	0,11	1	1	1	3

Abbreviations	P	Total number of non-differentiating components/functional units (8)
	n	Number of products in the product family that have the component/functional unit
	f1	Part size and shape factor
	f2	Material and manufacturing factor
	f3	Part assembly and fastening scheme factor
	PCI	Product Line Commonality Index

In round two PCI was calculated to 47,8% and introducing the platform increased it to 88,4% in round 3. The PCI only indicates the commonality between non-differentiating components, thus by optimizing the design and introducing the common product platform it was possible to reach a very high PCI. Even with design changes, we argue that the car variants are comparable across rounds.

3. Results

In the first round, teams produced in average 60,8 cars with a failure rate of 1,4%. Round two saw an average output per team of 35,5 with a failure rate of 2,9%. In the final round, teams produced 77,5 cars in average with a failure rate of 2,0% (Figure 5).

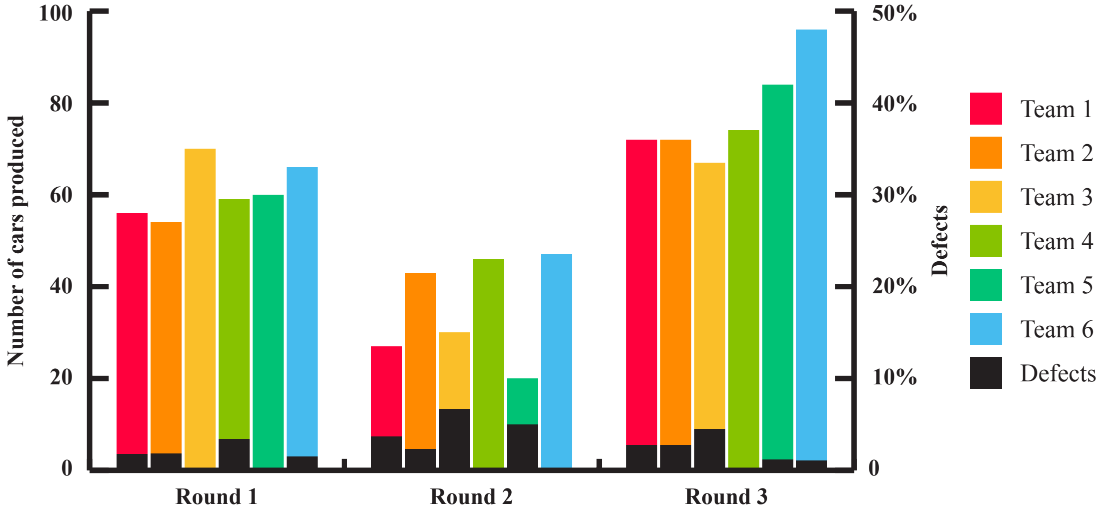


Figure 5. Collected data on production output and defects

Deviations per team can be observed in the data. Variance introduced in round two was for some teams difficult to handle and team 5 only had an output of 20 whereas team 6 had an output of 47 cars. In round two and three all teams chose the strategy of manufacturing cars in families of three to secure a better price for their finished products. Teams with low output in this round had a high number of product defects, which affected the output. Furthermore, deviations in output are assumed to be the result of teams spending time on readjusting and reorganizing to avoid further failures.

Compared to round one, productivity fell on average 41,6% in round two and increased with 27,5% in round three. However, as round one is used as benchmark and serves to let the teams familiarise themselves with the assembly process, rules of the game and organization of the "factory", the most interesting comparison is between round two and three. Introducing the platform and increasing the PCI from 47,8 to 88,4 in round three resulted in 118,3% increase in productivity and 31% reduction in failure rate. The experiment was executed without any disturbances and the data collected is believed to clearly reflect the number of cars produced and the defects.

4. Discussion

Sources to data uncertainty are mainly the high level of manual typing included in the experiment. Customers, Team Managers and Suppliers entering data in Google Sheets were during each round constantly working to ensure correct data were filled in. Mistakes could not be avoided. However, the accuracy of number of cars produced and number of defects logged is believed to be high. To check the accuracy, teams were after each round instructed to report their accumulated cash, which was then checked with the data entered in the sheets. Calculates showed how much cash each team should have based on the entered data. Discrepancy between the reported cash in hand and data from the system was 3,5%. Thus, it is assumed that the data entered is of sufficient quality to support our conclusions.

A learning effect should be considered when evaluating the results of the experiment. To some extend the higher output in round three can be the result of teams becoming better at assembling cars. However, running round one should ensure that teams already in round two were familiar with the assembly procedures, thus limiting the effects of experience in round two and three. From the collected data, it is possible to observe how assembly time for each car produced changes over the duration of the experiment. Comparing assembly times between rounds for individual cars and for all teams showed, that teams went from an average of 135s in round one to 261s in round two and 185s in round three. The increase from round one to two is assumed to be the result of increased product variance. As assembly time in round three on average are still higher than round one, we argue that the reduction from round two to three is due to the induction of the product platform.

The experiment is a simplification of a real world context. Industrial companies will often have portfolios with higher complexity i.e. number of variants, more complex products, complex manufacturing processes and extensive supply chains. Achieving a PCI above 88% without compromising the ability to satisfy customer requirements can be difficult. However, with a complex portfolio, the potential for harvesting benefits through incremental improvements of the PCI is present. The results of the experiment should be seen as an indication of the potential benefits. If, for example, specific components or functional units are critical for product quality, increasing commonality here, can, as indicated in the experiment, support a significant quality improvement. Further research is needed to quantify the effects of increased PCI in an industrial context. However the difficulty of doing this justifies the simplified and experimental approach applied in this paper. The simplification and the possibility to exclude noise existing in a company context are believed to be the strengths of the experiment. This allows simulating some of the actual effect of increased product commonality.

5. Conclusions

The experiment showed that increasing the Product Line Commonality Index allowed the teams to more than double the output of their "factories". Furthermore, a reduction of product defects of 30% was observed. However, effects of increased PCI are assumed to be more modest in a real world context, as it is difficult to reach PCI levels as high as seen in the experiment. As LEGO bricks were used, each having the same manufacturing methods and using the same materials, changing the physical orientation of bricks and limit the use of different bricks will increase the PCI significantly. Thus, the outcome shows significant improvement to productivity and product quality and this is when only considering 3 product variants (round 2 and 3) and simple products consisting of approximately 25 components and 8 main functional units. Considering an industrial context, product complexity and number of variants will often be much greater. Thus, a smaller increase in PCI across a high number of variants can have a larger impact. Based on the results of the experiment we conclude, that introducing a product platform and increasing PCI have a significant impact on assembly productivity and product quality.

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