

THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Platform Design for Producibility

Early-Stage Modeling and Assessment Support

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Cover Illustration:

A depiction of design-production responsiveness:
the ability to act quickly to changing conditions
in and across design and production domains.

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PREFACE

Approx. 12 years ago: night shift at a vehicle sub-supplier.

An assembly line for vehicle seats was nearly up and running. A contract with a vehicle manufacturer made it possible for a certain sub-supplier to increase its turnover significantly.

The workers in the production plant consisted of people of different ages, with different backgrounds and experiences. Most of them wanted nothing but receiving their paycheck each month to make a living.

I was 20 years old and had no experience of assembling vehicles. I had little responsibility but was determined to undertake my tasks and do a good job. When the vehicle seats were assembled, each seat was inspected for quality flaws, adjusted, approved, packaged and finally sent off to the vehicle manufacturer. At vehicle manufacturer, the seats were mounted onto the vehicle. My job was to inspect the seats for quality flaws, adjust small deviations and approve them before they were sent to the vehicle manufacturer.

Conveyor belts, lifting tools and advanced screwdrivers were installed, the assembly sequences were set, the workers were trained, and the first production series were initiated. In this production ramp-up phase, a producibility failure was detected. The seats did not fit into the vehicle because the diameter of a hole in the frame of the seat, with the function of fixating the seat in the vehicle, was too small to mount the rod into the hole. Over hundreds of seat frames were already produced. Scrap them, make a redesign and produce new seat frames would delay the complete assembly at the vehicle manufacturer. Such a delay would increase cost significantly. A production plant with hundreds of paid workers, installment of thousands of machinery and large buildings do produce high costs.

The producibility failure was created during the design stages. The cause of the problem was a design modification made at the vehicle manufacturer that was never communicated to the sub-supplier. The diameter of the rod in the vehicle was modified to convey loads produced during a potential vehicle crash. The hole in the frame was never adjusted to meet the design modification. A decision was taken: to prevent costly delays, the inferior seat frames had to be quickly remanufactured.

A few colleagues and I were redistributed to an empty industrial building with large tables, drilling machines, and numerous containers filled with roughly 30 seat frames in each container. Our job was to remanufacture the inferior seat frames. The process looked like this: a frame was picked up from the racking, carried and placed on top of a table. A drilling machine was positioned with the tip of the drill into the small hole. Metal splinters fluttered as the diameter of the hole was expanded. The frame was turned 180 degrees and the drilling operation was repeated. Remanufactured frames were stacked into an empty container, while new frames were picked up and the remanufacturing process was repeated.

This thesis concerns issues related to the above experience. The main purpose of the research presented is to devise strategies, models, methods and tools that can support engineers from both design and production in making informed design decision and reduce the risk that modifications of product designs, the production configurations or both occur during late stages when the cost to modify becomes excessive.

Engineer

[en-juh-neer]

Noun

A person who designs, builds, or maintains engines, machines, or structures.

Oxford dictionaries

A person whose job is to design or build machines, engines, or electrical equipment, or things such as roads, railways, or bridges, using scientific principles.

Cambridge dictionaries

A person trained and skilled in the design, construction, and use of engines or machines, or in any of various branches of engineering.

Dictionary.com

- a:** A designer or builder of engines.*
***b:** A person who is trained in or follows as a profession a branch of engineering.*
***c:** A person who carries through an enterprise by skillful or artful contrivance.*

Merriam-Webster

Someone who does precision guesswork based on unreliable data provided by those of questionable knowledge.

See also: wizard, magician

Unknown

ABSTRACT

In industry, platforms are commonly adopted to reduce unique parts among a variety of distinct product variants, which have proven to be cost-effective within a single platform lifecycle. However, when the platform becomes obsolete or modifications are required to capture changing customer and production needs and requirements, manufacturers often spill tears over the time-consuming and costly processes of reusing and adapting the current platform structure into new. In design, such a platform structure of parts is rigid and often characterized by redundant data and weak relations among and across product variants and existing production machinery. To improve the ability to reuse design and production information for assessing new concepts more quickly, non-rigid platform representations of product concepts and existing production machinery are necessary but not clarified in literature and rarely implemented in industry.

In this thesis, research studies have therefore been conducted to (1) investigate how early-stage information about a variety of products and existing production machinery can be represented to improve design-production responsiveness, and (2) develop methods and tools to model and generate a set of product-production alternatives as a basis for producibility assessments. A number of engineering case studies have been prepared by researchers and industrial specialists. Data, related to product and production variety and their mutual constraining factors, have been collected by interviewing industrial specialists, as well as examining corporate documents of both product design prerequisites and capabilities in production. The engineering case studies prepared have supported the creation of new knowledge and been used to demonstrate the usefulness of the improved models, methods and tool devised supporting platform design for producibility.

As opposed to rigid parts, findings show that platform entities can be represented as reusable and adaptable system objects containing early-stage information of product variety, existing production resources and processes. This information mainly consists of a common product-production structure of relations among functional requirements, design solutions, mutual constraining factors and target values. By creating a complementary producibility system, including rule-based and simulation-based models, early-stage producibility assessments of product concepts can be supported. Findings emphasize the dynamic consideration of producibility during the platform design as customer and production needs and requirements frequently change.

By employing the early-stage modeling and assessment support devised, manufacturers can (1) represent product and production variety as reusable and adaptable system objects with links to producibility constraints, available over generations of products and production systems and (2) dynamically and concurrently model, generate and assess product-production alternatives under producibility constraints during early design stages as a basis for putting inferior alternatives aside until new information becomes available. Theoretically, the number of costly and time-delaying late-stage modifications of product designs, production configurations or both can be reduced. However, to validate and generalize these hypothetical effects, they need to be measured in future studies.

Keywords: Mass customization, Variety, Platform design, Set-Based Concurrent Engineering, Reuse of design and production information, Producibility assessment, Systems engineering, Enhanced function-means modeling.

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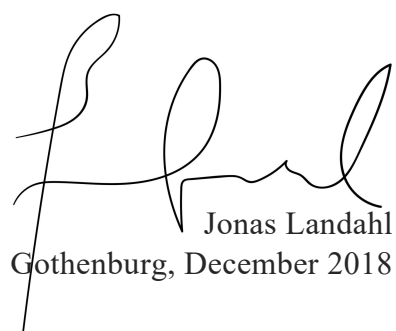
Supervisor Emeritus Professor Hans Johannesson: your commitment, counsel and belief in me are the main reasons for my feat. For this, I am ever grateful.

I would like to thank my co-supervisors Professor Ola Isaksson and Associate Professor Dag Bergsjö for contributing my progress through supportive advice. Some special thanks go to my former co-worker and friend PhD Christoffer Levandowski for the support, especially during times of doubt. Your patience and cheerful attitude have been invaluable. I also want to thank Professor Rikard Söderberg for making my research project possible through the infrastructure of the Wingquist Laboratory at Chalmers. Thank you, Rikard. Special thanks to Associate Professor Roger Jianxin Jiao for hosting me at the Design Systems Engineering research lab at Georgia Tech (Atlanta, GA) and offering helpful insights during our fruitful collaboration.

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Jonas Landahl
Gothenburg, December 2018

APPENDED PUBLICATIONS

The following publications are used to underpin the research presented in this thesis.

- Paper A.** Landahl, J., Levandowski, C., Johannesson, H., Söderberg, R., Wärmefjord, K., Carlson, J. S., Kressin, J., Isaksson, O., Vallhagen, J. (2016). *Using Product and Manufacturing System Platforms to Generate Producible Product Variants*. 6th CIRP Conference on Assembly Technologies and Systems – CIRP CATS 2016, May 16-18, Gothenburg, Sweden.
- Paper B.** Landahl, J., Levandowski, C., Johannesson, H., Isaksson, O. (2016). *Assessing Producibility of Product Platforms Using Set-Based Concurrent Engineering*. 23rd ISPE International Conference on Transdisciplinary Engineering – TE 2016, October 3-7, Curitiba, PR, Brazil.
- Paper C.** Johannesson, H., Landahl, J., Levandowski, C., Raudberget, D. (2017). *Development of Product Platforms: Theory and Methodology*. Concurrent Engineering: Research and Applications (CERA), (25)3, pp. 195-211.
- Paper D.** Landahl, J., Madrid, J., Levandowski, C., Johannesson, H., Söderberg, R., Isaksson, O. (2017). *Mediating Constraints across Design and Manufacturing Using Platform-Based Manufacturing Operations*. 21st International Conference on Engineering Design – ICED 2017, August 21-25, Vancouver, Canada.
- Paper E.** Landahl, J., Johannesson, H. (2018). *Product Variety and Variety in Production*. 15th International Design Conference – DESIGN 2018, May 21-24, Dubrovnik, Croatia.
- Paper F.** Landahl, J., Jiao, J. R., Madrid, J., Söderberg, R., Johannesson, H. (2018). *Concurrent Platform Modeling for Dynamic Product-Production Reconfiguration*. Concurrent Engineering: Research and Applications (CERA) (submitted).
- Paper G.** Madrid, J., Landahl, J., Johannesson, H., Söderberg, R., Isaksson, O., Löf, J. (2018). *Mitigating Risk of Producibility Failures in Platform Concept Development*. 31st Congress of the International Council of the Aeronautical Sciences – ICAS 2018, September 9-14, Belo Horizonte, MG, Brazil.

WORK DISTRIBUTION

The work in terms of writing, developing initial ideas, collecting data, producing core findings and commenting have been distributed among authors of each paper appended in accordance with the following.

- Paper A.** **Landahl, J.** was lead author of the paper and Levandowski, C. wrote sections. The initial ideas were formed by Johannesson, H., Söderberg, R., Wärmefjord, K., Carlson, J. S., Isaksson, O., and Vallhagen, J. Data were collected by **Landahl, J.** and Levandowski, C., whereas the core findings were created by the former two, as well as Kressin, J. and Wärmefjord, K. All authors provided comments of the full paper.
- Paper B.** **Landahl, J.** wrote the paper. The author formed the initial ideas of the paper with certain guidance from Levandowski, C. Data were collected by **Landahl, J.** The core findings were produced by **Landahl, J.**, whereas all authors provided comments of the full paper.
- Paper C.** **Landahl, J.** was lead author of the paper. Johannesson, H., Levandowski, C., Raudberget, D. wrote sections of the paper. The initial ideas were corroborated among Johannesson, H., Levandowski, C., Raudberget, D. and **Landahl, J.** Data related to the aerospace industry case were collected by Levandowski, C. and **Landahl, J.** Data related to the automotive industry case were collected by Johannesson, H. and Raudberget, D. Data related to the power industry case were collected by Johannesson, H. The core findings were created by **Landahl, J.** and Levandowski, C., whereas comments were provided by all others.
- Paper D.** **Landahl, J.** was lead author of the paper, while Madrid, J. wrote sections. The former two instigated the initial ideas, collected the data, as well as produced the core findings. Levandowski, C., Johannesson, H., Söderberg, R., Isaksson, O. provided comments of the full paper.
- Paper E.** **Landahl, J.** wrote the paper, dug out the idea, collected the data and produced the core findings. Johannesson, H. provided comments.
- Paper F.** **Landahl, J.** wrote the paper. The initial ideas were proposed by **Landahl, J.** and discussed among Jiao, J. R., Madrid, J., Söderberg, R., Johannesson, H. Data were collected by **Landahl, J.** and Madrid, J., whereas the core findings were produced by **Landahl, J.** Comments of the full paper were provided by all authors.
- Paper G.** Madrid, J. was lead author of the paper, while **Landahl, J.** wrote sections. The former two instigated the initial ideas, collected the data, as well as produced the core findings. All authors provided comments of the full paper.

ADDITIONAL PUBLICATIONS

The following publications are related to the research presented in this thesis, but do not fully contribute to the findings.

Landahl, J., Bergsjö, D., Johannesson, H. (2014). *Future Alternatives for Automotive Configuration Management*. 12th Annual Conference on Systems Engineering Research – CSER 2014, March 20-22, Redondo Beach, California, USA.

Stenholm, D., Landahl, J., Bergsjö, D. (2014). *Knowledge Management Life Cycle: An Individual's Perspective*. 13th International Design Conference – DESIGN 2014, May 19-22, Dubrovnik, Croatia.

Landahl, J., Raudberget, D., Johannesson, H. (2015). *Assessing System Maturity of Interacting Product and Manufacturing Alternatives Before Early Technology Commitment*. 24th Annual International Association for Management of Technology Conference – IAMOT 2015, June 8-11, Cape Town, South Africa.

Stylidis, K., Landahl, J., Wickman, C., Johannesson, H., Söderberg, R. (2015). *Structuring Perceived Quality Attributes for use in the Design Process*. 20th International Conference on Engineering Design – ICED15, July 27-30, Milan, Italy.

Isaksson, O., Arnarsson, I., Bergsjö, D., Catic, A., Gustafsson, G., Kaya, O., Landahl, J., Levandowski, C., Malmqvist, J., Müller, J., Raja, V., Raudberget, D., Stenholm, D., Ström, M. (2017). *Trends, Observations and Drivers for Change in Systems Engineering Design*. 21st International Conference on Engineering Design – ICED 2017, August 21-25, Vancouver, Canada.

Bokrantz, J., Landahl, J., Levandowski, C., Johannesson, H., Skoogh, A., Isaksson, O. (2017). *On the Interplay between Platform Concept Development and Production Maintenance*. 21st International Conference on Engineering Design – ICED 2017, August 21-25, Vancouver, Canada.

Gong, X., Landahl, J., Johannesson, H., Jiao, R. (2017). *Simulation-Driven Manufacturing Planning for Product-Production Variety Coordination*. 2017 International Conference on Industrial Engineering and Engineering Management – IEEM 2017, December 10-13, Singapore, Singapore.

Landahl, J., Panarotto, M., Johannesson, H., Isaksson, O., Löf, J. (2018). *Towards Adopting Digital Twins to Support Design Reuse during Platform Concept Development*. 12th Biannual Conference NordDesign2018 – NDES 2018, August 14-17, Linköping, Sweden.

Müller, J. R., Isaksson, O., Landahl, J., Raja, V., Panarotto, M., Levandowski, C., Raudberget, D. (2018). *Enhanced Function-Means Modelling Supporting Design Space Exploration*. Journal of Artificial Intelligence for Engineering Design, Analysis and Manufacturing (AIEDAM) (submitted).

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LIST OF ABBREVIATIONS

3D – Three-Dimensional Space	ICT – Information and Communication Technology
AM – Additive Manufacturing	IF – Interface
BOM – Bill of Materials	iib – is influenced by
BMPCE – Best Manufacturing Practices and Center of Excellence	IoT – Internet of Things
C – Constraint	ipmb – is partly met by
CAD – Computer Aided Design	isb – is solved by
CAE – Computer Aided Engineering	IT – Information Technology
CAM – Computer Aided Manufacturing	iw – interacts with
CAT – Computer Aided Tolerancing	KBE – Knowledge Based Engineering
CAPP – Computer Aided Production Planning	PDM – Product Data Management
CAX – Computer Aided Technologies	PLM – Product Lifecycle Management
CC – Configurable Component	PMC – Platform Modeling and Configuration
CCM – Configurable Component Modeler	QFD – Quality Function Deployment
CE – Concurrent Engineering	rf – requires function
CI – Control Interface	RMS – Reconfigurable Manufacturing Systems
CIM – Computer-Integrated Manufacturing	RQ – Research Question
CPM – Concurrent Platform Modeling	SBCE – Set-Based Concurrent Engineering
CS – Composition Set	SE – Systems Engineering
DP – Design Parameter	SysML – Systems Modeling Language
DR – Design Rationale	ToD – Theory of Domains
DS – Design Solution	TRS – Turbine Rear Structure
DfA – Design for Assembly	TTS – Theory of Technical Systems
DfM – Design for Manufacturing	UML – Unified Modeling Language
DfMA – Design for Manufacturing and Assembly	VP – Variant Parameter
DfX – Design for Excellence	VPV – Variant Parameter Value
DRM – Design Research Methodology	
DSM – Design Structure Matrix	Authors of the Papers Appended:
et al. – et alii (and others)	CL – Christoffer Levandowski
EF-M – Enhanced Function-Means	DR – Dag Raudberget
F-M – Function-Means	HJ – Hans Johannesson
FEM – Finite-Element Method	JLö – Johan Lööf
FMEA – Failure Mode and Effect Analysis	JSC – Johan S Carlson
FMS – Flexible Manufacturing Systems	JV – Johan Vallhagen
FR – Functional Requirement	JK – Jonas Kressin
GBOM – Generic Bill of Materials	JL – Jonas Landahl
GBOMO – Generic Bill of Materials and Operations	JM – Julia Madrid
IA – Interaction	KW – Kristina Wärmefjord
iaio – is an implementation of	OI – Ola Isaksson
icb – is constrained by	RS – Rikard Söderberg
	RJJ – Roger Jianxin Jiao

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“It is the pervading law of all things organic and inorganic, of all things physical and metaphysical, of all things human and all things superhuman, of all true manifestations of the head, of the heart, of the soul, that the life is recognizable in its expression, that form ever follows function. This is the law.”

– Louis Sullivan

INTRODUCTION

Products are designed and produced by people for people. In many cases, products are even designed to be utilized to produce other products; for example: to tighten a bolt in a car engine, a device can be designed and produced. One such device is the monkey wrench. Products can also be designed at diverse levels of functionality, performance and quality which can be traced back to the customer needs. Even though the needs of the customers can be met by creating product design solutions with intended behavior and optimized performance, the product designs may very well turn out to be inferior or non-producible during the production stage. This phenomenon is put to the test while designing a variety of products that meet a wide range of customer needs.

1.1 BACKGROUND

On the consumer market today, you have an abundance of choices; you can for example choose from over hundred types of coffee blends where each blend comes at a certain price and is said to have a distinct character. Coffee is all alike for some people, different for others. While coffee producers do profit from the consumption of coffee drinkers, they can strive for profitability by adopting different strategies. Some producers aim at meeting customers that care about price and sees coffee like a commodity, while other producers aim at meeting a wide range of customer needs by differentiating the coffee experience by such factors as taste, quality, sustainability profile, and brewing process.

A well-known success story that proves that it can be profitable to meet a wide range of customer needs with a variety of offerings is the Sony Walkman story (Sanderson and Uzumeri, 1995). Because music moves most people, Sony designed a portable music experience for people with low quality demands as well as for audiophiles with high quality demands. From 1980 to 1990, Sony was able to increase sales by meeting different customer needs with a range of 160 variants of cassette players while utilizing production resources effectively to reduce total cost (Meyer and Utterback, 1992).

Since then, the demand for differentiated solutions has increased on different markets and many industries now strive to improve their ability to customize solutions to meet different customer needs by developing and producing a variety of offerings. For instance, on the car market today a customer can mix pre-designed parts into a distinct car among a vast variety of offerings to reach certain performance, quality, price and other customer values. The magnitude of this vast variety of car variants can be symbolized by an example from 2006, when Ford provided customers with approximately 3.8 million variants based on model type, exterior/interior design, add-on packages, etc. (Simpson et al., 2006). Similarly in 2008, the BMW Group reached almost a quintillion number of variants with their 7 Series cars (Hu et al., 2008).

While the strategy of developing and producing a variety of offerings to meet a wide range of customer needs can be profitable on the business-to-consumer market, this same strategy can also be profitable on the business-to-business market; for example, for an aircraft manufacturer to serve an airline fleet with a variety of aircraft sizes, different types and performances of aero engines are required. Whereas aircraft manufacturers compete to meet the needs of airline companies, different aircraft manufacturers can share and request the design and production competence of the same aero engine sub-supplier.

Because of the functionally integrated nature of aero engine components and sub-systems, the sub-supplier is typically unable to just mix pre-designed parts into distinctive aero engines like car manufacturers do. The parts need much adaptation to fit different engine types, sizes, as well as the high safety and performance requirements posed. While the needs and requirements are prone to change during the product development process, those aero engine sub-suppliers that can adapt their operations quickly in and across design and production can also be increasingly competitive in signing lucrative contracts with several aircraft manufacturers. In this thesis, the interplay of design and production is termed *producibility**.

Even though many manufacturers from differing industries now strive to target a wide range of customer needs with customized solutions, this has not always been a goal or even a possibility because of the lack of supportive technologies in design and production.

*** Producibility** is *“the relative ease by which a product can be manufactured as measured in yield, cycle times, and the associated costs of options in product designs, manufacturing processes, production and support systems, and tooling.”* (BMPCE, 1999) p. 3. Priest and Sanchez (2001) p. 247 state that *“producibility is a discipline directed toward achieving design requirements that are compatible with available capabilities and realities of manufacturing.”*

1.1.1 *A Glimpse of the Technological Yesteryear and into Industry 4.0*

In Europe and the U.S. around 1800s, rural societies became industrial. Iron and textile industries advanced. Central for this first industrialization was the steam engine technology.

From around 1870 and 1914, the second round of industrialization occurred. Steel, oil and electricity enabled mass production of such products as the telephone, light bulb, phonograph and internal combustion engine. The first affordable car was introduced to serve the masses. Henry Ford, the man behind this idea, proclaimed that you could pick any color of the car—as long as it was black. This paradox came out as a joke because it would be too expensive to customize the car. Mass production of cars meant an extensive price drop compared with the established car market. This price drop was possible by means of high-volume assembly production propelled by a specialized assembly work force that stimulated the high utilization of expensive production machinery; thus, the production investments could exceed the revenues gained from the high car volume produced and sold. This high utilization of expensive production machinery is commonly termed economies of scale in production. Because of the extensive application of mass production in various industries, many manufacturers started to profit from economies of scale; thus, prices of goods fell, and worker salaries went up. Thus, industrialized economies were booming.

During the 1980s and approx. until the last decade, the third round of industrialization took place. The Internet was introduced. The advancements in computing and Information and Communications Technology (ICT) enabled increased digitalization of analogue solutions that support virtual customization of solutions. The transition into Industry 4.0 now prevails and technology breakthroughs have emerged from a number of fields, including robotics, artificial intelligence, nanotechnology, quantum computing, biotechnology, IoT, 3D printing, etc.

In Ford's mass production paradigm, offering a variety of variants while benefiting from economies of scale in production was technologically impossible. Yet today, after over hundred years of improvements, production systems have become increasingly efficient, flexible, and autonomous towards supporting mass customization.

1.1.2 *Customization, Variety and Complexity*

Customization is the action of modifying something to suit a particular individual or task (Oxford Dictionaries, 2018). The industrial use of customization typically refers to the ability to meet a range of customer needs by providing them with distinctive offerings.

Variety describes a range of things of the same general class that are distinct in character or quality. A thing is an object to which one needs not, cannot, or does not wish to give a specific name (Oxford Dictionaries, 2018). In botanical nomenclature, variety is a taxonomic rank below that of species and sub-species but above that of form. In product development, variety can be represented by a space that holds all possible design alternatives that can meet the bandwidth of requirements posed (design space). The common industrial use of variety is the range of product variants that can meet (1) a number of distinct customer needs: the product variety, or (2) different market segments: the product families. A family is a common concept to describe a group of related things (Oxford Dictionaries, 2018). Managing a product variety, or family, is a complex endeavor (ElMaraghy et al., 2012), and several challenges of product variety management have been identified (ElMaraghy et al., 2013).

A common variety-related concept is assortment. Variety can be regarded as the positive aspect of assortment; for example, an assortment of coffee can encompass a wide variety of blends. When determining an assortment, more variety is typically desired because high variety increases the likelihood that a variant among the variety can meet the needs of any given customer. The negative aspect of assortment is complexity. Too much variety increases complexity which affects decision-making. Complexity can cause a customer to delay or refuse to make a decision (Townsend and Kahn, 2013) because of confusion about the differentiation among variants (Huffman and Kahn, 1998). In engineering nomenclature, complexity typically concerns technical systems. A complex system holds two main characteristics: (1) high plurality and diversity of entities encompassing the system and (2) a high degree of interdependence and dynamics across entities (Bhise, 2013). This description of complexity may be blunt, yet can be further explored (ElMaraghy et al., 2012); however, in this thesis, the concept of complexity is not elaborated upon.

1.2 PROBLEM CLARIFICATION

In today's intensified global competition among manufacturers, meeting a wide range of customer needs with increased product customization and variety can be profitable. Mass customization is an aspiring paradigm employed to serve customers with customized products at high quality, fast delivery and at the price of standard products (Pine, 1993, Simpson, 2004, Jiao et al., 2007b, Ferguson et al., 2013, Tseng and Hu, 2014). However, customization based on these criteria is difficult to achieve. There are often high uncertainties concerning future market demand, product mix and volume (Jain et al., 2013), which is why there is a need to be responsive to these changing market conditions in and across all functions of a company, from market through design, production and delivery (Zipkin, 2001, Ferguson et al., 2013). To be responsive means the quality of reacting quickly and positively (Oxford Dictionaries, 2018). Those manufacturers that can be responsive to changing market conditions in and across design and production, while maintaining high product quality and minimized cost, can be well-equipped to move ahead of competitors.

While competitiveness is affected by acting quickly on changing market conditions, many manufacturers fail to be responsive in and across design and production. Either they commit to production technologies early in design when product information is uncertain at the risk of over-constraining the product design space, or they wait for designs to be finalized before assessing their producibility at the risk of over-designing and ending up with product variants that become inferior in production. The problem with these static interventions is that late modification of detailed product designs, production configurations or both can lead to excessive cost and delay the time-to-market.

1.2.1 *Introduction to Product Development*

Product development is a complex process characterized by design iterations involving a multitude of stakeholders and an immense amount of data from a variety of sources. The process is typically structured in a way that supports design engineers in solving a single design problem through the stages provided in Figure 1: planning, concept development, system-level design, detailed design, testing and refinement and production ramp-up.

1.2.1.1 Solving Many Different Design Problems Simultaneously

While solving a single design problem can be demanding, solving many different design problems simultaneously increases the pressure to streamline and coordinate the processes both in and across design and production. A common way of dealing with multiple variants is to employ platform design. The most common platform design approach suggests creating a pre-defined architecture of parts and standardized interfaces that are shared among a variety of products (Meyer and Lehnerd, 1997). An architecture postulates the complex or carefully designed structure of an artifact (Oxford Dictionaries, 2018). Product architecture is defined as “*the scheme by which the function of a product is allocated to physical components*” (Ulrich, 1995). Commonly, this scheme includes the arrangement of functional entities, physical components, and the specification of standardized interfaces (Fixson, 2007). Standardizing interfaces can enable relatively independent design of components or modules with minor effects on other modules of the product, also known as modularization (Baldwin and Clark, 1997). However, while product modules are modified because of changing market conditions, the modifications are likely to propagate and affect other modules, causing a high number of modifications (Sosa et al., 2007). In fact, modifications made to product modules do not only propagate to other product modules but do also propagate downstream to provoke modifications of the production system (ElMaraghy et al., 2012).

The common view of platforms and modularization suggest (1) increasing sales by designing distinct product variants that meet different customer needs and (2) reducing cost by maximizing the number of common parts shared among variants to provide production with a high volume per part and increase utilization of expensive production machinery. In striving to meet a wide range of changing customer needs, Muffatto and Roveda (2000) suggest that both distinctiveness and commonality may be increased by employing flexible architecture; see Figure 2. Being flexible refers to the ability to be easily modified (Oxford Dictionaries, 2018). Thus, flexible architecture accommodates representations of entities that can be easily modified. While attempting to serve mass customization, architecture of rigid and tangible parts may therefore be inferior as opposed to non-rigid, i.e. resilient or flexible, and intangible entities. A concept that can accommodate such intangible entities is system architecture. “*System architecture is an abstract description of the entities of a system and the relationships between those entities.*” (Crawley et al., 2004).

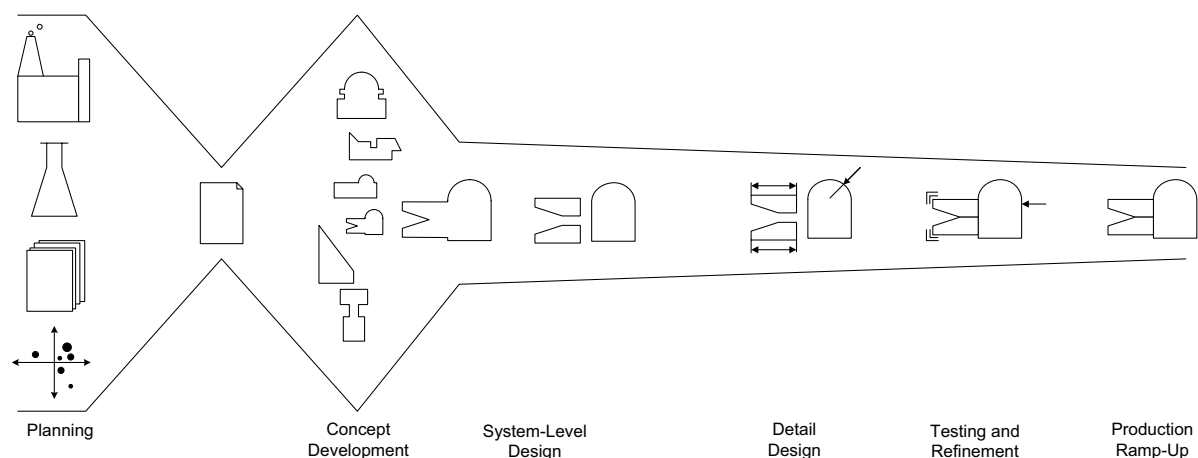


Figure 1. A generic product development process (Ulrich and Eppinger, 2012)

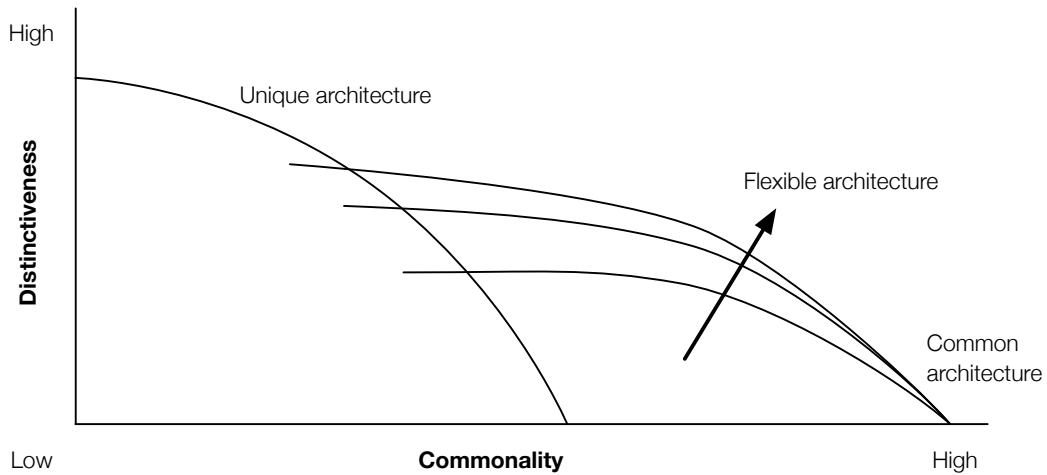


Figure 2. Different architecture types, and their respective effects on distinctiveness and commonality (redrawn from Muffatto and Roveda (2000), adapted from Sheriff (1998))

Yet, designing architectures accommodating many variants pose challenges beyond enabling flexibility. To efficiently lay down architectures of many product variants, Wheelwright and Clark (1992) emphasize that production needs and capabilities must be combined with customer needs and design requirements.

1.2.1.2 Early Design Stages

Early design stages are characterized by design freedom and great uncertainty. Uncertainty is defined as the gap between the amount of information required to perform a given task and the amount of information already possessed (Galbraith, 1973). During the early design stages exploration of new concepts can be conducted at low cost; however, little is known about the concepts to be developed, which makes it difficult to evaluate their caliber.

Reducing uncertainty: To reduce the uncertainty posed during early stages, reusing past designs in new design problems is useful (Khadilkar and Stauffer, 1996, Ong et al., 2008). A well-reputed design approach that supports reuse is platform design. Current commercial design tools that are used during platform design often suggest using parametric geometry models in CAD software. Parametric design basically means dealing with the structure and dimensions of a design as parameters and allowing them to change (Roller, 1991). However, commercial design tools often lack support during the conceptual stages before the embodiment of a design exists. CAD models are typically both too detailed and too rigid to serve the pace necessary for manufacturers to act quickly in response to changing market conditions. A key challenge of reusing past designs in new design problems concerns the modeling and simulation techniques that can represent the information available during early design stages.

Modeling information available: The input of early design stages typically consists of a mix of designer visions, previously designed Computer-Aided Design (CAD) models or alike, a broad range of data collected related to customer needs, as well as other important multidisciplinary information such as from production. Capturing information from both design and production require engineers from the two domains to work as a team (Calkins et al., 1989). Wang et al. (2002) and Chandrasegaran et al. (2013) among others emphasize that there is a lack of collaborative design tools that can support cross-disciplinary decisions

during early design stages. Among many cross-disciplinary challenges, design engineers lack support to systematically identify product concepts that may become inferior or non-producible in production. Because design and production disciplines are often separated in terms of literacy, development stage and geographic location, platform design is often characterized by poor coordination and collaboration across design and production (Jiao et al., 2007a). This separation often results in weak relations and redundant data among and across variants and production systems, which is why the ability to develop new variants based on previous ones is seldom well supported during early design stages (ElMaraghy et al., 2013, Alblas and Wortmann, 2014).

Assessing producibility of many different concepts: In the context of solving many different design problems simultaneously, a number of design solutions can be conceived. Design engineers typically rely heavily on assumptions while making early design decisions towards selecting final concepts, which is why only a few design solutions are selected, detailed, and modified in iterations to finally prove to be producible in production. Modifying designs and adapting them for production capabilities during late design stages is both time-consuming and costly. Glaessgen and Stargel (2012) state that heuristic design philosophies, physical testing and common assumptions made in early design will likely be inferior when addressing the extreme requirements of the future.

1.2.2 Research Scope and Aim

According to Ferguson et al. (2013) *“the expansion of the mass customization paradigm is dependent on developing rigorous models and tools that support designers throughout the mass customization product development process.”* In the context of product development, Lange and Imsdahl (2014) suggest that the product development process can be seen as the tactical vehicle to convey a business strategy and strategic objectives. The research scope of this thesis therefore comprises an aim to support two industrial dimensions: business strategy and strategic objectives by means of a tactical vehicle to meet the former two.

In Figure 3, the overall context and research scope of this thesis is illustrated. The contribution aspires to **support the business strategy of mass customization**, which implies meeting a wide range of changing customer needs by designing and producing a variety of offerings for a fluctuating market demand, product mix and volume. The strategic objective concerns **improving the ability to reuse and adapt product concepts and existing production configurations quickly in accordance with changing market conditions**. The tactical vehicle is *platform design*.

Platform design for producibility refers to reusing information of previously developed designs and existing capabilities in production while solving many different and new design problems. Platform design for producibility, and concepts alike, constitute an unexplored niche in engineering research (Simpson, 2004, ElMaraghy et al., 2013, Pirmoradi et al., 2014), which is why this thesis aims to contribute new knowledge within this niche.

1.2.2.1 Research Goal

The goal of this thesis is to create new knowledge within the research niche of platform design for producibility by contributing: (1) models, processes and insights that add to the theoretical base and (2) methods and tools that can support increased design-production

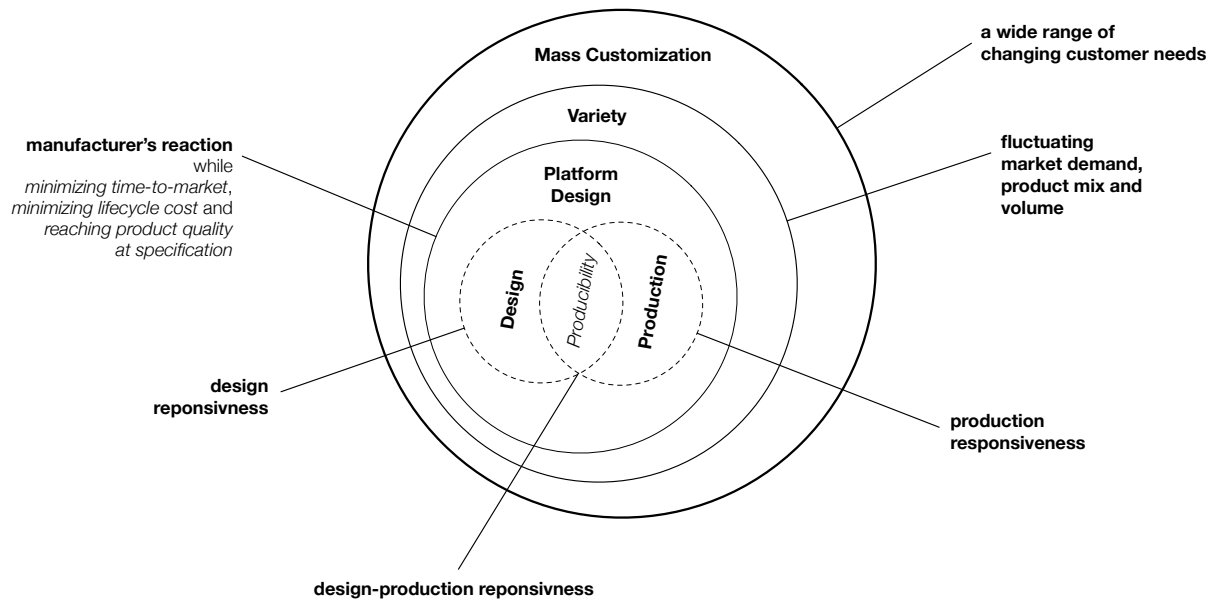


Figure 3. The research niche of main contribution: *Platform design for producibility*

responsiveness by early-stage producibility modeling and assessment. Producibility modeling is the devising, or use, of a representation of producibility. Producibility assessment is the activity of evaluating or estimating the producibility of products using a representation of producibility. By implementing such methods and tools, the number of late modifications of product designs, production configurations or both that are time-consuming and costly may be reduced.

1.2.2.2 Research Hypothesis, Questions and Deliverables

While solving many different design problems simultaneously during the early stages, modeling and assessment support for producibility requires well working coordination and collaboration across design and production, which is why models and methods created need to encompass information from both the disciplines as well as the technical systems invoked. This information needs to represent the interplay of products and production systems using models of low fidelity because of the early-stage support posed. While design processes involve multiple stakeholders, the design support needs to be fitted to engineering experts from both design and production. To propel the research, an hypothesis, two research question and a set of deliverables have been formulated based on the above aim and goal.

Hypothesis. Platforms can be resiliently designed to support early-stage producibility assessments of product concepts that are customized to changing customer needs and a fluctuating market demand.

RQ1) How can early-stage information about a variety of products and existing production systems be represented to support design-production responsiveness building on existing theories and technologies?

D1.1) A literature review

- D1.2) Creation of models and processes that can represent early-stage information of a variety of products and existing production systems
- D1.3) Creation and validation of a platform development methodology that holds functions of a computer software aimed at a group of collaborating engineering users during the platform development stages

RQ2) How can producibility information be generated and assessed to support informed platform design decisions during early design stages?

- D1.1) A literature review
- D1.2) Creation and validation of platform structures and processes that can support the exchange of data and information (representing producibility) across different CAX tools

1.2.3 Delimitations

The design support created targets manufacturers that design and produce complex products and systems; however, the concept of complexity is not elaborated upon in this thesis.

Because of their corporate strategy and the products they develop, mass customization is not likely to work for every company (Ferguson et al., 2013). The design support created as a contribution to this thesis does not specifically target manufacturers that maintain a strategy of meeting customer needs with a standard product adopting single product development and mass production; however, although scale benefits may be lost models, methods and tools created may also be applicable to single product development.

While the implementation of the design support created is sought from all stakeholders (researchers, industrial practitioners, politicians, society, etc.) involved in a research project like this, implementation is for various reasons not necessarily the primary goal of research. The maturity of the research niche is one such reason (reflected in the type of research (Section 3.2)), and the lack of validation of the design support may be another reason (Section 5.2.1). In this research, implementation is simply assimilated by demonstrating the models and methods in industrial cases using realistic data gathered in collaboration with industrial practitioners. The demonstration of findings is to a high degree limited to aerospace application. This does affect the generalizability of the findings, which is discussed in Section 5.2.1.

Organizational aspects do greatly affect implementation of a novel design support; however, these aspects do not receive much attention in this thesis.

Even though this thesis has a clear aim of reducing the common gap across the design and production domains, the production information included mainly support design decisions, which is why the term producibility has been adopted.

In literature, the concepts of “production” and “manufacturing” exist and the notion of the two may differ; however, in this thesis they are considered synonymous. Thus, although producibility and manufacturability may differ in definition, this is not up for any considerable clarification in this piece of research – yet the definitions of producibility presented in Section 1.1 is applied to provide clarification and coherence.

Many important aspects of design, such as sustainability, usability, maintainability, etc., are

excluded to maintain focus on the contribution. There is a wealth of research within these fields respectively, and as a reader of this thesis it is important to note that all these aspects need to be dealt with to achieve extravagant product design. Realistically however, because trade-offs are binding all aspects cannot be fulfilled equally well. In this thesis, extensive trade studies are not provided; however, the findings do contribute to form them.

The design support presented comes with software that supports the practical use of the models and methods prescribed. However, this research has not been focusing on the development of this software; it has rather been a means for validating models and methods.

Mass customization can follow the precondition stated by Ferguson et al. (2013): a product is not produced until the customer places an order. This definition includes the production settings such as make-to-order (Hvam et al., 2008), configure-to-order, and engineer-to-order (Brière-Côté et al., 2010). *“This eliminates the definition of a predefined product family, but allows for platform-based customization.”* (Ferguson et al., 2013).

1.3 OUTLINE OF THE THESIS

The thesis is divided into six chapters. The core content of each chapter is described below:

- 1** introduces the research context, scope and phenomenon studied.
- 2** delves into an assortment of concepts and theories that concern a few enabling factors of responsiveness in and across design and production: (1) design and production integration, (2) flexible and reconfigurable approaches in production, (3) platform design with the focus on reusing product and production information, (4) representations of early-stage design and production information, and (5) existing IT-tools in design.
- 3** provides you with the research approach applied, including framework and methods. The way in which the research was carried out and how findings are validated are presented as transparently as possible.
- 4** presents the core findings extracted from the papers appended. The studies conducted are clarified as far as content, execution, and participant roles are concerned.
- 5** answers and discusses the research questions posed and evaluates the research approach and findings with respect to validity and reliability.
- 6** concludes the findings and discussion and postulates a few key contributions, as well as some areas for future research within platform design for producibility.

2

FRAME OF REFERENCE

This chapter delves into an assortment of concepts and theories that concern a few enabling factors of responsiveness in and across design and production: (1) design and production integration, (2) flexible and reconfigurable approaches in production, (3) platform design with the focus on reusing product and production information, (4) representations of early-stage design and production information, and (5) existing IT-tools in design.

2.1 APPROACHES TO DESIGN AND PRODUCTION INTEGRATION

In large engineering enterprises, product design processes are inherently difficult to coordinate because of the wealth of disciplines and people who collaborate. When designing products, the disciplines that focus on customer needs are often in conflict with groups that concern themselves with parts and production processes, an issue that is even more demanding in platform design because of the many different design problems that need to be solved (Robertson and Ulrich, 1998).

A vast number of approaches have been suggested to emphasize the need to integrate design and production to support more efficient and effective coordination and collaboration. A well-reputed approach is Integrated Product Development (IPD) introduced by Andreassen and Hein (1987), which intertwines marketing, design, and production activities during development stages; see Figure 4.

Another approach that advocates design and production integration is Concurrent Engineering (CE). By adopting CE practices, better performance in product innovation and

quality can be achieved (Koufteros et al., 2001). CE practices emphasize cross-functional integration, early-stage communication with customers as well as suppliers, and the parallel development of products and production systems (Swink et al., 1996). CE is mainly seen as an organizational approach; however, the concurrency can also be reflected in how designs are modeled (Levandowski, 2014).

Zimdars (2003) state that it is possible to be responsive to fast-changing markets by adopting cross-functional integration because information from various functional areas can be efficiently shared among them. Suppliers can be part of such cross-functional team (Parker, 2003), which improve communication of the common interfaces and production processes (Henke et al., 1993). To organize and coordinate the design activities of complex systems among several design teams, the concept of modularization has been introduced (Erixon, 1998, Gu and Sosale, 1999, Gershenson et al., 2004), which means dividing the engineering work by means of modules with standardized interfaces.

Wheelwright and Clark (1992) contrast four different modes of information exchange across upstream and downstream activities, as illustrated in Figure 5. CE emphasizes the importance of accessing a wide range of information from various disciplines during early design stages.

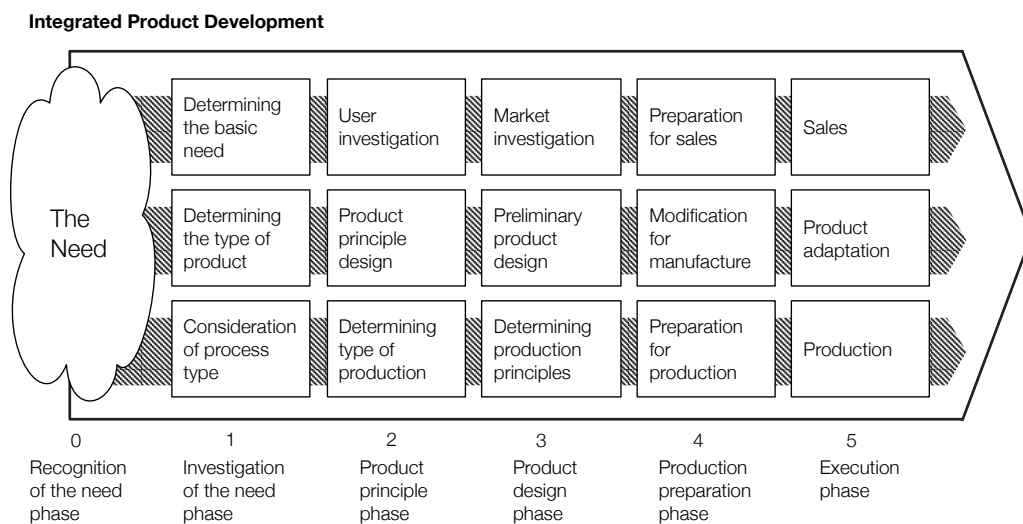


Figure 4. Integrated Product Development (redrawn from Andreassen and Hein (1987))

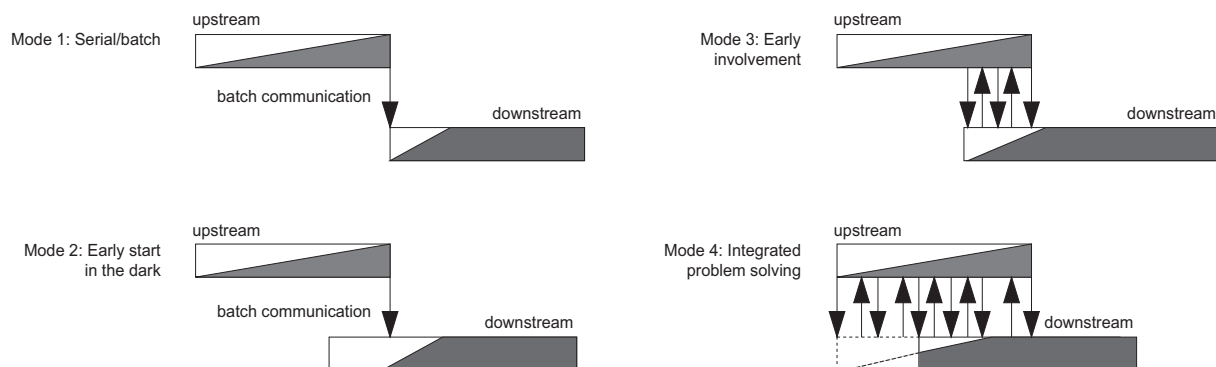


Figure 5. Four modes of information exchange (as drawn in Levandowski (2014), adapted from Wheelwright and Clark (1992))

A design approach that has received a great deal of attention during the last decades is Set-Based Concurrent Engineering (SBCE) (Sobek et al., 1999). Contrary to point-based selection of a solution based on assumptions, set-based design means exploring a broad range of solutions while systematically narrowing the solution space down by eliminating unfeasible regions as information becomes available (Malak et al., 2009). To achieve SBCE, three main principles are advocated: (1) mapping the design space, (2) integrating systems by intersection, and (3) establishing feasibility before commitment. Sobek et al. (1999) summarize SBCE as “*reasoning, developing and communicating about sets of solutions in parallel and relatively independently.*” Bernstein (1998) presents an elaborated five-step process to achieve SBCE and converge parallel working disciplines or systems into a confined solution. These steps are listed below and complement the illustration in Figure 6.

- (1) Disciplines map their individual design space
- (2) Disciplines establish a small region of overlapping design solutions
- (3) Working in collaboration, the overlapping region is expanded by finding a number of solutions that will satisfy the requirements of the combined system
- (4) Alternatives are now starting to be eliminated to further converge the overlapping region
- (5) The solution space is now narrowed until only one or a few feasible solutions remain

To support practical application of SBCE, Raudberget (2010) proposed recommendations to realize the implementation in industry. These recommendations include: avoid design freeze during early design stages, set broad target values of the most important requirements, leave the less important requirements unconstrained, reject alternatives on sound reasons only as soon as alternative information becomes available and finally, base decisions on results of tests, simulations, technical data, trade-off curves or other knowledge. Because of the common aim of reasoning around sets of alternatives, SBCE has been adopted to support platform design with positive effects (Levandowski, 2014).

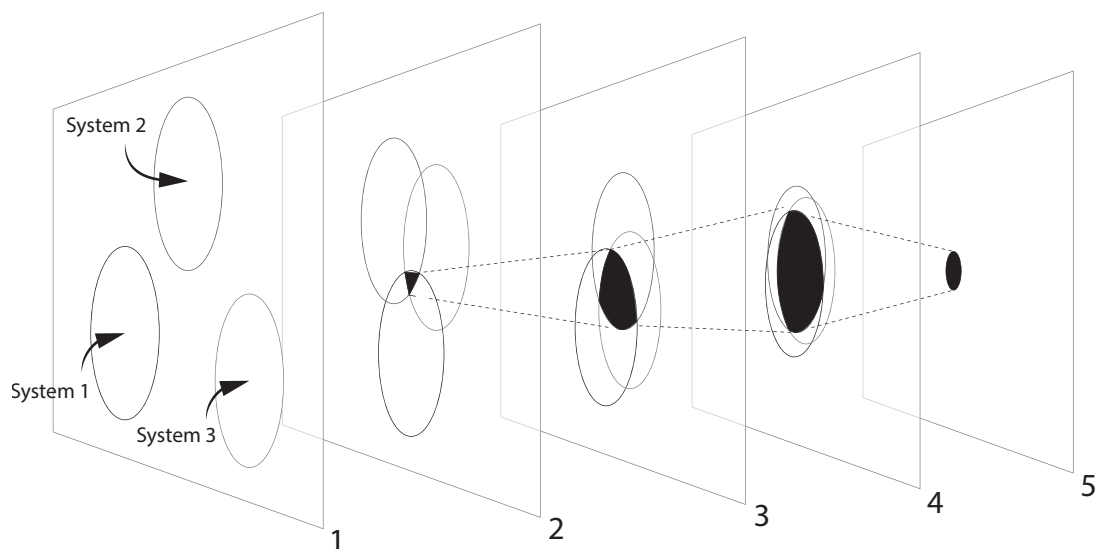


Figure 6. Illustration of a Set-based Concurrent Engineering process (slightly modified from Levandowski (2014), adapted from Bernstein (1998))

2.2 RECONFIGURABILITY AND FLEXIBILITY IN PRODUCTION

To cope with uncertainties regarding future product demand and mix, designing production systems for both hardware and software flexibility is advised (ElMaraghy, 2005). Greater reconfigurability and flexibility in production may solve many of the challenges posed by mass customization (Zipkin, 2001, Tseng and Hu, 2014).

Already in the 1960s, the concept of flexible manufacturing systems (FMS) was introduced to meet industrial challenges, including changes in work orders, production schedules, part programs, and tooling. While many industries started to face an increased demand for a variety of offerings, industry began to experience an enhanced need for flexibility beyond what the FMS could provide; for example, quick changeover across different product variants among a product variety. The concept of modularization of production systems entered the research arena, with work by, for example, Tsukune et al. (1993), Erixon et al. (1996) and Rogers and Bottaci (1997). Koren et al. (1999) later coined the comprehensive theory of Reconfigurable Manufacturing Systems (RMS) around these concepts to support the ever-increasing frequency of product introductions, changes in parts for existing products, large fluctuations in product demand and mix, changes in government regulations (safety and environment), and changes in process technology. Based on these premises, RMS poses five key characteristics (Mehrabi et al., 2000) presented in Table 1. The flexibility of RMS can be considered part of customization which means that the machines are designed around a certain product family (Tseng and Hu, 2014).

The future of production relies on 3D printing and Additive Manufacturing (AM) (Reeves et al., 2011) which aims to meet customers on-demand (Fogliatto et al., 2012, Tseng and Hu, 2014). AM is still an expensive technology and pose many challenges before becoming widely adopted in industry; for example, with AM there is a need to consider a fundamentally different product design. Because of the lack of design principles and production guidelines for AM, research on topics such as design topology optimization and Design for AM (DfAM) is advised (Gao et al., 2015).

Although product customization can be addressed by reconfigurable and flexible production technologies, some customization challenges originate from early product design stages when most influential decisions are made with respect to product functionality, quality, producibility, cost and environmental performance (Gu et al., 2004).

Table 1. Key characteristics of a reconfigurable manufacturing system (Mehrabi et al., 2000)

1. Modularity	<i>Design all system components, both software and hardware, to be modular.</i>
2. Integrability	<i>Design systems and components for both ready integration and future introduction of new technology.</i>
3. Convertibility	<i>Allow quick changeover between existing products and quick system adaptability for future products.</i>
4. Diagnosability	<i>Identify quickly the sources of quality and reliability problems that occur in large systems.</i>
5. Customization	<i>Design the system capability and flexibility (hardware and controls) to match the application (product family).</i>

2.3 MODELS AND METHODS FOR PRODUCIBILITY ASSESSMENT

The incorporation, assessment and decision support of a range of lifecycle aspects can be addressed by the concept of Design for Excellence (DfX) (Bralla, 1996, Holt and Barnes, 2010). In this thesis, the main lifecycle aspect targeted concerns producibility.

Sprung from the notion that the cost of producing a product is largely determined by its design, methods such as Design for Assembly (DfA) and Design for Manufacturing (DfM) have been developed (Boothroyd, 1994).

While DfA is composed of a set of guidelines that can support the ease of an assembly of parts, DfM supports the ease of manufacturing each part of the assembly. Sometimes DfM and DfA are combined into DfMA to serve a more extensive set of guidelines. DfMA consists of guidelines such as reducing part counts, simplifying assembly operations, standardizing parts, and loosening tolerances. An analogous concept to DfMA is Design for Producibility (DfP) (Blanchard and Fabrycky, 1990) which is a systematic methodology that supports the modeling and assessment of functional properties of a product while providing compliance with the available capabilities and realities of the production system (Priest and Sanchez, 2001, Elgh, 2007).

Producibility as a concept has been studied for decades (Torget, 1971, Calkins et al., 1989). As an overarching guideline for the creation of a successful producibility system, the “Best Manufacturing Practices and Center” (BMPCE, 1999) provides a five-step process:

- (1) Establish a producibility infrastructure
- (2) Determine process capability
- (3) Address producibility during conceptual design
- (4) Address producibility during detailed design
- (5) Measure producibility

While producibility is an important aspect of design, Ball (2015) provides examples of producibility assessment tools. However, such tools typically lack support for early-stage assessment (Sanders and Klein, 2012). Producibility is usually assessed in the form checklists, heuristic examples of good or poor designs (Poli, 2001), automated CAD simulations (Elgh and Cederfeldt, 2008, Heikkinen et al., 2016) and rule checkers used to determine if design engineers follow the recommended best practices or not. Sanders (2010) suggests three limitations of these approaches:

- The checklists and software are only as good as the rules
- It is difficult to quantify the impact of neglecting the rules
- The approaches are commonly applied when the design is near final and the information available is certain enough to answer all checklist questions or to run the CAD analysis

Several researchers have tried to provide aspects and variables that can be used to characterize producibility (Hadley and McCarthy, 2011); for example, geometrical robustness (Wärmefjord et al., 2014), accessibility in the assembly process (Hadley and McCarthy, 2011) and process quality (Vallhagen et al., 2013), which all relate to the

producibility of manufactured products. However, it is unclear when producibility can be first assessed during design stages.

Producibility can also encompass production planning activities (Torget, 1971). In fact, Feng and Song (2000) argue that production operation planning is a producibility assessment activity. In Figure 7, production operation planning is represented. Production operation planning includes the input of product information which is influenced by production capabilities. Production operation planning supports the modeling and selection of production process plans and corresponding resources that serve the production fulfilment of a product in terms of such factors as cost and process time. A production operation plan is hierarchically structured in a generic plan, a macro plan, a detailed plan, and a micro plan (Ming et al., 1998). Most models that represent production operations focus on the detailed and the micro plan, failing to support early design stages (Feng and Song, 2003). Mula et al. (2006) studied various models for production operation planning under uncertainty and highlight the need for new models that address the product structure and potential changes to this structure.

To support the evaluation and selection of production process and resources, Feng and Song (2003) presented an information model; however, the selection was based on detailed aspects of the design. Nguyen and Martin (2015) presented an approach that supports production process selection using CAD models that are assessed according to certain production constraints. In this way, inferior production alternatives were eliminated based on known constraints. However, the process is not clearly described, and the models embody high geometric detail which may restrict the design freedom and the number of feasible production configurations. In contrast to these design approaches, Zhang et al. (2012) proposed a pure production view and suggest production reconfiguration under constraints to coordinate product variety and corresponding production processes. However, the constraints in the approach presented by Zhang et al. (2012) relate to the detailed sequencing and routing of operations that require product models of high certainty which cannot support the early design stages well.

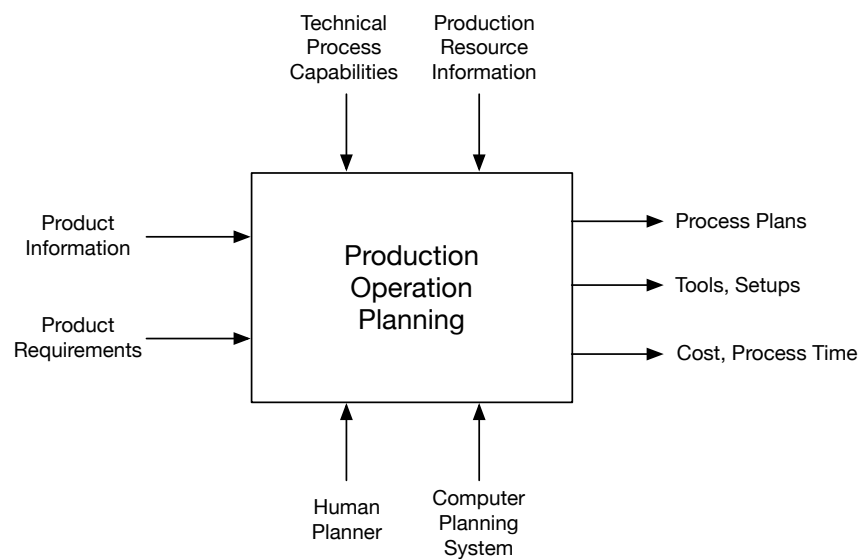


Figure 7. A representation of production operation planning (redrawn from ElMaraghy et al. (2013))

2.4 PLATFORM DESIGN

Many definitions of the concept platform abound. In research and industry, a platform generally concerns the use of a common base of sub-entities that can be shared or reused among a variety of systems. Different types of platforms exist, including product platforms, production platforms, co-platforms, function platforms, technology platforms, flexible platforms, etc.

2.4.1 Product Platforms

Perhaps the most well-established view of product platforms is provided by Meyer and Lehnerd (1997) p. 7: *“a product platform is a set of common components, modules, or parts from which a stream of derivative products can be efficiently created and launched.”* However, there are many variations of this definition. Simpson et al. (2001) define product platforms in the form of product families and as a set of parameters, features and/or components that remain constant within given market segments. Another view of platforms suggest architectures controlled by design, characterized by common structures, scaled variables and variable structures, which can support more than one product (Gershenson et al., 2004). This view articulates the need to meet certain customer segments by scaling and sharing parts or components among different configurations.

A more abstract view of product platforms is provided by Robertson and Ulrich (1998), who describe a product platform as a collection of assets, components, processes, knowledge, people and relationships that are shared among a set of products. Given this view, non-geometric knowledge is shared among a variety of products that allow commonality and reuse to still be achieved. However, these platforms must be represented vastly differently from part-based platforms which may be practically difficult to accomplish because of the lack of modeling methods and tools commercially available to support such an endeavor.

Researchers have proposed different frameworks, methods, and tools to define and make use of product platforms in a variety of industrial settings, including Simpson (2004), Jose and Tollenaere (2005) and Simpson et al. (2006). A well-known industrial example of Black and Decker is reported by Meyer and Lehnerd (1997) and Simpson (1998). Another industrial example from Rolls Royce is described by Prencipe (1998). A similar approach to product platform development is the product architecture master plan proposed by Harlou (2006) and further developed by Kvist (2010). However, these product platform approaches lack support to accommodate production system design (Michaelis, 2013).

2.4.2 Production Platforms and Co-Platforming

Koufteros et al. (2014) argue that a company that pursues a product platform strategy motivates a similar approach in production. Some of these approaches are reviewed in Section 2.2. However, concerning platform design, the integration of design and production is rare and not as sound as research on product platforms (Simpson, 2004, ElMaraghy et al., 2013). Although some examples suggest doing so, for instance using the DfMA techniques proposed by Emmatty and Sarmah (2012), they fail to support reuse of information from a common structure that represents the technical systems of both design and production. Michaelis et al. published a number of papers, with the aim of creating such a common

structure by using a technique for modeling functions and means representing the core knowledge of technical systems and their integration (Michaelis and Johannesson, 2011, Michaelis et al., 2013, Levandowski et al., 2014). Michaelis (2013) suggests using this common platform to support the co-development of products and production systems. Building on similar modeling, Sorensen et al. (2018) propose a production platform approach using a core platform to describe particular functional capabilities and how they are carried out via means; however, the mindset needed for thinking in principles rather than physical concepts was difficult to acquire for the industrial participants in their study.

Both Bryan et al. (2007) and Tolio et al. (2010) speak about co-evolution to support the design and production integration necessary to develop product variety and corresponding production systems. An analogous approach is the concept of co-platforming suggested by ElMaraghy and Abbas (2015) and Abbas and ElMaraghy (2018). Likewise, there are approaches supporting late stages that can determine whether a high variety of pre-defined product variants represented as a set of BOMs can be produced given a set of production operations (Ebrahimi et al., 2015). However, they all lack models that clarify the product and production interplay at a conceptual level and no comprehensive modeling and assessment support is provided.

2.4.3 Reuse and Reconfiguration of Design and Production Information

Reuse and reconfiguration of design and production information is key to platform design and its effectiveness. To support the reuse of design and production information, different representations of the information may be used. In Figure 8, some representations are illustrated following the different design stages. Accordingly, Shahin et al. (1999) advocate four different forms of design reuse: 1) a list of functions and basic requirements representing a concept, 2) an F-M tree representing functions and means, 3) a tree of parts representing the embodiment design and 4) a set of drawings or CAD models representing the detailed design. Pahl and Beitz (2013) write about two kinds of embodiment, preliminary and detailed embodiment. Preliminary embodiment, or overall layout, is represented as a draft or configuration of shapes that will form a detailed embodiment through iterative steps.

Kimura and Nielsen (2005) propose a way to design a product variety under production resource constraints by the reuse of production knowledge. They further state that aspects of production knowledge can be regarded as constraints.

According to Du et al. (2001), platforms are designed focused on technical or functional variety. Designing for technical variety focuses on reducing company in-house variety, whereas functional variety focuses on satisfying a wide range of customer needs. The way design and production information can be represented may be categorized according to the following two advantages in platform design: (1) the reduction of unique parts to gain economies of scale in production and (2) variety enabled through customization.

2.4.3.1 Reduction of Unique Parts to Gain Economies of Scale in Production

To reduce unique parts to gain economies of scale in production, the reuse of physical components, modules, or parts is typically advised. A recent study conducted at a large global LED lighting manufacturer shows that sharing components among many different products using a platform is more profitable than non-platform products (Meyer et al., 2017).

Soon to be parts, represented as a Bill of Materials (BOM) with parametric formulas and other design relationships between them, are typically sealed in design tools, such as CAD. A BOM is typically defined in terms of the fundamental ways in solving specified functionalities that mirror the customer needs, which makes the process of customizing and achieving design reuse beyond the certain form burdensome; for example, a function sealed in a function carrier (Pahl and Beitz, 2013), or product feature, may restrict the chance to act quickly in response to changing customer needs (Ong et al., 2008). In fact, Madni (2012) identifies risks inherent in part-based platforms. Because errors in a part-based platform architecture can permeate all variants, an organization can risk reducing its ability to evolve on a market that poses high uncertainties of future product mix and demand. Part-based platforms based on mixing parts into different configurations do not alone provide the support needed by design engineers to increase development efficiency (Gedell, 2011). This is particularly apparent in engineer-to-order companies (Brière-Côté et al., 2010) where the reuse of physical parts may prove insufficient to satisfy a wide range of customer needs.

2.4.3.2 Variety Enabled through Customization

To meet a wide range of changing customer needs while there are still high uncertainties regarding product mix and demand, platform design that supports variety through customization can be employed. The reuse of design and production information during the early design stages suitable for customization requires a sufficient and adaptable representation scheme, or structure, of the variants envisioned (Robertson and Ulrich, 1998, Chandrasegaran et al., 2013). van Veen (1991) suggests Generic Bill of Materials (GBOM) as such representation scheme to support design reuse, elaborated by e.g. Hou et al. (2011).

Some research on platform design focus on increasing the ability to customize (Simpson, 2004) by representing designs with intangible entities such as functions and technologies (Alblas and Wortmann, 2014) or functions and means (Johannesson and Claesson, 2005, Levandowski et al., 2014). Function platforms enable the reuse of functions and generation of engineering variants (Alblas and Wortmann, 2009). A function platform can make use of sub-systems that are scalable, or reconfigurable, to fit many different products while fulfilling the identical functions. The reuse of intangible entities can preserve design freedom during design stages which is lost when reusing merely finalized designs and physical parts.

Focusing on the integration of product and production aspects, Jiao et al. (2000) proposed the Generic Bill-Of-Materials-and-Operations (GBOMO) representing product and process variety generically and mutually. Later, Jiao et al. (2007a) proposed integrating product and process platforms to support the coordination across product and process variety during platform development. Their approach includes detailed information of the process variety, including process parameters and routing data. According to Jiao et al. (2007a), a process platform involves: (a) the common process structure shared among a set of variants, (b) the configuration of process variants using the common structure, and (c) the coordination between the product and process variety. An analogous integrated platform approach has been presented by Levandowski et al. (2014), who suggested using production operations as integration models for product-production trade-offs. The same platform approach was improved by Michaelis et al. (2015) in which production operations were modeled. However, the models are too detailed to be practical in modeling at an early conceptual stage.

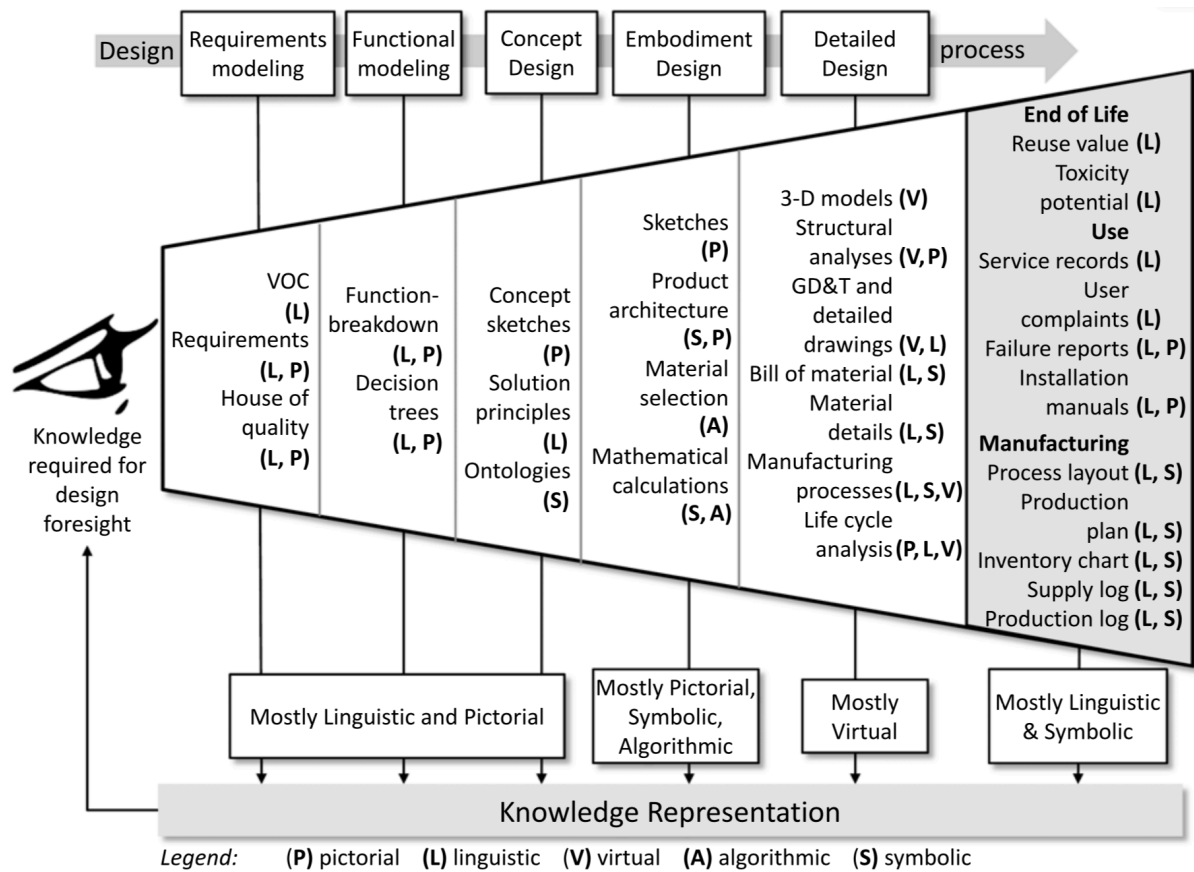


Figure 8. Ways of representing knowledge following the design process (Chandrasegaran et al., 2013)

2.5 MODELS FOR EARLY-STAGE PLATFORM DESIGN

During the early stages of engineering design, concepts and ideas are created to meet customer needs based on uncertain information. While developing complex products and systems, the engineering models can be represented based on systems theory. In fact, systems theory and systems engineering may be especially supportive in platform design because many different design problems need to be treated simultaneously.

2.5.1 Systems Theory and Engineering

A system is an example of an entity in which the whole is more than the sum of its parts. More specifically, the behavior of a system depends on its sub-systems and their interactions (Checkland, 1981) that cannot be attributed to any specific part of the system. Rather, they emerge only when the system as a whole is considered. Hitchins (2003) expresses, “*the properties, capabilities, and behaviors of a system derive from its parts, from interactions between those parts, and from interactions with other systems.*”

Systems Engineering (SE) is a multidisciplinary and collaborative approach for engineers from various disciplines, such as mechanical, electrical and computer science engineering (Bhise, 2013). SE focuses on defining customer needs, mapping functionality, documenting requirements, synthesizing design, and validating systems (Blanchard and Fabrycky, 1990). The process of SE reflects the transformation of customer needs into designs with the

performance, size and configuration of meeting these needs. SE advocates a top-down approach used to analyze a product as a whole and decompose it into various levels, such as systems, sub-systems, and components. Decomposition is a way of limiting the task. However, it has its drawbacks. Hitchins (2003) describes how decomposition will make the parts lose their interactions and thereby their context. Interactions can be maintained by encapsulating parts of a system and allow for the independent elaboration of parts. Encapsulation and elaboration do not cut interactions as decomposition does; rather, the interactions remain intact.

Hubka and Eder (1988) presented the Theory of Technical Systems (TTS). A technical system exists only to realize a transformation from input to output. A combination of input and internal states of the system will define its output, as well as the internal state it will adopt. Hubka and Eder (1988) presents five abstract models of technical systems: purpose, process structure, function structure, organ structure and component structure. Andreasen (1991) proposed the Theory of Domains (ToD), based on Hubka and Eder's Theory of Technical Systems. Their model consists of four domains: process domain, function domain, organ domain, and component domain. Following ToD, Mortensen (1999) developed the chromosome product model as a generic structure of these domains.

In engineering, function modeling is an early design activity as a basis for consecutive activities. Different techniques for function modeling in early-stage design exist.

2.5.1.1 Function Modeling for Early-Stage Design

Eckert (2013) has performed an extensive interview study to map the use of function modeling in industry. She found that design engineers in industry are prone to use function modeling through conventional methods such as Quality Function Deployment (QFD) and Failure Mode and Effect Analysis (FMEA). However, these methods are mainly used to generate and structure requirements rather than support design synthesis (Eckert, 2013).

There are various techniques for systematic function modeling. A function modeling technique that has a clear process focus is IDEF0 (Buede and Miller, 2016). In contrast to IDEF0, Function-Means (F-M) modeling has a clear artifact focus describing both design requirements and solutions.

F-M modeling is a systematic way of finding design solutions (DSs) that fulfill functional requirements (FRs). An FR describes what a product, or an entity of a product, actively or passively, shall do. The FR motivates the existence of a specific DS. The DS (or mean/organ) is a solution that may fulfill a specific FR, for example a tangible component or feature, a fuzzy design principle, concept or a non-physical solution such as a service or software.

An F-M model is a hierarchical architectural model of a particular system which is decomposed into subordinate sub-systems. The F-M architecture follows *Hubka's law*, which states that: "*The primary functions of a machine system are supported by a hierarchy of subordinate functions, which are determined by the chosen means (organs)*". The F-M model was originally developed by Tjalve (1976) and Andreasen (1980) and has evolved over time. As a contribution to the F-M theory, axiomatic design was introduced. Suh (1990) describes the zigzagging between FRs and design parameters (DPs). DPs and DSs are considered equal. The zigzagging points out the fact that a requirement cannot be decomposed into other requirements without intermediate solutions being identified.

Schachinger and Johannesson (2000) enhanced the F-M model, as illustrated in Figure 9, by describing additional types of relationships and separating FRs from non-functional requirements, termed constraints (Cs). The Cs indicate the required capabilities of DSs.

The modeling of the E-FM architecture begins with the modeling of an overarching FR. A number of different DSs that can solve this FR are then modeled. Constraints that limit these design solutions can be simultaneously modeled.

While considering a single EF-M architecture, there are some rules to respect in terms of cardinality across objects:

- FR-DS is $1 \leftrightarrow 1$ and is denoted *is solved by* (isb)
- DS-C is $1 \leftrightarrow n$ and is denoted *is constrained by* (icb)
- DS-FR is $1 \leftrightarrow n$ and is denoted *requires function* (rf)

A DS can be decomposed into lower hierarchical levels, following *Hubka's law*. The constraints at lower levels can be shared among a number of DSs, for example a weight constraint may be evenly distributed. This relation is denoted *is partly met by* (ipmb).

Apart from the pure hierarchical relations, a semi-lateral and a lateral dependency can be modeled. The first one, the semi-lateral, is a relation between an FR and the DS of another FR. It indicates that the fulfillment of a main FR is influenced by another DS. This relation is denoted *is influenced by* (iib). The second one, the lateral, is an interaction between two DSs at the same hierarchical level. This relation is denoted *interacts with* (iw). Both types of relations can be used to perform matrix-based analyses of the structure model, such as assessment using the Design Structure Matrix (DSM) (Steward, 1981) and axiomatic couplings (Suh, 1990). Also, additional information, such as attributes, external documents and other external models, can be linked to relations and objects in the model.

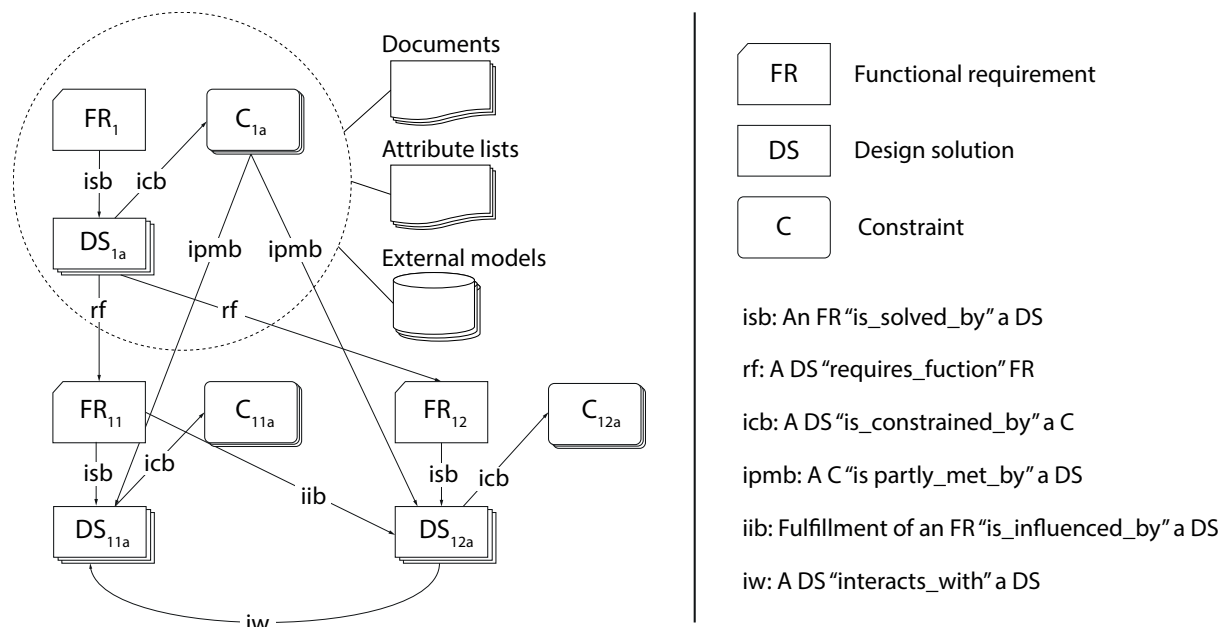


Figure 9. Enhanced Function-Means architecture
(as drawn in Levandowski (2014), adapted from Johannesson and Claesson (2005))

2.5.1.2 System Assessment for Early-Stage Design

New design solutions are typically generated based on creativity, combination, or modification (Tomiyama et al., 2009). An important step in the conceptual design process is the morphological matrix (Pahl and Beitz, 2013), or combination table (Ulrich and Eppinger, 2012), used to combine a set of design solutions into a number of concepts (Weber and Condoor, 1998). Some examples of generating product concepts using an implemented morphological matrix in software exist; however, even though some regards conceptual exploration (Strawbridge et al., 2002) most of them focus on optimization (Ölvander et al., 2009). When combining solutions, it is difficult to ensure the physical and geometrical compatibility early in design and find technically and economically feasible concepts by early evaluation (Pahl and Beitz, 2013).

A common model as a basis for system assessment is the Design Structure Matrix (DSM). A DSM provides a structure of interactions, or interfaces, between entities of a system architecture. With the increasing complexity of products, it becomes cumbersome to manage a large system of interrelations, which is why the value of the DSM increases with increasing complexity (Eppinger and Browning, 2012). Various types of assessments can be performed using the DSM, such as the partitioning or clustering of a system and its sub-systems (Eppinger, 1991) to support modularization and DfA, and change propagation predictions to support how design modifications affect an entire system (Clarkson et al., 2004, Raudberget et al., 2015), etc.

In design, many conflicting requirements need to be incorporated. The systems to be developed can be assessed based on trade-offs of these requirements. Data can be generated from physical tests or virtual simulations to expose the possibilities and limitations posed by certain design solutions and technologies. To make trade-off studies, these data can be presented as trade-off curves (Blanchard and Fabrycky, 1990, Ward and Sobek II, 2014) or as limit curves (Kennedy et al., 2014). A trade-off or limit curve is a graph that shows two conflicting criteria and how they affect each other. Trade-offs that include many aspects can be illustrated using response surfaces (Kennedy et al., 2014). Ward and Sobek II (2014) emphasize the use of trade-off curves as a means of understanding design. Trade-off and limit curves are vital parts of Set-Based Concurrent Engineering (elaborated in Section 2.1) as ways of mapping a design space, evaluating design alternatives, and eliminating inferior designs based on proof (Kennedy et al., 2014).

2.5.2 A System Object Model for Early-Stage Platform Design

A model that describes abstract platform entities contrasting physical parts was proposed by Claesson (2006), termed the *configurable component (CC)*. In Figure 10, the CC object is illustrated. The CC is based on systems theory principles (Hitchins, 2003) and design theory (Hubka and Eder, 1988, Andreasen, 1991). The CC contains a description of a variety of systems in the same model. The underlying requirements and motivations of the CC object, its design rationale (DR), build on the EF-M architecture model.

Besides the DR of the system, a CC object contains a *composition set (CS)* and a *control interface (CI)*. The CS and CI are used to communicate hierarchically across a set of CC objects by exchanging *variant parameter values (VPVs)* hierarchically from the CS of CC1 to the CI of CC2. The CC objects and their links are incorporated in CC objects as

composition elements (CEs). Design rules needed to model a CC object are implemented as formulae. CC objects also contain certain configurable *interfaces* (IF) to communicate laterally. The lateral exchange across CC objects is incorporated in an *interaction* (IA).

2.5.2.1 Modularity and Scalability of the System Object Model

Most design problems have both modular and scalable solutions. In terms of platforms, a set of modules can be designed to be interchanged among variants. By changing a module for another, different properties can be achieved (Gonzalez-Zugasti and Otto, 2000). The EF-M architecture of the CC consists of objects FRs, DSs and Cs and their inherent relations. The EF-M architecture can accommodate modular and scalable bandwidths. Modular bandwidth can be accomplished by creating a set of alternative DSs whereby each DS in the set can solve the same FR (Wahl and Johannesson, 2010). Modular bandwidth can be exemplified by the different types of bearings used in a car. Bearings are used on the wheel axis and in the gearbox. The main function of a bearing is to convey mechanical loads, both axially and radially. Thus, a bearing system, and the module character thereof, can be reused for the wheel axis and gearbox. Therefore, the design principles of a bearing can be reused.

Scalable bandwidth can be accomplished by defining target value ranges into the parameters of the objects in the CC (Berglund and Claesson, 2005). In scalable platforms, a design can be stretched and shrunk to fit specific customer requirements (Simpson, 2004); for example, the size of one type of bearing may change with the mechanical loads it has to convey which is why design parameters need to be modified.

Both Michaelis et al. (2013) and Levandowski (2014) continued to elaborate on these bandwidths of the CC in the context of platform design.

2.5.2.2 Adaptable Interfaces of the System Object Model

An interface is the connection between two entities. Compatible entities must carry the same shared parameter values in the interface (Bhise, 2013). In part-based platform design,

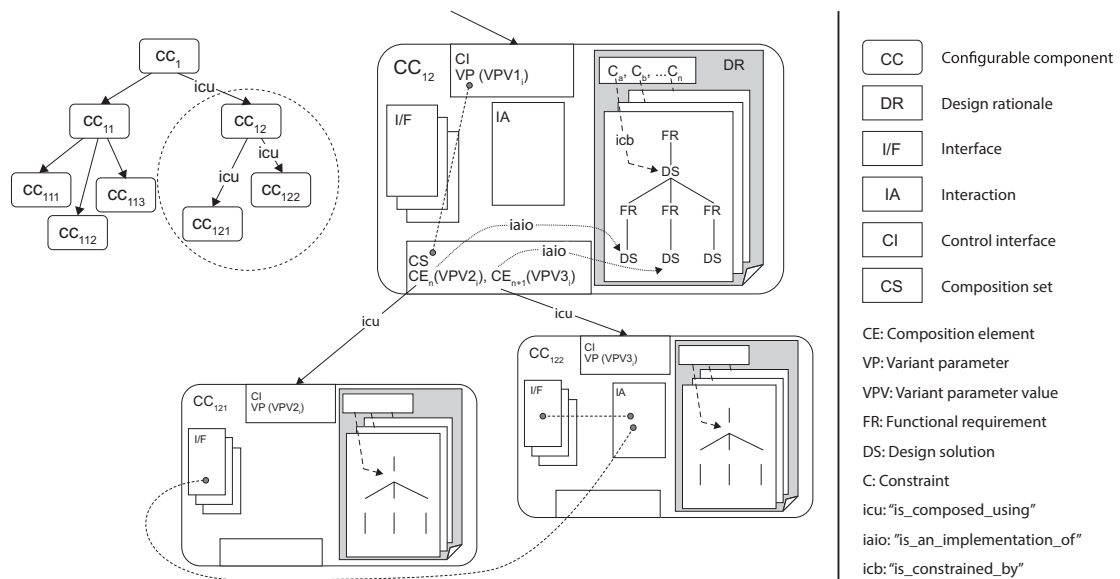


Figure 10. A structure of Configurable Components (CCs) including its objects and relations of the CC (slightly modified from Michaelis (2013), adapted from Claesson (2006))

interfaces must be identified during the early design stages to be properly analyzed and managed in the following, detailed design stages. Engineers must know how and what an interface should exchange to make the entities work together and fulfill the functionalities intended (Bhise, 2013). Pimmler and Eppinger (1994) suggested that the interface or interaction between entities can involve four different types of exchange: 1) *physical space*, 2) *energy*, 3) *material*, and/or 4) *data or information*.

While redesigning a pre-defined modular architecture, Sosa et al. (2007) identified that a design modification in one module is likely to propagate to other modules causing a high number of modifications. Based on the definition of a system object, these modifications may be managed through adaptable modules and interfaces (Gu et al., 2004), that is an adaptable system will share the identical information across the modules that compose the system without losing trace, which is enabled in the system object model. This is especially important for complex products and systems where numerous interfaces exist and many modules interact.

2.6 IT-TOOLS FOR SYSTEMS DESIGN MODELING AND ASSESSMENT

Computer Aided Technologies (CAx) is the umbrella term for most IT-tools employed to model and assess different aspects of a design.

To support the modeling of a common structure that can facilitate design reuse among a set of systems, formal modeling techniques are sought. Hvam et al. (2018) show that companies using formal modeling techniques of product knowledge are better at keeping track of product variants and rules implemented in configurators than companies using non-formal modeling techniques. An example of such formal modeling of complex systems is the Unified Modeling Language (UML). UML was later adapted to fit Systems Engineering purposes that require explicit modeling of requirements, forming the Systems Modeling Language (SysML). SysML has four pillars in a series of diagrams: structure, behavior, requirement and parametric to capture several elements of complex products and systems (Buede and Miller, 2016). Designing complex products and systems require good management of a high number of systems and their numerous interactions. To support platform and variety modeling in and across design and production, both UML (Alblas et al., 2012) and SysML (Wu et al., 2013) have been adopted. However, capturing interactions among diagrams in SysML is difficult (Chandrasegaran et al., 2013), which is an important feature for variety modeling. To meet increasing complexity of systems that comes with variety modeling, Bhise (2013) identifies some areas where software capabilities are needed, including areas to support system decomposition, graphical modeling and managing of components, systems, functions, requirements, and interfaces, in addition to import/export capability for CAx tools, as well as document generators.

To model and visualize three-dimensional geometries and create drawings as bases for production, CAD tools can be used (Ulrich and Eppinger, 2012). In mass customization, enabling responsiveness to meet changing requirements, flexibility needs to be built into the geometry models. This flexibility can be achieved through the parameterization of CAD models. Parameterization is a way of governing the parameters that define the design to create alternatives. Even though a CAD model can be parameterized, CAD tools do not support conceptual design well (Deng et al., 2000) because of the pre-defined structure which

is impractical to adapt. However, for optimization purposes during detailed design stages, CAD tools provide wide support, exemplified in work by La Rocca and Van Tooren (2007).

To analyze CAD models through multipurpose simulations, CAE tools are typically complementary (Ulrich and Eppinger, 2012), such as finite-element method (FEM) analysis, computational fluid dynamics (CFD) analysis, or robust design analysis using Computer Aided Tolerancing (CAT) tools (Soderberg and Lindkvist, 1999). La Rocca and Van Tooren (2007) state that current design activities, including CAE tools, are time-consuming and repetitive, and that too little time is spent on investigating additional product alternatives and better exploit the skills and creativity of design engineers. To make time for this, increased automation of processes can be implemented. Such approaches were enabled Knowledge Based Engineering (KBE), which has proven to be a powerful means to automatically generate and evaluate detailed designs and variations of products through parametrization of CAD models (Chapman and Pinfold, 2001), or both parametrized CAD models and combinatorial experimentation allowing the formation of a large number of new concepts (La Rocca, 2012). However, because the knowledge is typically sealed in a specific CAD tool, KBE approaches are typically stiff and rigid (Isaksson, 2003, Verhagen et al., 2012).

Specific tools for Platform Modeling and Configuration (PCM) are rare; however, the Configurable Component Modeler (CCM) is one such tool. CCM supports modeling of reusable system descriptions including relations and rules among objects ready for pre-embodiment evaluation. CCM is developed parallel with the research presented in this thesis, spawn from work by Claesson (2006), Johannesson (2014), among others. Wang et al. (2002) identified that decision support tools for conceptual collaborative design are rare. CCM is no exception. The modeling and assessment of producibility is not supported.

2.7 IT-TOOLS FOR EXCHANGE OF DATA AND INFORMATION

Coordinating activities and the handling of changing data during product development can be managed with the use of Product Lifecycle Management (PLM) tools (Stark, 2015). PLM encompasses the organization, a collection of engineering processes, methods, and tools, as well as products and their related data and information (Abramovici, 2007). PLM can be seen as an integrator of tools and technologies facilitating the exchange of data throughout the lifecycle of a product (Terzi et al., 2010). To manage the data, Product Data Management (PDM) tools can be used as part of a PLM architecture (Abramovici, 2002). In addition, a CAD tool is often well integrated into the PDM tool and thus provides access to product metadata (Abramovici, 2002). However, in most cases information is manually transferred and in some cases integrated in one direction alone (Abramovici, 2002, Burr et al., 2005). Future research direction points at integrating real-time product data collected along the product lifecycle using sensor technologies (Abramovici et al., 2016).

IT-tools used for production purposes are not elaborated upon; however, allow us to mention Computer-Integrated Manufacturing (CIM) tools (Alting and Zhang, 1989): PLM for production systems, including Computer Aided Manufacturing (CAM) tools and Computer-Aided Process Planning (CAPP) tools (ElMaraghy et al., 2013). CAD and CAPP tools can be integrated to support producibility assessments, such as using FMEA (Zheng et al., 2009); however, there is still a lack of approaches that support producibility assessments using models beyond certain product form in CAD.

3

RESEARCH APPROACH

This chapter provides you with the research approach applied, including framework and methods. The way the research was carried out and how the findings are validated are presented as transparently as possible.

According to Creswell (2013), there are three different research approaches: 1) *qualitative research* – to explore and understand phenomena, 2) *quantitative research* – to test theories by examining the relations between variables, and 3) a mix between the two – *mixed methods research*. The work presented in this thesis follows a qualitative research approach and the empirical data are gathered and validated by the researchers in collaboration with industrial practitioners, which entitles the scientific mindset to be constructivist. In qualitative research, the reasoning logic can follow deduction and induction. Deductive reasoning accounts for the process of testing a theory based on theoretical premises whereas inductive reasoning is the process of gathering data, analyzing the data and making generalizations in accordance with theory and past experiences (Creswell, 2013). Elements of both deduction and induction have characterized the applied research process described in Section 3.5.

3.1 RESEARCH IN ENGINEERING DESIGN

Engineering design regards the development of products, including services and processes, by using validated design methods and tools. The creation of the design methods and tools

used by design engineers is not a dominant part of the daily work in industry – partly because of the lack of time and capital. However, some institutions of academia strive to improve models, methods and tools to support engineers while solving design problems in industry: the common aim of academia and industry is to design better products of the future. The research provided in this thesis adheres to an academic institution that focuses on improving design methods and tools to facilitate design practice and support engineers in making more informed design decisions.

Research in engineering design can be regarded as a type of meta-development. Horvath (2001) defines research in design as “*generating knowledge about design and for design.*” It involves the creation of models, methods and tools that can support design engineers in developing products to serve effectiveness and efficiency beyond legacy practice. To Horvath (2001), design research has three objectives: (1) the systematization of design processes, (2) the mechanisms of design decision-making, and (3) the improvement of design modeling, representation, analysis, simulation, evaluation, and physical testing techniques. To support design research, a four step process (Figure 11) was introduced by Duffy and Andreasen (1995). These four steps aim to improve understanding of a reality using a phenomenon model, information model, and computer model by validating against reality iteratively to provide research rigor. A phenomenon model describes the basic constructs identified during empirical studies.

3.2 FRAMEWORK OF THE RESEARCH CONDUCTED

Because the research conducted aspires to provide manufacturers with novel design support and insights concerning platform design for producibility, a framework that can support both increased understanding and the creation of design support is needed. A research framework that supports these objectives is the Design Research Methodology (DRM) introduced by Blessing and Chakrabarti (2009). The DRM framework encapsulates two main purposes. The first purpose regards the understanding of design – descriptive: *how things are*. The second framework regards the systematic creation and development of models, methods and tools to support design engineers to make design better– prescriptive: *how things ought to be*.

The DRM framework comprises four steps: (1) *research clarification*, (2) *descriptive study I*, (3) *prescriptive study* and (4) *descriptive study II*. The framework suggests a basic way in which to support each step to attain main outcomes of each steps: The DRM is not intended to be linear, as illustrated in Figure 12 where arrows iterate back and forth to previous steps (Blessing and Chakrabarti, 2009).

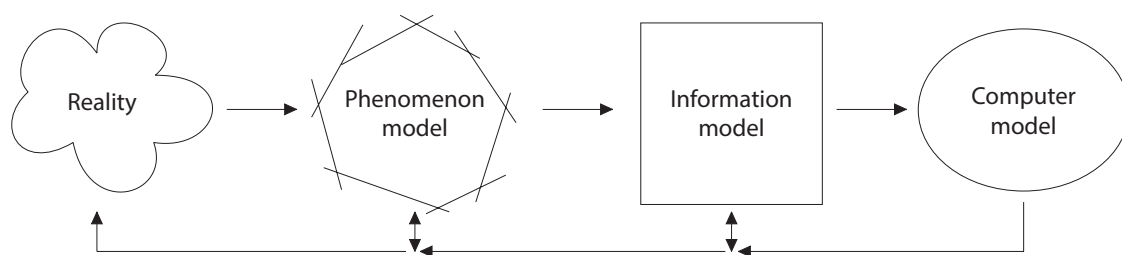


Figure 11. Research approach for design modeling (Duffy and Andreasen, 1995)

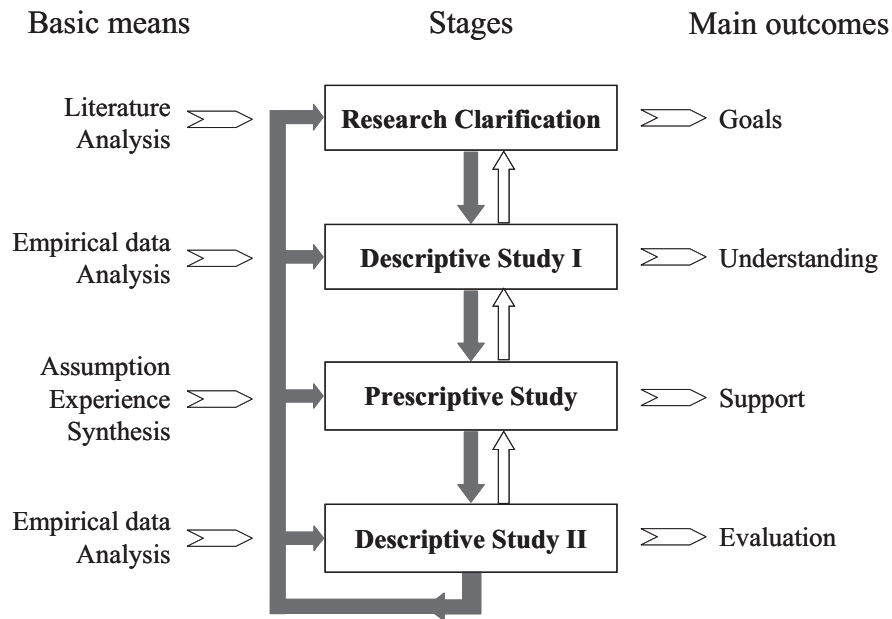


Figure 12. Design Research Methodology (DRM) framework
(Blessing and Chakrabarti, 2009)

To clarify the phenomena studied, the scope, aim and goal of this research are articulated in Section 1.2. The goal is decomposed into research questions and deliverables that have propelled the research work.

In accordance with the DRM, research can be of different types and therefore directed towards various outcomes and contributions that add to the design research community. The type of research proposed in this thesis is provided in the next section.

The positioning, or focus, within the DRM framework is key to the planning and execution of the research and affects the research path and consistency of findings derived from the research process. The focus of the research presented in this thesis is clarified by adopting Type 5, shown in Figure 13.

Research Clarification (RC): The knowledge gap and clarification of the phenomenon to be studied were identified by reviewing literature such as books, research articles and official public reports (Creswell, 2013) from a variety of Areas of Relevance and Contribution (ARC) (Blessing and Chakrabarti, 2009) which were corroborated with industrial needs and challenges within the research niche.

Descriptive Study I (DSI): The understanding of the phenomenon and conventional methods and tools that support platform design and producibility modeling and assessment are obtained from continuing the analysis of literature and by conducting empirical studies.

Prescriptive Study (PS): To support design engineers to meet the challenges within the research niche and find practical solutions that meet the industrial needs, models, methods and tools have been created.

Descriptive Study II (DSII): The evaluation of the practical use of the design support created is emphasized during this stage. However, based on the comprehensive focus on the DSI and the PS, merely an initial DSII was planned.

The data collection methods adopted to support the research conducted in this thesis are described in the following section.

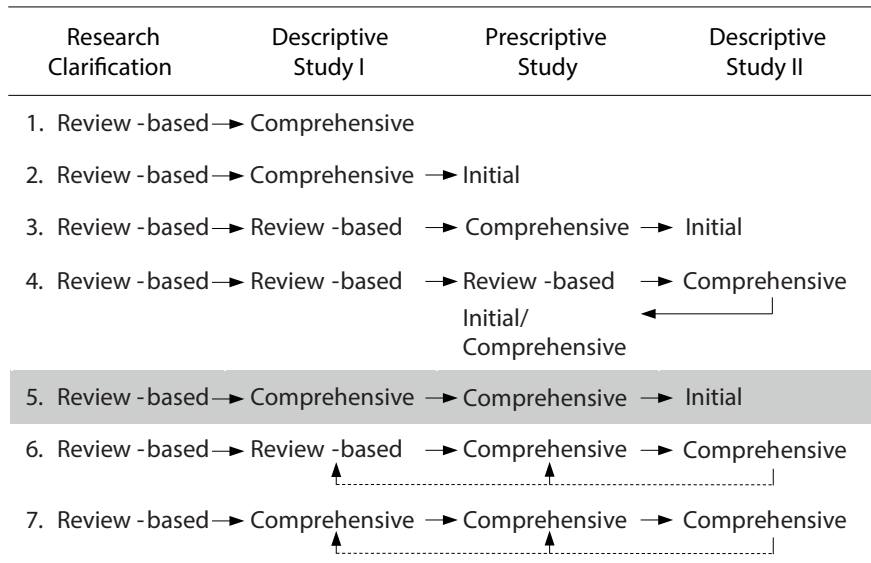


Figure 13. Types of research: the type of this research is highlighted in grey (redrawn and applied from Blessing and Chakrabarti (2009))

3.3 DATA COLLECTION METHODS ADOPTED

There are various ways in which data within engineering design research may be collected. The relevance of the data collection methods depends on the research approach and type. Because of the qualitative research approach and focus on the DSI and PS as indicated in Figure 13, it is important to validate the phenomenon identified in RC, as well as creating a solution to *how things ought to be*. Bryman and Bell (2007) state that qualitative research may be used to validate theories, not solely creating them. This thesis combines the two approaches of creation and initial validation. Firstly, to gain increased understanding of phenomena, observations, interviews, and document examination have been key sources of data (Creswell, 2013). Secondly, simulation tools have been used to generate new data about products, production systems and processes, as well as to demonstrate models, methods and tools.

3.3.1 Observing, Interviewing, and Examining Documents

Observations are properly executed in the field by taking notes of the behavior and activities of individuals (Creswell, 2013). Creswell (2013) also writes about the use of interviews and how they can be structured as a means of qualitative data collection. Interviews are carried out face-to-face and are either unstructured (do not prescribe precise questions), structured (precise questions with pre-defined multiple-choice answers), or semi-structured (precise and open-ended questions) (Blessing and Chakrabarti, 2009). To extract a combination of views and opinions from participants, a few unstructured and open-ended questions can be asked in focus groups that typically engage six to eight people (Creswell, 2013).

Other ways of collecting data entail examining documents and products. Blessing and Chakrabarti (2009) emphasize the use of products, drawings, notes, and meeting minutes to increase the understanding of phenomena. The process can include the searching for internal and external sources (Ulrich and Eppinger, 2012). Internal sources do involve industrial

design practices and processes (Blessing and Chakrabarti, 2009). Also, external sources can be used, including books, research articles and official public reports (Creswell, 2013).

The researcher has to some degree been part of change processes of the study objects in industry. This participatory research approach can be referred to as action research. Action research was developed to increase the relevance of research findings and produce sufficient solutions to societal problems (Blessing and Chakrabarti, 2009). The action research approach is based on both action and research. Blessing and Chakrabarti (2009) state, *“through cycles of action and research a better understanding is obtained.”* A main characteristic of action research is the role of the researcher, being a co-participant in the activities of the study objects (Chisholm and Elden, 1993). Even though action research can be effective for implementation, the research provided in this thesis has not adopted action research because of the relatively low maturity of the research niche.

3.3.2 Generating Data from Simulations

To complement the data collected from product and production design and process specifications and descriptions, models have been created in different types of simulation software to generate new data and information. This data and information have been used to better articulate the findings presented, as well as to demonstrate models, methods and tools created using real, but to some degree masked, industry data. By concurrently analyzing the data generated from the simulations and the data collected from other sources, a greater system knowledge has been gained. Most engineering case studies described in this thesis have been carried out using the CCM software. The software has been developed in tandem with the research process. However, the development of the software is not part of this research work; rather, the software is used as a means of validating models and methods making practical sense beyond what plain information models can provide.

3.4 VALIDATING RESEARCH USING ENGINEERING CASE STUDIES

To ensure that the findings are useful for academic and industrial practitioners, validation of design research is important. Validation can be supported by demonstrating the research using case studies. Yin (2003) state that there are four quality criteria in case study research: construct validity, internal validity, external validity, and reliability.

Construct validity in this study refers to the organizational and user acceptance of the findings. This is supported by the definition of verification by acceptance as stated by Buur (1990). Verification by acceptance implies that experts have accepted the contributions. Internal and external validity is of foremost concern to ensure such acceptance. Bryman and Bell (2007) define (2) internal validity as a good match between the observations of the researchers and the theoretical ideas they develop. Internal validity is related to logical verification as explained by Buur (1990) as completeness and consistency of research findings, which can amount to a confirmation that the findings fit into existing state-of-the-art and show a clear contribution. Completeness refers to when the findings agree with established theory, whereas consistency is when the terminology is clear and conforming. Because extensive efforts are needed to gain an in-depth understanding of the phenomena studied, internal validation is of utmost importance in case study research. Bryman and Bell

(2007) also define (3) external validity; thus, findings can to a certain degree be generalized across different settings. In case study research, external validity is a weakness in contrast to internal validity (Bryman and Bell, 2007).

According to Yin (2003), case study research relies on analytical generalization, whereas quantitative research relies on statistical generalization. In quantitative research, the test sample is the basis of external validity. In defense of external validity in case study research, Yin (2003) continues to argue that the number of case studies used can be seen as a test sample. Because the research approach partly includes collaboration across researchers and industrial practitioners in creating the design support, (4) the reliability of the research can be discussed. Participatory research suffers from bias as there is a risk that researchers have been influencing the people that judge the findings. Bias is further addressed in Section 5.2.3.

3.5 DESCRIPTION OF THE RESEARCH PROCESS APPLIED

The research process that has supported the studies conducted is illustrated in Figure 14. Essentially, Figure 14 is based on several established research models and processes.

First and foremost, the research framework has been adopted from Blessing and Chakrabarti (2009). An identified phenomenon can be studied from at least two main perspectives: literature and empirical studies. Following the research process presented by Jørgensen (1992), both these studies can be conducted in parallel to support the development of new insights. The data collection methods adopted for the research presented are found in the work by for example Blessing and Chakrabarti (2009) and Creswell (2013). Following elements of both deduction and induction and especially the parallel research process

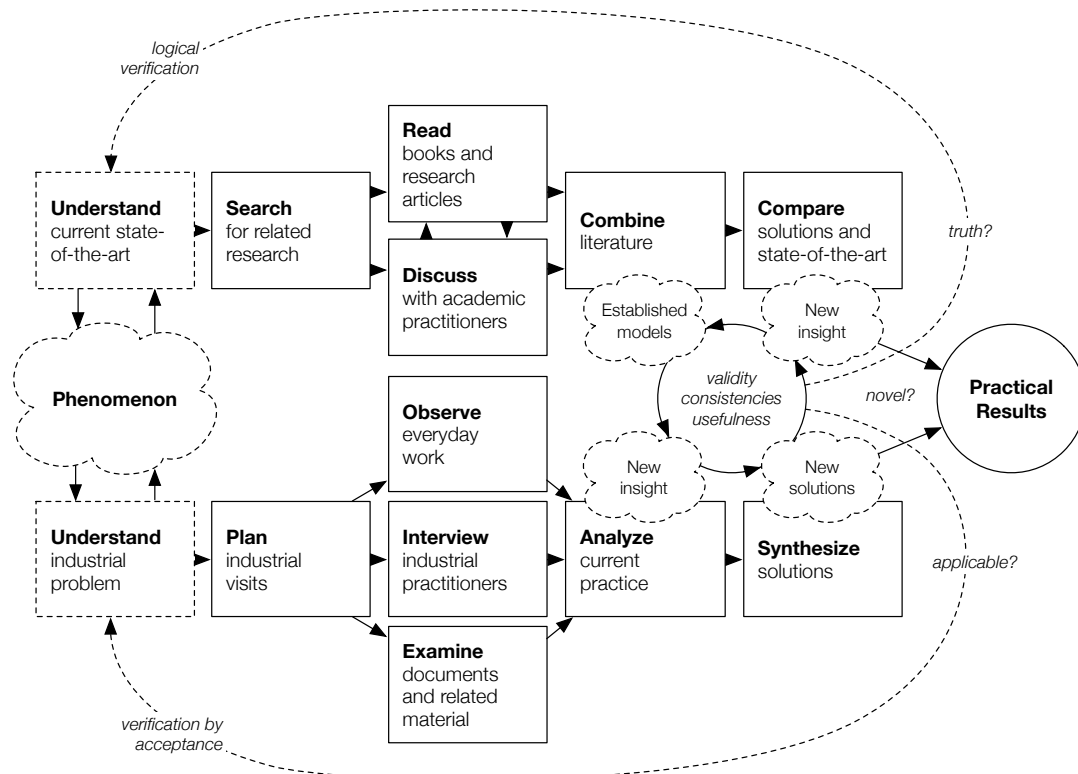


Figure 14. The research process applied in the work presented in this thesis

presented by Jørgensen (1992), the data collected from a body of literature and empirical studies is analyzed and combined to support the synthesis of design support and comparison to existing models, methods and tools. The theory models as well as design support are validated according to the two main approaches by Buur (1990).

3.5.1 *Study I*

This specific study was conducted as part of a project funded by the The Strategic Programme for Production Research and Innovation in Sweden (Production2030) supported by Sweden's Innovation Agency (VINNOVA). The project was propelled in collaboration with a few industrial partners, with the main collaborator being GKN Aerospace Sweden AB – a sub-supplier of aero engine components and sub-systems. The project was spanning over a period of three years (2013-2016). The goal of the project was to create a virtual demonstrator for parallel product and production system development, with the focus on a few design and production aspects of a specific sub-system of an aero engine.

To understand the current design practice at GKN, in-depth knowledge about products and processes of GKN was of main interest. At the Company, unstructured interviews were conducted with four product design specialists working with CAD-oriented methods for platform design, as well as four production specialists working as experts of welding methods and processes. Workshops have been conducted in collaboration with design and production engineers at GKN. To gain a deeper understanding, design guidelines and process descriptions were retrieved from the Company and examined by the researchers and observations have been made of both the design department and the production shop-floor. In parallel with the industrial visits, related literature, such as books and research articles, have been reviewed.

To spawn new insights, the researchers interpreted and analyzed the information gained. Based on analysis of industrial practice and literature review, new solutions were synthesized and then compared with the state-of-the-art for consistency. Based on the information and insights gathered, a platform model was prepared to be executed as a demonstrator. The demonstrator has been presented in various settings, at exhibitions, company presentations, and conferences. The compliance with theory and industrial needs, as well as the novelty of the findings, has been discussed with academic and industrial practitioners at conferences and during workshops.

3.5.2 *Study II*

Three real-life sub-studies have been conducted in collaboration with three different companies: (1) GKN, (2) an automotive company, and (3) a company in the power industry. The GKN sub-study was part of an EU funded research project (TOICA) spanning over a period of three years (2013-2016). The sub-study of the automotive company and that of the company in the power industry were both conducted as extended parts of Study I for generalization purposes.

Platform models of aero engine sub-systems, vehicle seats and electro-mechanical components were created in retrospect by industrial system specialists and researchers. The purpose has been to obtain in-depth system knowledge of the functions that systems and their

parts are aimed to provide and the constraints thereof, how this is manifested in design solutions, and why a particular solution has been chosen. The process has been conducted by means of iterative processes where: 1) specialists have been interviewed through semi-structured and unstructured interviews and workshops to gain in-depth knowledge about the systems, supported by relevant documentation of processes and design guidelines, 2) the researchers have interpreted the information provided and prepared the platform models in accordance with the theory, and 3) the proposed models have been evaluated together with specialists and researchers during feedback sessions during which models have been explained and demonstrated. Taking the feedback into consideration, 4) platform models have been revised and refined.

3.5.3 *Study III*

Study III pro-longs Study I, trenching insights among researchers from related research fields, into two connected research projects funded by Sweden's National Aeronautics Research Programme (NFFP): "Optimization of lifecycle robustness in early development phases II" (NFFP6) spanning a four-year period (2013-2017) and "Digital Platform Twin" (NFFP7) spanning 2017-2018.

Apart from the collaboration across research projects, additional design guidelines and process descriptions were reviewed to better support the integration of production aspects in product platform models. In parallel with industrial visits, literature such as books and research articles were continuously reviewed. The work was extended to collaboration with a research team at the Design System Engineering Lab at Georgia Tech, Atlanta, USA. Concepts related to product variety and variety-related concepts in production were contrasted and analyzed to form the basis of a concurrent platform model for products and production systems. The researchers interpreted and analyzed the information gathered and new solutions were synthesized and compared with the state-of-the-art for consistency.

4

RESEARCH FINDINGS

This chapter presents the core findings extracted from the appended papers. The studies conducted are clarified as far as content, execution, and participant roles are concerned.

4.1 CORE FINDINGS FROM THE APPENDED PAPERS

Each appended paper has several respective authors. According with each paper, the work distribution among these authors is presented in Table 2, as well as on page vii.

Table 2. Work distribution among the authors of the appended papers: initials “**JL**” refers to the author of this thesis (full name of authors is found under the List of Abbreviations on page xii)

<i>Papers</i>	<i>A</i>	<i>B</i>	<i>C</i>	<i>D</i>	<i>E</i>	<i>F</i>	<i>G</i>
<i>Contribution</i>							
Lead author	JL	JL	JL	JL	JL	JL	JM
Writing section(s)	<i>CL</i>	-	<i>HJ, CL, DR</i>	<i>JM</i>	-	-	JL
Initial ideas	<i>HJ, RS, JSC, OI, JV</i>	JL, CL	<i>HJ, CL, JL</i>	JL, JM	JL	JL, RJJ, JM, HJ	<i>JM, JL</i>
Core findings	JL, CL, KW, JK	JL	JL, CL	JL, JM	JL	JL	JM, JL
Commenting	<i>HJ, RS, KW, JK JSC, OI, JV</i>	<i>OI, HJ</i>	<i>HJ, DR, CL</i>	<i>HJ, CL</i>	<i>HJ</i>	<i>JM, HJ, RJJ, RS</i>	JL, RS, HJ, JLö

4.1.1 Paper A: A PLM Architecture for Producibility Assessment

Title: Using Product and Manufacturing System Platforms to Generate Producible Product Variants

Background and Challenge in Short

Aero engine components and sub-systems with highly demanding requirements, such as extreme temperatures or safety aspects, are typically optimized on product performance before producibility is assessed. Design decisions that affect the proclivity of a product to be producible are seldom well executed because production models are lacking during early design stages. While some production aspects of a single detailed geometric model in CAD can be assessed using third party software, it is difficult to assess multiple production aspects of many different designs simultaneously.

Key Contribution

This paper explores the possibility of using various simulations related to producibility to narrow down a design space to respond to customer requests more quickly than before. A PLM architecture (Figure 15) and supporting models and processes are created. Through the PLM architecture, data related to producibility is exchanged across four different software. The PLM architecture consists of a CAD tool for geometry modeling, two CAE tools for producibility assessments, as well as a platform modeling and configuration tool (CCM). CCM is used to model rules and to keep track of processes and data while conducting the assessments. The approach is demonstrated on an aero engine sub-system, produced through welding.

Pieces of Insight

Virtual assessment of multiple production aspects during design is a necessity to respond to customer requests quickly. Without such assessment, there is a risk of committing to design variants that turn into inferior production giving rise to both excessive cost and lead time delays. While producibility assessments based on simulations of conceptual CAD models may not provide reliable producibility metrics of the variants accommodated by the platform model, it may still ease the balancing of product performance and production capabilities, which is a typical trade-off for aero engine components and sub-systems. The structure created can also reduce keyboard mashing commonly necessary to assess multiple aspects of producibility.

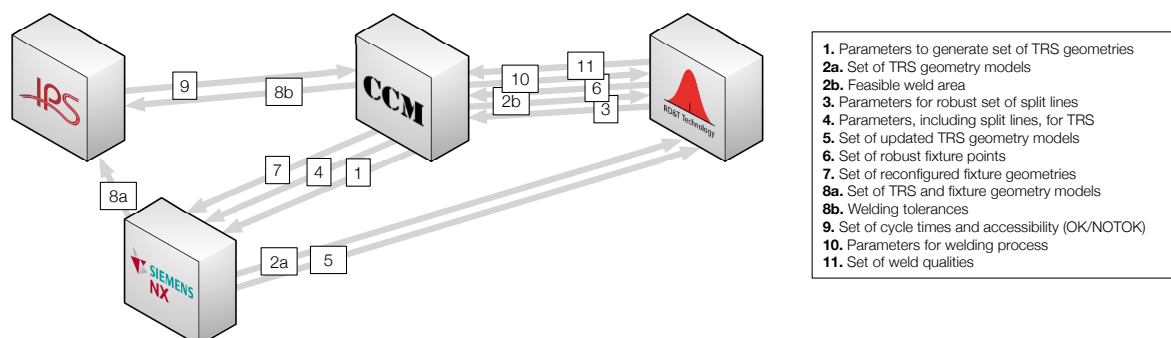


Figure 15. The PLM Architecture and the flow of data related to producibility assessment

4.1.2 Paper B: A Platform Assessment Process Block

Title: Assessing Producibility of Product Platforms Using Set-Based Concurrent Engineering

Background and Challenge in Short

Simulation tools can be used to assess product performance as well as production capabilities. Producibility simulations in design are typically used to verify whether a final design is producible or not, which may require design modification that can turn out to be costly. During late verification stages, design modifications are more expensive compared to those of conceptual stages. Being able to better assess multiple producibility aspects for a range of design alternatives and assess them in concurrency can provide the efficiency needed to support design engineers in making cross-disciplinary design-production decisions. However, there is a lack of models that adopt a clear systematic approach to assess multiple producibility aspects for many different design alternatives.

Key Contribution

A method that supports design engineers to prepare various types of producibility assessments using the systematic principles of set-based concurrent engineering is presented as a platform assessment process block (see Figure 16). In this way, it is possible to explore and narrow down a design space towards feasible alternatives (see Figure 17). The approach is demonstrated on an aero engine sub-system, produced through welding. A case including tool accessibility and assembly robustness of an aerospace sub-system platform is used to demonstrate the approach.

Pieces of Insight

Assessment process blocks can be prepared in parallel and be arranged to find producible design alternatives within the platform bandwidth. The order of the process blocks, or assessments, needs to conform to the input and output of the activities. It is therefore important for engineering users to both have an adequate knowledge of how different design and production aspects influence each other, as well as the corresponding design and production information available. The assessment process can be used to generate new information to be reused for new settings.

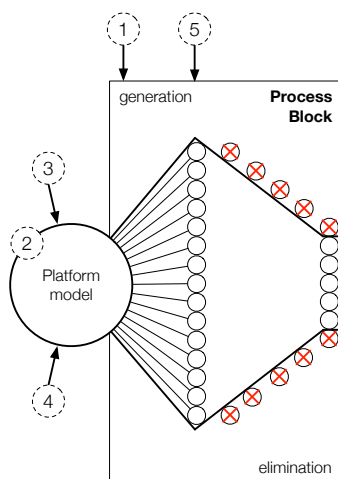


Figure 16. The platform assessment process block

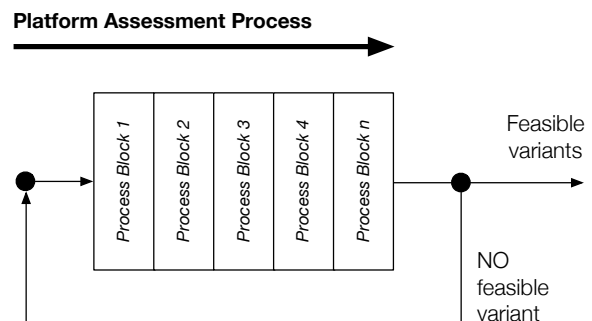


Figure 17. A platform assessment process

4.1.3 Paper C: A Platform Development Methodology

Title: *Development of Product Platforms: Theory and Methodology*

Background and Challenge in Short

Historically, most applied product platform approaches suggest mixing components into different configurations with the highest priority of minimizing the use of unique components and maximizing common components among the configurations. The balance concerns differentiation among the configurations to meet a wide range of customer needs while increasing utilization of expensive production machinery by providing production with high volume per part. Whereas efficiency in design relies on leveraging the knowledge gained from previously developed products, these applied platform approaches lack support for reusing design knowledge over generations of products. Reusing finalized parts can be achieved; however, the design knowledge sealed in the parts is difficult to reuse when the platform becomes obsolete. The use of formal representations to support the reuse of design concepts and the concurrent assessment of multiple concepts is rare. Even though there are platform modeling approaches that advocate the reuse of intangible entities there is a lack of comprehensive product platform development methodologies that can be applied in different product design scenarios along platform development.

Key Contribution

Existing platform processes, models, and methods are reviewed, combined and improved to form a holistic object-oriented methodology that supports platform development teams to reuse and reconfigure system descriptions among system families (see Figure 18). Two modes of platform development have been identified and addressed: platform and platform execution. Platform preparation concerns the formal modeling of multiple concepts in the same function-means structure, as well as parameter ranges that can be accounted for in a variety of products. Platform execution concerns the instantiation of architectural options based on different design solutions modeled, and configuration of product variants, each variant including a unique set of parameters. The methodology enables the exploration of product alternatives, analysis of pre-embodiment and embodiment designs, as well as the comparison and communication of feasible product variants among different stakeholders of a platform development project.

Pieces of Insight

To demonstrate the methodology, three case examples are provided: a family of aero engine sub-systems, a family of vehicle seats and a family of electromagnetic contactors. The three case examples show that the same approach can be used for three different design scenarios representing conceptual, system, and detailed platform development stages. The long-term benefits of implementing the methodology can exceed the initial preparation effort as the systems modeled can be reused over generations of products. Currently, all three manufacturers develop product families applying practices more suitable to single product development. By introducing and implementing the unconventional platform development methodology on a large scale, a change of engineering routines and mindset is required, which is a great challenge.

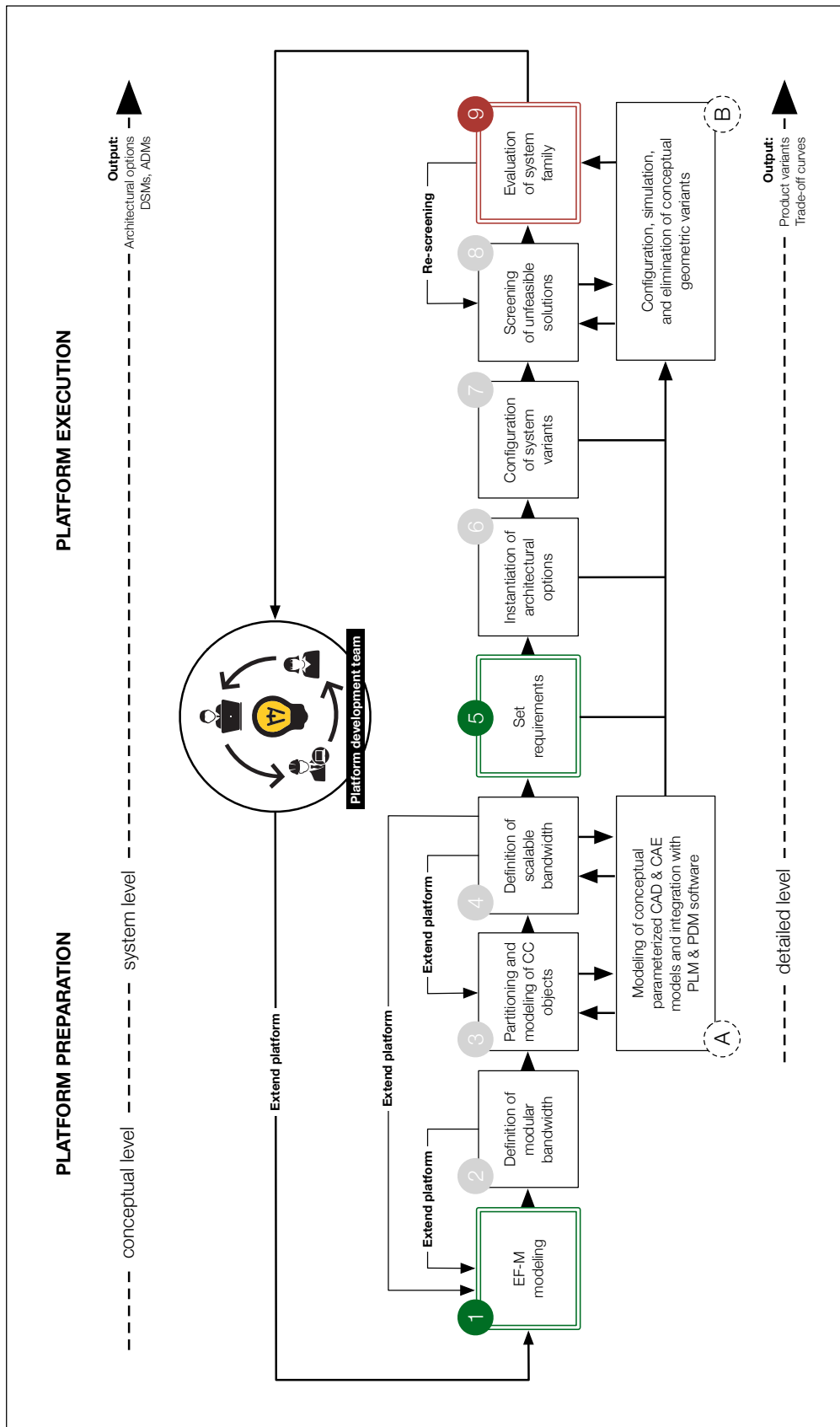


Figure 18. A platform development methodology

4.1.4 Paper D: A Producibility Model for Platform Design

Title: Mediating Constraints across Design and Manufacturing Using Platform-Based Manufacturing Operations

Background and Challenge in Short

During early platform design stages, product concepts and production concepts may be explored in parallel. However, the concurrent processes needed to support this parallel exploration rely heavily on existing models that connect the design and production domains. Current platform approaches focus on modeling of products and production systems separately, which is why parallel exploration of the two becomes difficult. While there are models that represent products and production systems respectively, there is a dearth of elaborated models that represent the interplay between the two.

Key Contribution

A producibility model is presented and is represented as a production operation: where products and production equipment meet. Essential to the fulfillment of a production operation are the operational functions (FRs) that define what the operation shall accomplish. To support the inclusion of both design and production aspects, the modeling of constraints as parameters (qs) related to both domains is devised (see Figure 19). Along a sequence of operations and controlled by the constraints, a set of design key characteristics (KCs) are transformed until the product is produced into a desired state.

Pieces of Insight

To prepare the producibility model adequately, constraints that may limit the feasibility of product-production alternatives need to be well-understood. The interplay of the constraints will influence the design key characteristics (KCs) and how products and production equipment can constrain the design space of one another. The model created is preliminary. Further development to link the model in a common platform model of product variety and variety in production to support producibility assessment is needed.

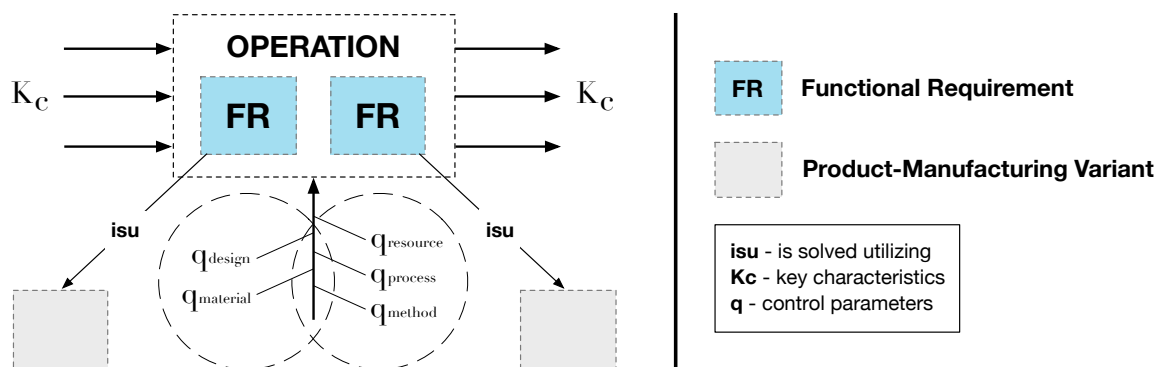


Figure 19. A platform-based producibility model that takes both design and production functional requirements (FRs) and constraints (qs) into account

4.1.5 Paper E: Literature Review on Variety-Related Concepts

Title: Product Variety and Variety in Production

Background and Challenge in Short

The sequential approach “product performance first and producibility second” is commonplace and becomes demanding when designing and producing a high product variety. While product variety is a common concept, similar concepts in production that handle variety are scattered. Currently, there is a void of research that clearly describes and explains variety in production like product variety, which may hinder the creation of proper support for producibility assessment of multiple product-production alternatives simultaneously.

Key Contribution

A systematic literature review of concepts related to variety in production and their relation to product variety is conducted and presented. The contribution of this paper is: (1) a model that describes product variety and variety in production on a general level (see Figure 20), (2) a qualitative mapping of established research concepts akin to product variety and variety in production, and (3) a depiction of the number of publications related to product variety and variety in production.

Pieces of Insight

It is difficult to separate product variety from variety in production; however, paradoxically manufacturers still struggle with the integrated development of the types of variety presented. Oftentimes, variety in production is a result of product variety; for example, without the need to satisfy a wide range of customer needs, no product variety nor variety in production may be necessary, which relate to the market strategy adopted.

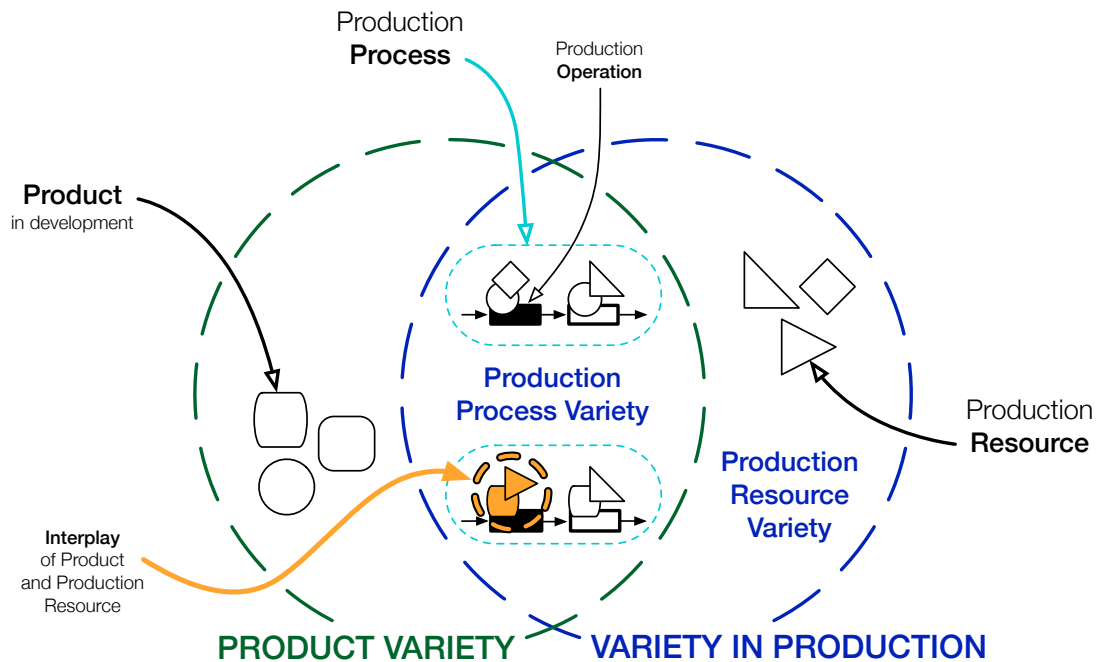


Figure 20. Product variety and variety in production and their interplay

4.1.6 Paper F: A Model for Dynamic Product-Production Platform Design

Title: Dynamic Platform Modeling for Concurrent Product-Production Reconfiguration

Background and Challenge in Short

Product variety triggers a variety of production processes, which can trigger costly and time-consuming changes to jigs, fixtures and machinery. To avoid the over-designing of products before producibility is assessed, real production capabilities need to influence the multiple designs that can be prospected during platform development. The designs need to be dynamically reassessed as new information becomes available. While the production operation is the mediator of products and production resources, production process reconfiguration may support the ability to act in fast response to changing customer and production needs dynamically and concurrently.

Key Contribution

A dynamic platform modeling approach is presented to support the modeling of a common platform model, including representations of product variety, production process variety, and production resource variety and their interplay. By executing the platform, a set of product-production alternatives, including production operation plans, can be reconfigured. Based on producibility constraints modeled, inferior alternatives can be put aside towards a producible set, adopting SBCE principles. The approach is demonstrated on a case from the aerospace industry.

Pieces of Insight

The approach should not be used for final selection of production resources and operations, but rather to indicate momentary compatibility of product concepts and production capabilities. The value of the approach lies in the dynamic platform modeling and the exposure of inferior product-production alternatives. Whereas the inferior product-production alternatives are not permanently eliminated, the platform model can be reused over generations of products and production systems when customer needs change and new technologies get introduced.

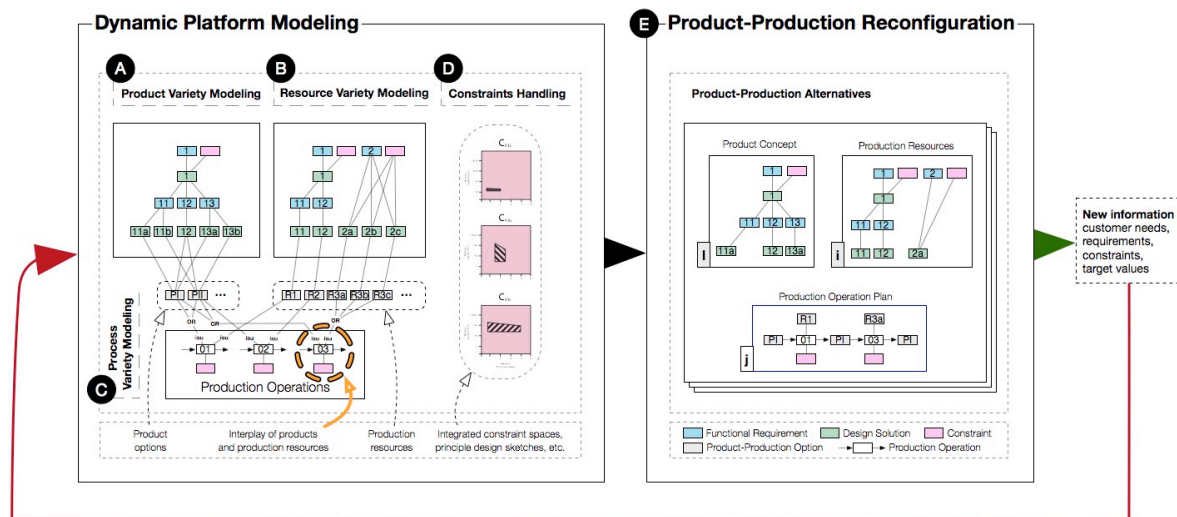


Figure 21. Dynamic platform modeling

4.1.7 Paper G: Validating Producibility Models

Title: Mitigating Risk of Producibility Failures in Platform Concept Development

Background and Challenge in Short

Aero engine manufacturers characteristically design high-variety variants of complex products and systems at low production volumes per variant. During the early stages, design engineers analyze the risk of failure during the product use phase whereas production engineers analyze the risk of failure of production machinery and tooling during the production use phase. However, failure that occur in the product-production interplay (producibility) caused by design is seldom assessed. A key reason is the lack of product-production models that support systematic producibility assessment during the early design stages.

Key Contribution

To mitigate the risk of producibility failures during the early platform design stages, a systematic two-stage producibility assessment approach based on producibility FMEA is proposed. The approach supports narrowing down product-production variants following rapid and precise producibility assessments based on both operational and quality failures. Operational failure inhibits the operation from being executed. Quality failure will cause the product to produce inferior quality levels.

Pieces of Insight

The lack of support to mitigate producibility failures may be a symptom of the separation of product and production models during early design stages. This symptom may be treated by applying the systematic two-stage producibility assessment approach devised. The great information uncertainty of early platform design stages may be partly absorbed and the risk of producibility failures mitigated.

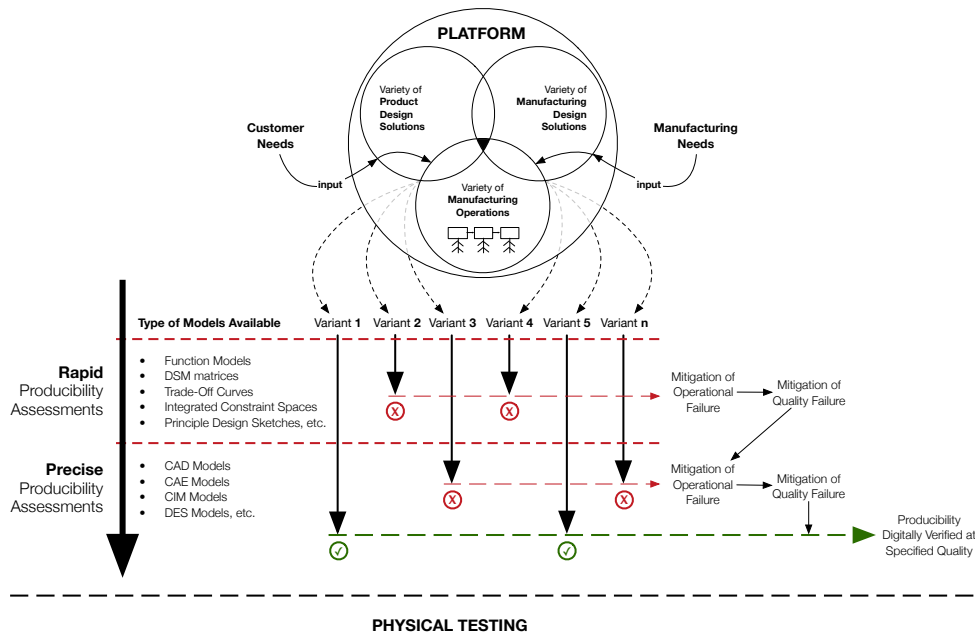


Figure 22. A systematic two-stage producibility assessment approach

4.2 BRIEF SUMMARY OF THE APPENDED PAPERS

Full texts of the appended papers can be found in the back of this thesis. Below, a brief summary of the new and key contribution of each paper is listed:

Paper A contributes a PLM architecture that link different simulation software and the corresponding processes used to generate some quantified producibility metrics.

Paper B generalizes findings of Paper A and contributes a platform assessment model based on set-based concurrent engineering principles.

Paper C delves into platform theory and contributes a comprehensive methodology that holds functions that can support collaborating platform engineering team members during conceptual, system and detailed stages of platform development.

Paper D contributes a producibility model that represents a production operation described through both functional requirements and constraints. Both design and production constraints affecting the key characteristics of a design can be modeled and mediated in a sequence of operations.

Paper E contributes a systematic literature review to contrast the concept of variety in and across design and production.

Paper F contributes dynamic platform modeling for concurrent product-production reconfiguration by modeling variety streams in and across design and production.

Paper G contributes an application-driven approach to FMEA that concerns producibility, strengthening findings of Papers A, B and D.

In Table 3, the relative contribution of each appended paper in relation to the research questions (RQs) and deliverables (Ds) posed is presented.

Table 3. The relative contribution (low, medium, high) of each appended paper according with the research questions (RQs) and deliverables (Ds) posed

		<i>Paper A</i>	<i>Paper B</i>	<i>Paper C</i>	<i>Paper D</i>	<i>Paper E</i>	<i>Paper F</i>	<i>Paper G</i>	
<i>RQ1</i>	<i>Deliverables</i>	<i>D1.1</i>	-	-	<i>medium</i>	<i>medium</i>	<i>high</i>	<i>high</i>	-
		<i>D1.2</i>	-	<i>low</i>	<i>medium</i>	<i>high</i>	-	<i>high</i>	<i>low</i>
		<i>D1.3</i>	<i>low</i>	<i>low</i>	<i>high</i>	<i>low</i>	-	<i>medium</i>	-
<i>RQ2</i>		<i>D2.1</i>	<i>high</i>	<i>low</i>	<i>medium</i>	-	<i>medium</i>	<i>low</i>	<i>medium</i>
		<i>D2.2</i>	<i>high</i>	<i>high</i>	<i>medium</i>	<i>low</i>	-	<i>high</i>	<i>medium</i>
<i>D1.1 A literature review</i>					<i>D2.1 A literature review</i>				
<i>D1.2 Models and processes representing early-stage information of a variety of products and existing production systems</i>					<i>D2.2 Platform structures and processes that can support the exchange of data and information (representing producibility) across different CAx tools</i>				
<i>D1.3 A platform development methodology that holds functions of a computer software aimed to support collaborating engineering users during various development stages</i>									

5

“In questions of science, the authority of a thousand is not worth the humble reasoning of a single individual.”

– Galileo Galilei

DISCUSSION

This chapter answers and discusses the research questions posed and evaluates the research approach and findings with respect to validity and reliability.

While the research aim presented in this thesis is to improve the ability of manufacturers to employ the business strategy of mass customization, the objective is to contribute improved responsiveness in and across design and production while building on available theories and technologies. To achieve mass customization, the concept of platform design is adopted which means solving many different design problems simultaneously.

Because it is difficult to model, generate and assess a large number of design alternatives, engineers typically rely on assumptions to make early-stage decisions and select a product concept for further advancement. The selected product concept is then typically over-designed and over-optimized on product performance before producibility is assessed for verification. Producibility is seldom part of the early design process because there is a lack of support for engineers in design and production to model, generate and assess a high number of product-production alternatives and “separating the wheat from the chaff” based on realities rather than assumptions.

The research niche identified and addressed concerns platform design for producibility. Within this niche, early-stage modeling and assessment support are devised. Such design support may improve the coordination and collaboration across design and production engineers, as well as reduce time spent and cost accumulated during late verification stages.

A high level of information uncertainty and frequent changes during the early design stages requires modification, which is why improved responsiveness in and across design and production is sought by many manufacturers. In this thesis, this responsiveness is discussed by adopting three main concepts that are common to platform design: customization, reuse and reconfiguration in and across the design and production domains. While addressing a wide range of customer as well as production needs, the variety of design problems to be solved needs to be uniformly represented. To support design-production responsiveness that permeates the technical systems, their interplay is of main concern.

Views on Design-Production Responsiveness

Because of advancements in reconfigurable and flexible production technologies, economies of scale in production may no longer be fully dependent on high volumes per part. The production bandwidth, represented by the function and performance of production resources and processes, can make up for such flexibility. However, there is a predominant belief that expensive flexible and reconfigurable production technologies can solve the mass customization challenges by themselves; however, some of these shortfalls originate from product design and cannot be solved by production technologies alone (Gu et al., 2004). Even though modern production technologies possess convincing capabilities, a product design must still prove to be producible within its function and performance, as well as within the limitations of the production machinery or else, the design may become economically infeasible. Therefore, there is a need for design support that utilize existing production possibilities and limitations – capabilities – as a basis for platform design decisions; thus, a producible design has been assessed based on production capabilities.

Uncertain product concepts cannot prove the behavior of the product and are typically difficult for industrial practitioners to represent in a way that is practical (Sorensen et al., 2018). In contrast to product concepts, existing production systems and their corresponding production resources have known behavior patterns. Therefore, the capabilities of existing production systems can be used as a basis for producibility assessments of product concepts, especially in providing a design direction during stages where there typically is none. However, to practically support such producibility assessments, these capabilities need to be integrated into the models that can represent a range of different product concepts.

To allow for design reuse during early stages and synthesize new solutions with the use of the validated solutions, these solutions need to be represented in the same type of formal ‘language’. In this thesis, formal representations of platform entities are of main concern, and common practice in industry suggest representing platform entities as rigid parts. Although many systems modeling languages that advocate more abstract representations exist, there is a lack of support for: modeling many different design problems simultaneously, including relations among and across variants and production systems, and assessing and comparing alternatives based on their producibility early on.

5.1 ANSWERING THE RESEARCH QUESTIONS

The research questions posed in Section 1.2.2.2 are answered based on a synthesis of the appended papers. To articulate the distribution of the appended papers in relation to the research questions posed, a contribution mapping has been created.

In Figure 23, the papers appended to this thesis are positioned according to their contribution to the models, methods and tool devised, as well as their relative focus on theory versus application. The dotted arrows show the order in which the appended papers (A, B, C, D, E, F and G) came to be based on the different studies (I, II and III) conducted. The thick arrows show the knowledge gained and how the new knowledge contributes to the following papers. Each paper is also linked according to its contribution in answering the two research questions posed. RQ1 is marked in blue coloring and RQ2 is marked in yellow coloring. Green coloring means that the papers contribute notably to both RQ1 and RQ2.

5.1.1 Research Question I

How can early-stage information about a variety of products and existing production systems be represented to support design-production responsiveness building on existing theories and technologies?

5.1.1.1 Representations and Modeling of Platform Entities for Producibility

To be responsive to changing customer needs in and across design and production while designing many different product concepts simultaneously, there is a need to represent a variety of products and existing production systems, as well as their interplay. This interplay can be termed producibility. Early-stage variety and producibility representations exist; however, no comprehensive frameworks in this combination have been found in literature.

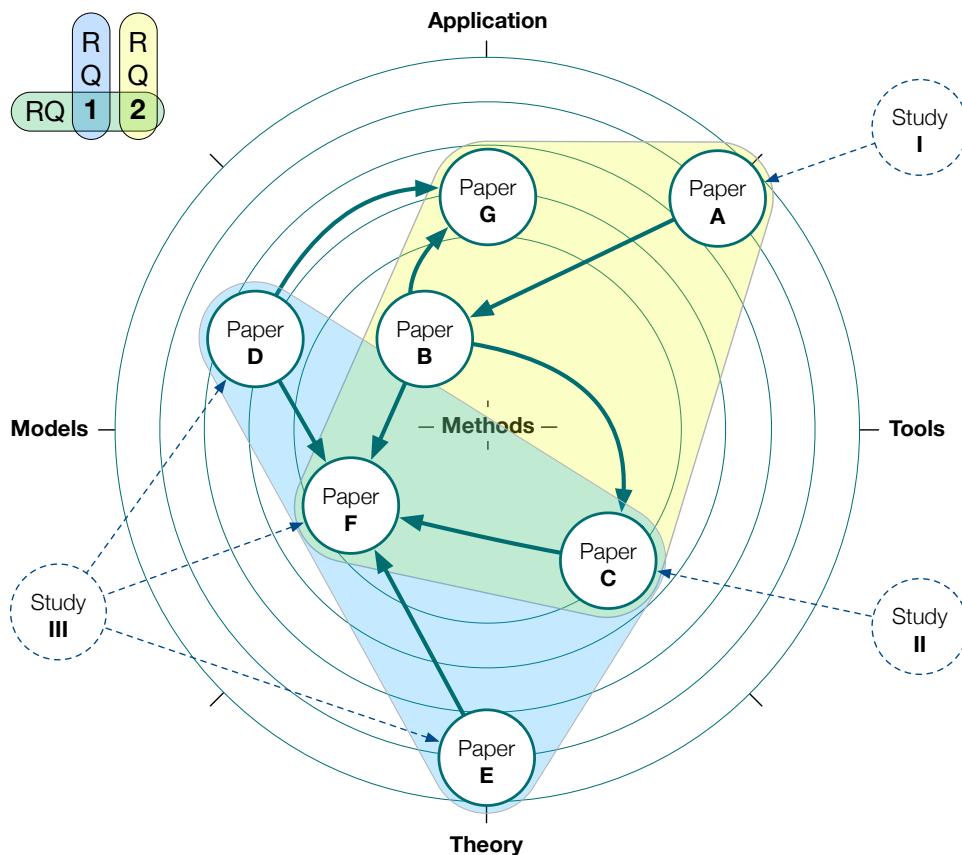


Figure 23. Contribution mapping of the appended papers

Variety can be accommodated by the concept of a platform. A platform is a common concept employed to increase sales by targeting a wide market (increased distinctiveness), as well as to reducing cost by reusing parts (increased commonality) among a variety of products. A platform is designed as a common structure of such reusable entities (Meyer and Lehnerd, 1997). Because mass customization involves meeting a wide range of customer needs using a variety of product variants, a variant derived from a platform is not supposed to hold the exact same characteristics as any other such variant.

To provide means of modeling reusable and adaptable entities including strong relations among and across variants and production systems, design and production information can be represented as system objects (Section 2.5.2). The EF-M modeling part of the object allows for modeling of design intent, history and rationale without designing geometric form.

The system object is reusable among a system variety and is represented by functional requirements, design solutions and constraints, including a set of relations and interfaces that can easily be adapted to include the latest target values derived from customer and production needs and requirements. To provide basis for responsiveness, these target values must mirror the most up-to-date knowledge of mutual customer and production needs and requirements. For instance, the target values shall be updated whenever customer needs change or when production capabilities have been extended because of newly acquired production technologies, whenever production specialists have been trained, and whenever new techniques have been adopted in physical testing and virtual simulation. The reuse and reconfiguration capabilities are essentially enabled through the concepts of both modular and scalable bandwidths which are part of the definition of the system object. The modular bandwidth concerns the type of design solutions or technologies modeled which can be functionally interchangeable. The scalable bandwidth concerns the target parameter value ranges that affect performance properties and key characteristics. The modular and scalable bandwidths can be constrained and controlled in terms of parameters linked to the product design and material, as well as the production resources, processes, and methods available. These parameters are represented in the producibility models proposed.

Because the needs of a single customer correspond to a set of functionalities and performance properties, the needs of any other customer may very well correspond to another set of functionalities and performance properties. Likewise, a functional requirement that is solved by a certain production technology may be inferior for one type of product design solution but feasible for another. Also, the range of design sizes can be accommodated based on the same principle. While modules refer to the type of solution, the scales refer to the stretching of parameters within the same type of solution. The bandwidth of the platform is fundamental to its scope and the generation of a set of product-production alternatives ready for producibility assessment. By employing the common platform model, all possible functions and solutions can be modeled for reuse and reconfiguration in a variety of product-production alternatives that constitute the base for quality assured variants designed during the late stages.

Platform design for producibility can be regarded as a process spanning the design stages. The process of modeling the platform is termed *platform preparation* and follows three main platform development stages: conceptual, system, and detailed. The main outcome of the *platform preparation* is a common platform model including information regarding anticipated product variety, production resource variety and production process variety, as

well as a producibility system. The common platform model in itself can be used to communicate design intent, rationale and history among collaborating team members and scope platform boundaries that define product variety and existing production systems. By aligned the producibility system with the common platform model, a collection of models and methods that support producibility assessments can be employed, which are further answered and discussed in RQ2.

5.1.1.2 Platform Modeling Strategies and Recommendations

A platform based on parts can only support pre-defined customization, meaning that all parts need to be pre-designed before they can be rearranged and mixed into a variety of configurations. To make manufacturers profitable within one generation of products and production systems, this mixing of physical parts may prove to be a fine strategy. However, to make manufacturers profitable over generations of products and production systems while tackling frequent modifications because of the rapid pace of changing customer needs, regulations and technologies, abstract representations of platform entities are preferred. These two modeling strategies are illustrated in Figure 24.

The way the entities accommodated by the platform are represented and structured may affect how well the two main advantages in platform design can be met. Even though these advantages may be conflicting to some degree, they can complement each other in how the platform entities are represented. In Figure 25, the two main advantages searched for in platform design and how the platform entities are represented are bluntly illustrated. Six fictitious manufacturers with different need for customization are exemplified. An arrow highlights that there is a one-way enabling modeling strategy to achieve both advantages. Whereas physical components, modules, or parts can only support economies of scale, abstract representations devised in this thesis are easily customized and can be formed into physical representations, which is why both advantages can be supported.

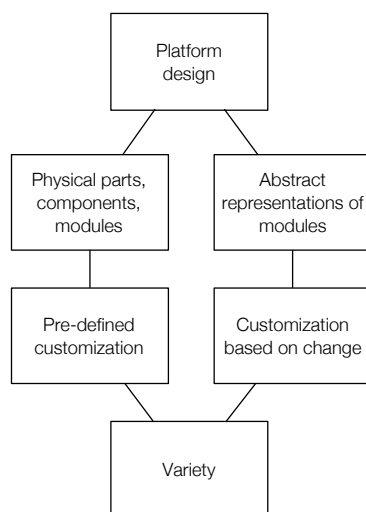


Figure 24. Platform design by modeling platform entities as tangible parts or abstract representations

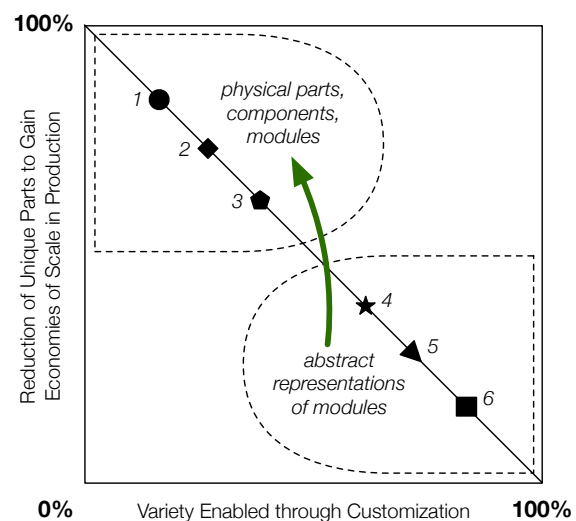


Figure 25. Two main advantages of platform design and the modeling strategies of six different manufacturers (the arrow indicates the one-way enabling modeling strategy advised)

Whereas employing a part-based platform does compromise the ability to respond quickly to market changes, abstract platform entities may stretch the ability to respond quickly to changes without compromising the ability to later in development create a physical structure that can support economies of scale in production. However, to select an adequate modeling strategy, an in-depth market analysis may be required, which is outside the scope of this research.

5.1.2 Research Question 2

How can producibility information be generated and assessed to support informed platform design decisions during early design stages?

The process of generating and assessing product-production alternatives based on the common platform model is termed *platform execution* and supports three main platform development stages: conceptual level, system level, and detailed level. The main outcome of *platform execution* is a set of product-production alternatives. The execution process can be employed to reconfigure both modular and scalable solutions, specify target values based on customer and production needs, analyze pre-embodiment and embodiment solutions, conduct concurrent screening within sets of alternatives, in addition to creating comparative information to support collaborative platform development teams in order to make informed platform design decisions.

5.1.2.1 Platform Structures for Generating Product-Production Alternatives

The system object, including the EF-M architecture with its relations across sub-objects, as well as the producibility models prescribed, are among the foremost enablers for representing the producibility information characterizing both product concepts and existing production systems and their mutual constraining factors.

Whereas variety is represented as modular and scalable bandwidths, the system object embodied in the platform modeling tool CCM provides the practical means for both platform preparation and execution. The combination of specific instances of modular bandwidth and specific target values of variant parameters represented by the scalable bandwidth form the key parts of the platform execution process. These bandwidths enable the set of generated product-production alternatives that constitute the producibility information modeled.

Apart from the EF-M architecture, which is used as the backbone of the platform, a PLM architecture can be created to enable the exchange of data and information related to multiple aspects of producibility. In the PLM architecture, CCM is a key software player supporting the reuse and reconfiguration of design and production information. The PLM architecture comprising a set of tools for producibility assessments as well as the design and production information modeled in the platform and producibility representations constitute the producibility system.

5.1.2.2 Producibility Assessments of Product-Production Alternatives

Producibility assessments are seldom deliberately made because of the lack of producibility models and assessment processes employed during early design stages. Whereas ensuring

producibility of a single design is difficult, ensuring producibility of many different designs can be overwhelming.

By generating a set of immature product-production alternatives and systematically putting alternatives with the least potential aside based on existing and generated design and production information, producibility can be assessed at an early stage. Such systematic process has been enabled by adopting SBCE principles in a platform assessment model. The producibility assessments devised in this thesis range from creating basic design and production rules to the combination of producibility simulations. The three main producibility assessment approaches covered by this thesis are:

- (1) Rule-based models represented as EF-M models, principle design sketches, trade-off and limit curves that outline design and production constraints.
- (2) Simulation-based models represented in a PLM architecture constituting CCM and a set of CAE tools to exchange producibility data and generate multiple producibility measures as a basis for evaluating new trade-off and limit curves to be reused.
- (3) Producibility FMEA, embracing both the above (1) and (2), to mitigate the risk of producibility failures at an early design stage.

5.2 EVALUATION OF THE RESEARCH PROCESS AND FINDINGS

The research methods chosen affect the quality of the data collected, and the quality of data affects the validity of the research conducted. Research that is unclear in research method may be considered questionable. Therefore, it is important to gain validity by several means, reviewed in Section 3.4. If a large number of researchers and industrial practitioners were to accept certain findings that build upon and contribute to the existing state-of-the-art, these findings may be considered valid, at least at a given point in time.

5.2.1 *Validation and the Issue of Generalization*

The models, methods and tool devised to support platform design for producibility have mainly been demonstrated for aerospace application. However, studies from the automotive and power industries have been conducted to support analytical generalization. In contrast to analytical generalization, statistical generalization that characterizes quantitative research has not been adopted because of the qualitative data needed to answer the research questions; thus, the research to be conducted defines the choice of methods for data collection. It is, however, duly noted that certain research findings are deprived of analytical generalization and additional research is necessary to confirm the usefulness of models, methods and tool devised. Additional case studies from other industries and using other types of products and production systems are called for.

Part of validating the research can be made through verification by acceptance (Buur, 1990), i.e. experts within the field accept the research contributions. Papers A, B, D, E and G are peer reviewed conference papers, accepted for publication and presented at the respective conferences. Paper C is a peer-reviewed journal paper, whereas Paper F is submitted to a journal and is in the process of being peer-reviewed. Successive findings have also been presented at the Annual Wingquist Laboratory Day, during which a hundred

practitioners from different manufacturing companies generally attend. Representatives from these companies have shown an interest in specific research findings presented in this thesis.

5.2.2 *Verification and the Issues of Completeness and Consistency*

In qualitative research of this kind, verification refers to the process of checking, confirming, ensuring, and arriving at incremental certainty during the research process, thus providing research rigor (Morse et al., 2002). To verify a piece of research, one can evaluate the logic of the findings in terms of completeness and consistency (Buur, 1990). In essence, research findings show completeness if they fit into established theories and concepts, and these findings show consistency if the terminology is clear and conforming, which can be accomplished by moving back and forth between the descriptive and prescriptive parts of the research to ensure coherence among questions, literature, data collection strategies, and analyses (Morse et al., 2002). By adopting a research process (described in Section 3.5) that builds on the notion of combining empirical data from different settings (Section 5.2.1) and a broad range of literature, such iterations have been conducted. The research presented in this thesis has adopted a broad and sound theoretical foundation with references from Engineering Design and Systems Engineering, as well as from the design and production domains. In this multidisciplinary context, consistency can be difficult to achieve, which is why some key definitions and concepts underpinning the research presented have been clarified in Chapter 1.

5.2.3 *Evaluating the Research in Terms of Quality, Bias and Reflexivity*

The evaluation of the research presented in this thesis has been based on the quality of studies performed and the reliability of findings. Design research relies upon the application of rigorous methods in both the construction and evaluation of a design model (von Alan et al., 2004). Long-term collaboration with corporate partners provides a viable basis for application-driven studies that merge academic and industrial needs.

Whereas the findings provided in this thesis comply with and add to the existing frame of reference, it is possible that bias are masking the true nature of the analyses. Bias can affect decision-making processes. To reduce the risk of focusing on certain information at the expense of other information, a wide range of references of different authors has been included and concepts have been discussed in collaboration with researchers and industrial practitioners. However, during a five-year research period, there is a risk of overlooking contradictory research findings which may distort perception and thinking. To reduce this risk, publications spanning a wide range of years have been reviewed. Anchoring and shaping findings based on initial decisions are also risks, which is why the research has been continuously re-evaluated by discussing the phenomenon addressed with both industrial and academic practitioners, for example during industrial and academic conferences.

As a researcher it is essential to remain open, sensitive, creative, insightful and willing to relinquish any ideas that are poorly supported regardless of the potential they may provide at first sight (Morse et al., 2002). Therefore, the following perspective on research has been adopted: findings cannot be seen as immutable truths, but must rather be regarded as successive approximations (Russell, 2004) prepared to be probed and improved by others.

6

“Science does not aim at establishing immutable truths and eternal dogmas; its aim is to approach the truth by successive approximations, without claiming that at any stage, final and complete accuracy has been achieved.”

– Bertrand Russell

CONCLUSION

This chapter concludes the findings and discussion and postulates a few key contributions as well as some areas for future research within platform design for producibility.

6.1 CONTRIBUTION AND CLAIMS

The findings show that platforms can be resiliently designed to support early-stage producibility assessments of customized product concepts.

Late-stage and static verification of producibility is not enough to support development efficiency during platform design. Although tools used to verify aspects of producibility of a sole finalized design exist, there is a dearth of support for assessing multiple producibility aspects of many different design alternatives simultaneously, especially during early design stages when customer needs and requirements frequently change.

In design, a platform structure of parts is rigid and often characterized by redundant data and weak relations among and across product variants and existing production machinery. To improve the ability to reuse design and production information for assessing new concepts more quickly, non-rigid platform representations of product concepts and existing production machinery are necessary but not clarified in literature and rarely implemented in industry.

In this thesis, a platform structure of system objects is devised, which are more resilient than parts and better suited to platform-based customization, supported by researchers such as Ferguson et al. (2013). System objects can accommodate early-stage design and

production information, including functional requirements, intangible design solutions and constraints, as well as strong relations across entities and domains.

To respond quickly to changes in and across design and production, modeling a common platform using system objects, as well as a complementary producibility system, is advised. Such a platform and producibility system can be prepared and executed through the following:

Platform Preparation: Dynamic modeling of a common platform represented as reusable and adaptable system objects accommodating early-stage design and production information about an anticipated product variety and existing production resources and processes, including the creation of a producibility system.

Platform Execution: Producibility assessments can be achieved through concurrent reconfiguration of the common platform model, generating a set of product-production alternatives and estimating their producibility using rule-based and simulation-based models. Rule-based models represent existing producibility information and simulation-based models can be used to generate new producibility information as a basis for creating trade studies. In this way, non-producible alternatives can be put aside until new information becomes available and the platform needs to be modernized.

Adopting platform preparation and execution processes can stretch the ability to respond quickly to changes in and across the design and production domains without compromising the ability to form a part-based platform structure during the late design stages, supporting economies of scale in production.

Whereas both customer and production needs change, early-stage producibility assessments are by no means static. Findings emphasize that early-stage models and assessments must be dynamically considered as they cannot verify producibility, rather only provide an estimation and direction in the platform design process. Given the platform design support provided, manufacturers can:

- Represent product and production variety as reusable and adaptable system objects with links to producibility constraints, available over generations of products and production systems.
- Dynamically and concurrently model, generate and assess product-production alternatives under producibility constraints, as well as put inferior alternatives aside until new information becomes available.

Theoretically, the number of costly and time-delaying late-stage modifications of product designs, production configurations, or both, can be reduced.

6.2 FUTURE WORK

To enable design-production responsiveness by producibility assessment while preserving design freedom during platform design, a great deal of work remains to be accomplished.

- To prove usefulness on a large scale, the models, methods and tool devised need to be validated and generalized in other industrial applications than those presented.
- Concerning customization during fluctuating market demand, the findings do not fully comply. Production metrics that relate to this demand, such as Work in Progress (WIP), utilization rate and cycle time are not extensively elaborated upon. Models used to estimate these metrics typically require a high degree of certainty compared to those devised in this thesis; yet, it would be of interest to study how production metrics may be employed to estimate producibility during early design stages. An initial study, employing SysML, was conducted to investigate the feasibility of such an approach (Gong et al., 2017). However, SysML has drawbacks concerning capturing interactions among diagrams (Chandrasegaran et al., 2013), which is important to support reuse of design and production information (ElMaraghy et al., 2013). Therefore, an extended study may be conducted employing the system object model devised in this thesis.
- By modeling system objects among and across product variants and production system, relations can be strengthened and redundant data can be purged, which cannot be achieved conducting platform design based on parts or CAD models. However, there is still a lack of research regarding relations and data content across models of different abstraction level. Function models that are easily modified seldom have an established connection with product parts and production systems. On this note, Landahl et al. (2018) concluded that transcending from physical assets to function model, and from function model to new concepts is a challenge for future studies.
- The models and methods presented support early-stage platform modeling for producibility using models that have not yet been finalized in design; however, the methods devised in this thesis fail to support producibility assessments on models completely beyond form. Although the reuse and reconfiguration of information regarding product concepts and capabilities of existing production resources may be quite viable in putting inferior product-production alternatives aside until new information becomes available, additional research on and creation of other types of producibility assessment methods are advised, for example matrix-based methods similar to initial attempts by Ball (2015) and Landahl et al. (2015).
- The CCM software can be further improved to become even more useful in supporting platform design for producibility in practice. CCM can potentially also be supplemented by assessments of other lifecycle aspects, such as sustainability or maintenance of products and production systems, respectively so that comprehensive trade studies can be conducted using a common platform model.
- Software is highly integrated in today's mechanical products and controls much of the flexibility and automation of modern production systems. The notion of how these flexibility and automation aspects, embedded in software, can be represented with respect to the producibility models presented in this thesis are subject to future investigations. In this regard, the concept of 'software product lines' (Hallsteinsen et al., 2008) is of interest and needs to be further studied in relation to platform design for producibility.

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