Modular and Platform-based Product Development in the Process Industry

Enabling Efficient Product Variety Through Complexity Management

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BY
RASMUS ANDERSEN

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AALBORG UNIVERSITY
DENMARK

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CV

Rasmus Andersen was born in Aalborg, Denmark and since a very early age was certain that engineering was the right path for him. After completing a BSc degree in Global Business Engineering in 2016 at Aalborg University, he finished a MSc in Operations and Supply chain management in 2018 at the same institution. Since 2018, Rasmus has been with the Mass Customization research group at the Department of Materials and Production, Aalborg University. In 2019 he started as a PhD Fellow on a research project about product platforms in the process industry with an industrial partner. During his PhD project, Rasmus enjoyed a three-month stay as a visiting researcher with the Department of Industrial Engineering at the University of Bologna, Italy.

ENGLISH SUMMARY

This thesis presents the result of a three-year long research project at the Department of Materials and Production, Aalborg University, which is done in collaboration with an industrial partner company from the process industry. The project takes outset in the overall practical problem experienced by the industrial partner: how to efficiently deliver customized products through modular and platform-based product design principles. This problem is relevant as the industrial company experiences market pressures of shorter product development lead times, diverse customer needs, and lower product costs. These challenges are experienced at large by manufacturing companies whether they belong to the discrete industry (products designed and manufactured based on assembled and fastened structures) or the process industry (products designed and manufactured based on e.g., mixed, separated, or formed compositions). In discrete industry, exploiting modular and platform-based product architectures as means of balancing the internal and external complexity experienced by companies are not uncommon. Indeed, methods, tools, and benefits related to these types of products are reported at plenty in literature. However, this is not the case in the process industry, where literature and industrial examples are scarce, despite experiencing similar market pressures. Consequently, this research project aims to solve this practical problem by developing and applying methods and tools for modular and platform-based product design with practical relevance, as well as report potentials of this approach, in a process-industrial context. Taking outset in design science research, this project has designed multiple different artifacts, using literature reviews and case studies to ground the artifacts in literature and demonstrate their efficacy. As mentioned, this research project has found that literature on the topic studied is scarce, and industrial cases even more so. Nevertheless, studies applying constructs and methods from discrete industry in the context of the process industry have been identified, lending credence to the application of existing methods in a novel context. Through analysis and adaptation of existing methods this research project has developed, and demonstrated application of, novel artifacts to support process industry manufacturers in developing modular and platform-based products. Based on instantiations of artifacts as well as reviewed literature, potentials and challenges like those reported in discrete industry were identified, further arguing in favor of this development approach. Consequently, this project has contributed to research and practice by thoroughly investigating and demonstrating the application of modular and platform-based product design principles through the design and instantiation of multiple artifacts.

DANSK RESUME

Denne afhandling er resultatet af et 3-årigt forskningsprojekt ved Institut for Materialer og Produktion på Aalborg Universitet i samarbejde med en industriel partner virksomhed fra procesindustrien. Projektet tager i det overordnede problem, som opleves af partnervirksomheden: hvordan kan kundetilpassede produkter effektivt realiseres via modulære og platformsbaserede produktdesign principper. Dette er et praktisk relevant problem da partnervirksomheden oplever pres fra markedet ift. kortere produktudviklingstider, forskellige kundekrav, og forventning om lavere priser. Disse udfordringer opleves generelt blandt produktionsvirksomheder, uanset om de tilhører den diskrete produktionsindustri (kendetegnet ved produkter designet og produceret ud fra samlede eller fastgjorte strukturer) eller procesindustrien (kendetegnet ved produkter designet og produceret baseret på blandede, separerede eller formgivne strukturer). I diskret produktionsindustri er det ikke ualmindeligt at benytte principper om modulære og platformsbaserede designs til at balancere den interne og eksterne kompleksitet som virksomhederne oplever. I litteraturen findes rigelige eksempler på metoder, værktøjer og fordele ved denne type produkter i diskret produktionsindustri. Det samme gør sig dog ikke gældende for procesindustrien, hvor litteratur og eksempler fra industrien er få på trods af at begge industrier oplever lignende markedskrav. Dette forskningsprojekt søger derfor at løse dette problem ved at udvikle og anvende metoder og værktøjer til modulær og platformsbaseret produktudvikling som har en praktisk relevans samt at rapportere potentielle fordele ved denne tilgang i en procesindustriel kontekst. Med udgangspunkt i en designvidenskabelig tilgang har dette projekt designet forskellige artefakter. En kombination af litteraturstudier og casestudier har henholdsvis forankret forskningen i den eksisterende vidensbase samt demonstreret dens praktiske relevans. Dette forskningsprojekt har som nævnt konkluderet at mængden af eksisterende litteratur samt eksempler fra industri er begrænset. Dog er flere studier, som anvender begreber og metoder fra diskret produktionsindustri i en procesindustriel kontekst blevet identificeret, hvilket giver tiltro til anvendelse af eksisterende metoder i en ny kontekst. Gennem analyse og tilpasning af eksisterende metoder har dette forskningsprojekt udviklet og demonstreret anvendelse af nye artefakter til at understøtte virksomheder i procesindustrien, som ønsker at anvende modulære og platformsbaserede principper til udvikling af deres produkter. Med udgangspunkt i instantieringer af artefakter såvel som undersøgt litteratur har projektet identificeret potentialer og udfordringer tilsvarende diskret produktionsindustri, hvilket giver yderligere tilsagn om værdien af denne udviklingstilgang. Dette projekt har således bidraget til såvel forskning som praksis ved indgående at undersøge og demonstrere anvendelse af modulære og platformsbaserede produktudviklingsprincipper, hvilket er gjort gennem design og instantiering af designede artefakter.

ACKNOWLEDGEMENTS

While a PhD project and research in general is sometimes viewed as the result of a solitary researcher sitting in a dimly lit office behind a huge stack of unorganized papers, this could not be further from reality – well, at least the part about working alone. I would truly not have been able to complete the massive undertaking a PhD project is without the support I have received throughout the past three years.

I would first and foremost like to thank the industrial partner company for making this project possible. My gratitude goes to the collaborators on my research activities as well as the colleagues in the R&D department with whom I have had the pleasure to share offices with part time.

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Aalborg, March 2022

Rasmus Andersen

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CHAPTER 1. INTRODUCTION

This section introduces the PhD project by first motivating the research in a broader scope followed by the concrete introduction to, and motivation of, the collaborating company, which forms the industrial case for this project.

1.1. MOTIVATION

> *"Any customer can have a car painted any color that he wants so long as it is black."*

So said Henry Ford, founder of Ford Motor Company, so famously about his company's Model T (Crowther & Ford, 2005). And while this thesis is by no means the first to include this quote, the power of it lies in the stark contrast it paints when compared to today's car market, where you can get (almost) any color you like. As part of their Audi Exclusive initiative, the German automaker offers its customers the ability to get nearly any color they want turned into a customized paint for their car (Audi AG, 2022). However, the exterior paint is but one of myriads of options that car buyers can choose between when customizing their new car to fit their preferences.

The proliferation of product variants available to customers can be observed in virtually every market and is a result of the move away from the one-size-fit-all paradigm of mass production and towards the market size one paradigm of mass customization (Koren, 2010; Pine et al., 1993). The plethora of product options available to customers means that they have become accustomed to ever-more product variants, cheaper products, shorter product life cycles, and higher product quality. These factors result in increased external complexity, which force manufacturing companies to respond accordingly or see their competitiveness eroded. The responses adopted by these companies tend to increase their internal complexity, often at the expense of higher product costs and lower performance (Piya et al., 2017) across the organization (Andersen et al., 2019).

These market forces have coerced manufacturing companies to diverge from traditional single product, sequential development processes and to a greater extent adopt parallel product development approaches, where products are not designed one-at-a-time to meet customer needs. Rather, products are viewed as belonging to a family of similar products, which share some characteristics. Such a perspective facilitates elicitation of needs for customization and opportunities for standardization of components. This aggregate view on new product development is fundamental to the concept of platform-based product development which has been applied successfully by manufacturers various products such as power tools (Meyer &

Lehnerd, 1997), cars (Simpson et al., 2006), and household appliances (Sanchez, 2004), to name a few. However, the market requirements driving this change affects not only manufacturers of assembled products. The changes are likewise observed for products which are not assembled by nuts and bolts or other fastening techniques, but rather manufactured through chemical reaction processes or other non-assembly processes, such as food (Fuller, 2016) or chemicals (Crama et al., 2001) – i.e., process industry products. Even so, despite being subjected to similar market trends, the process industry is sparsely covered regarding examples of platform-based products (Andersen et al., 2022d) yet can potentially benefit from the same product development principles (Meyer & Dalal, 2002) successfully demonstrated for assembled products.

1.2. INDUSTRIAL PARTNER

This PhD project is made in collaboration between Aalborg University and an industrial case company in the process industry. The case company experiences challenges related to the research topic of this project, thereby making it a suitable case contributor. The company is a medium-sized manufacturer of technical chemical products and has experienced an increase in their internal complexity in terms of both product development and production processes. These changes are mainly in response to external pressure in the form of changing customer needs and regulations.

The company is involved primarily in the business-to-business market with customers including large retailers situated mostly in Northern Europe but reaching as far as customers in the Americas and Asia. The company's product portfolio comprises more than a thousand different product variants spread across 18 product families. Figure 1 illustrates the development of the company's product portfolio from 2010 to 2018. The figure demonstrates a relatively high renewal rate of the product portfolio which, over the period covered, has averaged 32 % corresponding to an introduction of almost 400 new product variants every year.

Products are typically customized to individual customer preferences, whether it be the performance or appearance of the chemical product, the size and shape of the packaging, the number of consumer guidance labels, or the total cost of the product. These factors limit the productivity of the product development resources in the company as every customized product recipe is engineered to the specifications of the customer, often involving several iterative development loops involving expensive laboratory testing. A concrete example of this challenge is the company's documentation workload which has increased by 36 % over a four-year period and is expected to increase by more than 43 % in the following four years. Furthermore, as the total product portfolio size is nearly constant, an almost equal number of products are phased out every year, further adding to the complexity experienced by the company.

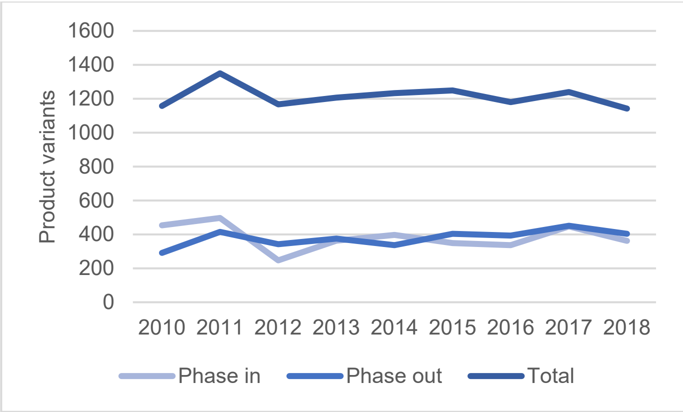

Figure 1: The case company's product portfolio development over an eight-year period.

A key competence of the company is their high-performing, environmentally friendly product formulations, which make up more than 50 % of the product portfolio and is a continually increasing part of the business. However, the increase in more sustainable products brings its own challenges, as product development becomes more complex due to the transition from petrochemical-based materials towards more sustainable materials, design limitations imposed by consumer label certifications, and an ever-present desire to reduce product costs and development lead times.

As described in Section 1.1, many of these challenges are not unique to the case company but experienced at large by manufacturing companies in both discrete and process industries. Inspired by the successful application of platform-based product development in discrete industry, so does the case company seek to gain knowledge of these principles and methods as well as how to apply them in the context of their industry. In doing so, the company aspires to eventually reap benefits similar to those reported by the leading manufacturers of platform-based products, such as lower product costs, reduced product development lead time, more efficient product customization, and higher development capacity.

CHAPTER 2. BACKGROUND

The purpose of this section is to provide a theoretical context to the research project. This is achieved by first describing the industry within which the project is relevant and subsequently introducing the concepts and principles that underpin the main research topic i.e., platform-based product development.

2.1. THE PROCESS INDUSTRY

Manufacturing industry can fundamentally be divided into either process or discrete industry (King et al., 2008) and Andersen et al. (2022d) noted that definitions of these industries vary according to the specific perspective adopted. From literature, they identified three different perspectives:

1. **Process types:** continuous, batch, mixing, blending, forming, baking, extrusion, etc. See e.g., Abdulmalek et al. (2006).

2. **Product characteristics:** solids, powders, slurries, liquids, gases, sheets, rolls, etc. See e.g., Dennis and Meredith (2000)

3. **Industry sectors:** chemicals, food and beverages, metals, minerals, pharmaceuticals, pulp and paper, steel, etc. See e.g., Samuelsson et al. (2016).

Depending on the perspective adopted, a broader or narrower view on the process industry is achieved (Andersen et al., 2022d). Combining the different perspectives, however, shows that the process industry comprises multiple sectors producing a wide variety of products using different production processes. Figure 2 provides examples of typical process industry product types and their associated industry sectors.

Figure 2: Examples of products typically produced by process industry companies. Based on (Abdulmalek et al., 2006; Dennis & Meredith, 2000; King et al., 2008).

To the average consumer, the process industry may seem somewhat distant. However, a great share of the products produced by this industry are used by consumers on an everyday basis (e.g., glass ware, food, beverages, and cleaning agents), while others are primarily of industrial relevance (e.g., ore, specialty chemicals, polymers, and lubricants).

Regardless of the perspective adopted or topic studied, considering the process industry as a homogenous entity of products and production systems results in an oversimplification and provides a distorted view of reality. Even so, several characteristics have been identified in literature, for which more manufacturers share characteristics within the process industry than with manufacturers in the discrete industry.

2.1.1. PROCESS INDUSTRY CHARACTERISTICS

Although the focus of this PhD project is modular and platform-based product development, the close relationship between products and production processes in the process industry (e.g., Frishammar et al., 2012; Lager, 2017) warrants the discussion of industry characteristics relating to subjects besides product characteristics, such as production processes and inventory management issues. The following, therefore, describes a variety of process industry characteristics and issues from different management disciplines, all relating to the unique characteristics of process industry products when compared to discrete industry products. These characteristics are listed in Table 1 and elaborated on in the following.

Table 1: Typical characteristics, relevant to product development, differentiating process industry from discrete industry. Based partially on (Andersen et al., 2021).

Process industry	Discrete industry
Variable raw material quality	Predictable material quality
Often simpler product structures	Product structures are often complex and multi-level
Product as blended formula or recipe	Product as assembled structure
Material transformation	Material reconfiguration
Products are continuous and require containerization	Products are discrete and do not require containerization
Existence of co- and by-products	No co- or by-products
Production setup differentiated by discretization point	No discretization point in production
Frequent storage limitations	Storage limitations are rare
Changes often restricted by regulations	Changes typically not limited by regulations

In process industries, raw material quality is often variable (Abdulmalek et al., 2006; Crama et al., 2001; Finch & Cox, 1988), which is attributed to the natural origin of many input materials (Fransoo & Rutten, 1994). Examples include differences in product composition for agricultural products (Akkerman et al., 2010) and crude oil (Fransoo & Rutten, 1994). Such uncertainty in composition of input materials is rarely a cause for concern in discrete industry, where materials are often manufactured to standards and thus more predictable.

The complexity of the product structure is another differentiating characteristic. Typically, process industry products are comprised of few input materials and have simple product structures (Lyons et al., 2013). Even so, while process industry products may not be complex, they may still be complicated (Dennis & Meredith, 2000). The breath or depth of a BOM is, therefore, not necessarily indicative of how simple a product is to develop or manufacture.

Whereas discrete industry manufacture products by means of assembly techniques, process industry products are typically produced by mixing or blending operations (Lyons et al., 2013) or other transformative processes (King et al., 2008). Another characteristic of these production processes is that materials are often transformed into identifiably new products rather than being reconfigured, as is the case for discrete industry (Floyd, 2010).

The materials most often used in production processes in the process industry are in the form of liquids, powders, solids, or gasses (Lyons et al., 2013). Common to these materials is that they are unable to maintain their properties (e.g., shape, performance, quality) without being containerized. This contrasts with discrete industry products which maintain their properties without containerization. (Abdulmalek et al., 2006; Dennis & Meredith, 2000)

In discrete industry, products are designed from components to result in a specific configuration. Process industry products, however, are often the result of processing a raw material by means of e.g., chemical reactions or mechanical separation. Such processes typically result in multiple output streams: the desired product and one or more products which may or may not be valuable to the company (Flapper et al., 2002). These adjacent products are referred to as co- or by-products, respectively (Ashayeri et al., 1996; Flapper et al., 2002).

Although the process industry is considered as comprising only continuous products and production systems, nearly every product becomes discrete at some point (King et al., 2008). The point at which this occurs is the discretization point which may reside at an early or late stage of production (Abdulmalek et al., 2006).

Raw materials used in the process industry are often perishable (Finch & Cox, 1988; Flapper et al., 2002; van Kampen & van Donk, 2014) and have limited shelf life (Lyons et al., 2013). This imposes frequent limitations on both storage conditions (Crama et al., 2001) and storage time, and may apply to semi-manufactures as well as finished products (Flapper et al., 2002). Furthermore, the non-discrete nature of process industry products means that inventory management is challenged as use of storage silos limit the storage of products (Crama et al., 2001; Flapper et al., 2002) to a one-to-one or one-to-many relation between product types and storage silos, but never the opposite.

Lastly, industry regulations pose a more pronounced challenge in the process industry compared to discrete industry (Kohr et al., 2017). The presence of these regulations limits the feasible choices concerning product or process changes for process industry companies.

2.2. PLATFORM-BASED PRODUCT DEVELOPMENT

Platform-based product development was popularized by Meyer and Lehnerd (1997) in their seminal book, where they provided compelling real-world cases and tools proven in industry to let others be inspired and pursue improvements through platform-based products in their own organizations. Since then, a multitude of knowledge has been published about platform-based product development. So, what exactly *is* a product platform? The answer to that question may be specific or broad, depending on which definition is adopted (Simpson et al., 2006). Definitions range from focusing on the "*components, modules, or parts*" (Meyer & Lehnerd, 1997, p. X) over "*elements, especially the core technology*" (McGrath, 1995) to the most abstract: "*[a] collection of assets*" (Robertson & Ulrich, 1998). Although omitted from the quotes, all three definitions emphasize that product platforms are about the components, elements, or assets that are shared across all product variants within a product family i.e., the common core of each derivative product variant.

2.2.1. KEY CONCEPTS IN PLATFORM-BASED PRODUCT DEVELOPMENT

Designing a product platform to support efficient development of a product family and its constituent product variants requires knowledge and application of the core concepts related to platform-based product development, listed in Table 2.

Table 2: Essential concepts in platform-based product development and their descriptions.

Concept	Description
Product architecture	The arrangement of, and relation between, physical components in a product.
Module	A collection of components that fulfil a specific function, and which may be added or subtracted from a product with respect to functional needs.
Interface	The governing link between modules, specifying the limits and constraints for compatible modules.
Product platform	The shared product elements, which have been standardized across a product family.
Product family	A collection of related product variants derived from the same product platform.

Product architectures can be configurable or parametric, depending on the nature of the product customization approach (Simpson et al., 2006). Configurable product architectures are characterized by accommodating varying performance or aesthetic needs through different modules. The modular structure of a personal computer is a classic example of a configurational architecture, where functionality or performance is adjusted by e.g., adding additional memory sticks or upgrading the graphics card to a more powerful model. Parametric architectures utilize modules which may accommodate different customer needs by stretching dimensions. The core section of a turbofan engine is an example of a parametric product architecture as the thrust capacity of the engine can be increased by adjusting the dimensions of this module (Simpson et al., 2006).

Modules are designed to support the strategic objectives of a business (Erixon, 1998) such as more efficiently accommodating customers' individual aesthetic preferences or meeting varying performance requirements across market segments. Cars today utilize modular designs, as buyers may customize performance or aesthetics by choosing between different power trains or selecting different body finishes, respectively. Good modular design is characterized by achieving functional purity of the modules within a product (Erixon, 1998; Ulrich et al., 2020), although absolute functional purity may not yield the best practical design. Rather, the optimal product design is often achieved through a balance of integral and modular design elements. (Ulrich et al., 2020)

Connecting modules and enabling overall product functionality are the interfaces in between modules. Multiple types of interfaces exist with different purposes, such as ensuring geometric fits or transmitting information, forces, fluids, or energy (Erixon, 1998). A well-known and ubiquitous interface is the USB port and connector, which also has the benefit of demonstrating the existence of different interface types. To function, a USB connector must fit in the port and remain securely attached to avoid signal interruption. The first aspect is achieved by the geometric fit (fixed interface) whereas the second aspect is achieved by the six small tabs, which apply pressure (force transmitting interface) to the inserted USB connector and holds it in place. To ensure that the connected device can function properly, the USB interface can supply power (energy transmitting interface) and communication signals (information transmitting interface). The specification of such interfaces is an important part of modular and platform-based product design as they determine the limits of product customization.

During a major product redesign program at Black & Decker in the 1970's the company designed a common electric motor platform utilizing a new insulation technology to be used across its power tool product families (Meyer & Lehnerd, 1997). Today, power tool manufacturers like DeWalt have adopted battery pack platforms which can be used across multiple product families (Rubenstone, 2016). Thus, everyday examples of product families include types of power tools (e.g., drills, saws, grinders), consumer electronics (e.g., cell phones, tablets) and household appliances (e.g., dishwashers, ovens, stoves). Product platforms – or common units – may be implemented across product variants within a product family or across multiple product families, yielding different degrees of economies of scale for the manufacturer.

2.2.2. POTENTIAL BENEFITS AND CHALLENGES OF PLATFORM-BASED PRODUCT DEVELOPMENT

The ability to efficiently customize products towards individual customers or utilize common assets across entire product families are but some of the benefits that companies have realized from adopting platform-based product designs. Indeed, platform-based products can provide benefits to manufacturing companies through multiple means, such as:

- Reduced time-to-market (Vickery et al., 2015)
- Increased market share (Simpson et al., 2006)
- Higher production flexibility (Simpson et al., 2006)
- Improved product quality (Pirmoradi et al., 2014)

- Lower manufacturing costs (Liu et al., 2010)
- Lower product costs (Cameron & Crawley, 2014)

Although the potential benefits are plentiful, platform-based product development can also be challenged by several drawbacks. These include risk of cannibalization within a company's product portfolio, due to design limitations imposed by platforms (Simpson et al., 2006), higher initial development costs due to more complex development (Ulrich et al., 2020), and potentially higher product costs for low-end products due to component sharing across product families (Bhandare & Allada, 2008).

2.3. EARLY WORK ON PLATFORM-BASED PRODUCT DEVELOPMENT IN THE PROCESS INDUSTRY

While examples and literature on platform-based products in process industry are few, earlier works on this topic exist. One of the earliest examples of platform-thinking in process industry addressed the issue of balancing variety and commonality in products and production at a plywood manufacturing company (Atkins et al., 1984). They did so by identifying optimal plywood sheet thicknesses to support the variety demanded by the market. Among the first to explicitly relate constructs and terminology of platform-based product development to the process industry were Ulrich and Eppinger (2000), who described Intel's use of platform technology for their chipsets, and Meyer and Dalal (2002) who – besides also including an industry example of integrated circuits – presented platform-based photosensitive film products. Common to these early studies on platform-based products in a process industry context are their positive assessment of this product development principle for the cases reviewed, providing credence to the feasibility of applying the concept in this industry.

CHAPTER 3. STATE OF THE ART

This section presents the state-of-the-art literature and its main findings related to platform-based product development in the process industry. The content of this section summarizes the findings from Andersen et al. (2022d) concerning drivers of platform-based development, definitions of key concepts, and related methods and approaches.

3.1. DRIVERS OF PLATFORM-BASED PRODUCT DEVELOPMENT IN THE PROCESS INDUSTRY

In Chapter 1, the motivation of discrete industry manufacturing companies regarding adoption of platform-based product development was alluded to. These driving factors were to some extent likewise shared by the case company. But what about the process industry at a larger scale? What factors drive the interest in platform-based product development in this industry? Andersen et al. (2022d) based their analysis of this question on three core drivers of platform-based product development originally proposed by Muffatto (1999): cost reduction, productivity of product development, and development lead time reduction. Overall, while the frequency of occurrence differs between the three categories, the frequency range is between 47 % to 57 % with development lead time reduction representing the lowest occurrence and cost reduction the highest occurrence.

While several studies note benefits like those found in discrete industry, the broad interest in platform-based product development from a cost reduction perspective is the ability to achieve higher yielding chemical processes. This is partly to make biofuels more competitive with fossil-based fuels and partly to achieve economies of scale for specialty chemicals (Andersen et al., 2022d). Other aspects identified by Andersen et al. (2022d) include reduction of costs related to production, supply chain, or the environment in general.

From a product development productivity perspective, several studies likewise cite benefits achieved in discrete industry cases and focus on how product variants can be generated efficiently from a set of common elements, or how complexity of product development projects may be reduced (Andersen et al., 2022d).

In addition to studies focusing on general reductions in development lead time, the ability to reduce testing requirements during production was identified as a major driver. Increased integration of organizational functions as a means of reducing development lead time was also identified as a driver. (Andersen et al., 2022d)

Despite several studies citing potential benefits from discrete industry as drivers of platform-based development, most results were validated only on a laboratory scale and thus lacks industrial relevance. As one of the few studies identified, Meyer and Dalal (2002) provide evidence from industry concerning the impact of platform-based product development in a process industry context.

3.2. KEY CONCEPTS IN A PROCESS INDUSTRY CONTEXT

The review findings of Andersen et al. (2022d) showed notable similarity of concept definitions for product architectures between discrete and process industry. Identified definitions focused on shared assets and interfaces (Meyer & Dalal, 2002), and emphasized the simultaneous independency and interrelatedness of modules within a modular product architecture (Siiskonen et al., 2018). Despite these apparent similarities, Andersen et al. (2022d) noted a lack of literature about establishing product architectures in the process industry.

Modules in a process industry context typically take one of two perspectives (Andersen et al., 2022d). Modules may be process elements, such as biochemical pathways, which perform similar actions, or they may be defined based on the similarity of the elements that comprise the modules, such as which food nutritional group they belong to. Module definitions in the process industry are also similar in concept to those found in discrete industry, as they likewise focus on decomposing complex systems into simpler entities, while aiming for functional purity of these (Andersen et al., 2022d).

Despite the identification of several studies mentioning product architectures, defining modules, and mentioning interfaces; Andersen et al. (2022d) found no studies explicitly defining interfaces in a process industry context. They even identified a study arguing against the applicability of such concepts in the context of the process industry (see Lager, 2017).

For product platforms, Andersen et al. (2022d) identified a total of six different definitions in literature, of which the majority emphasize the commonality aspect of platforms. Just as product platform definitions in discrete industry can be more or less narrow (Simpson et al., 2006), so are definitions from the process industry diverse. Some take an abstract system-based perspective (Meyer & Dalal, 2002), while others take outset in a product family (Lager, 2017), technology (Dadfar et al., 2013), or component-based perspective (McIntosh et al., 2010). Besides product platforms, Andersen et al. (2022d) identified several other platform definitions related to product development in the process industry, including raw material platforms, production platforms, process platforms (Lager, 2017), and knowledge platforms (e.g. Karayel & Ozkan, 2006).

Despite several studies mentioning product families, definitions of these were scarce, with only Alizon et al. (2010) providing definitions in a study that also involves process industry products. However, as the front-end i.e., market-oriented side, of the platform-based product development process is considered more like the discrete industry than the design and back-end aspects of the process (Andersen et al., 2022d), fewer differences in definitions, and thus fewer instances of these, are expected.

3.3. METHODS AND APPROACHES FOR THE PROCESS INDUSTRY

The findings concerning identified methods and approaches are categorized as belonging to either the front-end, design and development, or back-end of platform-based product development activities in accordance with the framework adopted in Andersen et al. (2022d).

3.3.1. FRONT-END ACTIVITIES

Decomposing complex systems into manageable units differentiated by function is central to product architecture design also in the process industry (e.g., Papin et al., 2004). Meyer and Dalal (2002) illustrate how such a product architecture may be defined for photosensitive film, while Temme et al. (2012) propose a method for pathway design and control inspired by electronic circuit design. Taking outset in a method originating from discrete industry, Siiskonen et al. (2018) apply the configurable component method for product architecture design of pharmaceutical products, without modifications to the fundamental approach. Establishing product architectures may, however, negatively impact the long-term ability of a company to respond to changing market needs, as the often-high capital investments of production systems in this industry may induce inertia opposing changes to the product architecture (Meyer & Dalal, 2002).

Using platform leveraging strategies inspired by Meyer and Lehnerd (1997) in combination with product function similarity, Alizon et al. (2010) present a platform configuration method and demonstrate it for both discrete and process industry products. However, details on how to apply important aspects of the method are not described for the process industry example.

Product family modeling is addressed by Cherubini et al. (2009), who propose a graphical method based on four aspects (platforms, products, feedstock, and processes), which define different potential biorefinery structures and associated product families. Altogether, the method encapsulates design knowledge, which is valuable in the early stages of product family selection and biorefinery design.

Several methods exist to support product portfolio positioning in the process industry. Andersen et al. (2022d) note that the issue of product portfolio positioning appears similar for both discrete and process industry products. Even so, identifying the appropriate product mix may be computationally more demanding in the latter case (Adler et al., 2010) as these products typically have many attributes to account for.

3.3.2. DESIGN AND DEVELOPMENT ACTIVITIES

In the process industry, more so than in discrete industry, the consideration of both products and production processes during product design is important (Andersen et al., 2022d). This is likewise evident from the multiple platform types identified, see Section 3.2, as well as from several of the platform design methods involving multiple platform perspectives. Siiskonen et al. (2020), for example, propose a combined product-production platform perspective while Lager (2017) proposes an even more extensive “integrated knowledge platform”, which additionally comprises a raw material platform. Furthermore, multiple studies proposing either modular or platform-based designs for chemical pathway construction were identified. Of the methods identified, only Siiskonen et al. (2020) present an industrial case example, with the remaining methods being mostly conceptual (Lager, 2017) or laboratory-scale demonstrations (e.g., Layton & Trinh, 2014; Sheppard et al., 2014).

Studies focusing on identifying the proper variety-commonality trade-off have been identified for wood and paper products (Andersen et al., 2022d). In the former case, optimization models were used to determine the optimal variety to offer to maximize revenue (Atkins et al., 1984) while the latter case relied on a more aggregate framework to guide this trade-off decision (Chambost et al., 2008).

Design optimization in a process industry context is characterized by product and process performance often being optimized by means of combined modular and combinatorial approaches. These methods search the solution space through numerous module combinations to uncover high-performing product variants. This explorative approach to design optimization appears popular in chemical and biochemical engineering, perhaps due to the difficulty in predicting interactions between the comprising elements of these products. (Andersen et al., 2022d) Of the studies concerned with design optimization, a significant majority originates from chemical and biochemical engineering domains, while Ortuño and Padilla (2017) present a more market-related perspective by optimizing food bank products against individual customer needs.

Several studies proposing design support systems have been identified. Most are concerned with sheet metal products, while two studies presented design support systems for glass and chemical products (Andersen et al., 2022d). A major difference between the systems developed for sheet metal products and the other product types is that the former category is more comprehensive in scope, including multiple aspects of the product design process, such as manufacturing considerations. By contrast, the glass and chemical products design support systems are more confined in scope, omitting manufacturing completely despite the importance of simultaneously considering this aspect. (Andersen et al., 2022d)

3.3.3. BACK-END ACTIVITIES

The success of a product design also depends on its manufacturability. Kühle et al. (2019) address this issue for wood products by mapping a chain of requirements from the finished product to its constituent modules and further onto production processes and technology. Thereby, they have linked product design and production considerations somewhat similar to the approach proposed by Lager (2017).

In total, Andersen et al. (2022d) identified five different metrics to assess product designs according to various market or financial aspects. The market-oriented metrics proposed by Siiskonen et al. (2020) and Alizon et al. (2010) consider how well a product fits the needs of a consumer and how product commonality affects platform strategies, respectively. From the performance perspective, one measure of platform efficiency incorporated capital investments to accommodate the often-higher capital investments in the process industry (Meyer & Dalal, 2002). Lastly, Dadfar et al. (2013) utilizes several enablers of innovation in relation to financial performance, yet do not provide details on their definitions.

Progressing naturally from the product and production platforms is the need for a supply chain setup to support these (Jiao et al., 2007). Two studies applied similar research methods (industry surveys and hypothesis testing) to identify relationships between product modularity and supply chain performance. Even though no indications are provided on the magnitude of improvement, both find that there is a positive impact on company and supply chain performance. (Andersen et al., 2022d)

Relating to postponement in the process industry, McIntosh et al. (2010) analyze multiple alternative strategies in relation to industrial cases from food manufacturers and find that several strategies are viable in this context. Two additional studies of a bakery (Bech et al., 2019) and a dairy (van Kampen & van Donk, 2014) likewise identified a potential in applying postponement strategies in the process industry through application of platform-based products. Beside these more elaborate studies, others provide anecdotal evidence of the application of postponement strategies in other sectors of the process industry, such as in breweries or paper manufacturers (Lager, 2017). Lastly, Siiskonen et al. (2020) briefly discuss the potential for applying postponement principles for pharmaceutical products.

3.4. SUBCONCLUSION

This section briefly concludes on the findings from Andersen et al. (2022d) concerning the three overall elements of drivers, concepts, and methods related to platform-based product development in the process industry.

The drivers mentioned for pursuing platform-based development in the process industry share some similarity to those often associated with the discrete manufacturing industry. Indeed, in this regard the process industry is likewise driven by cost reduction and increased product variety. A major driver for the process industry appears to be cost reduction through means of increased product yield. However, while several studies demonstrate promising results from laboratory experiments, very few studies include results validated in an industrial context.

Concerning definitions of key concepts in platform-based product development (platforms, modules, architectures, etc.), there is likewise a relatively high similarity with how these are defined and described in discrete industry. Several studies even directly adopt definitions from discrete industry literature. However, in the case of interfaces no definitions were found, and the issue of specifying these for process industry products were likewise absent from the studied literature. Furthermore, the literature is not unanimous concerning applicability of these fundamental concepts in the process industry. (Andersen et al., 2022d)

For methods and approaches related to front-end activities, studies adopting methods from the discrete industry (see Siiskonen et al., 2018) or simultaneously demonstrating application in both discrete and process industry (see Alizon et al., 2010) were identified. Concerning design and development activities, the combined product and production perspective is especially relevant in process industry (Andersen et al., 2022d). This is evident by several studies including both product and production platforms in their design methods (e.g., Lager, 2017; Siiskonen et al., 2020). Multiple studies proposing methods that combine modular product structures with high-throughput screens were identified in relation to design optimization (Andersen et al., 2022d). These studies were predominantly related to chemical product design and few of them included consideration of customer needs. Design support systems were identified for different product types including glass, chemicals, and metal products, although these systems varied in their organizational scope (Andersen et al., 2022d). Assessing platform performance was covered by multiple studies and included metrics adapted to accommodate the characteristics of the process industry (e.g., Meyer & Dalal, 2002), although several metrics appeared applicable in both discrete and process industry contexts. Manufacturability and supply chain considerations were sparse among the papers identified. Several studies applied, or suggested application of, postponement strategies based on platform-based products, adopting the same postponement strategies as discrete industry. (Andersen et al., 2022d)

CHAPTER 4. RESEARCH OBJECTIVES

From the background and state-of-the-art it is evident that the process industry potentially stands to achieve benefits from adopting platform-based development approaches for products. However, as the knowledge base on this subject is scarce, knowledge of methods and tools to support efficient and high-variety product development is needed. An important element of this thesis is to support this endeavor through research contributions as well as practical applications. The main research objective of this PhD project is therefore defined as:

> *"To develop and validate methods and concepts to assist academics and practitioners in designing platform-based and modular products in a process-industrial context."*

To support the individual research activities comprising this PhD project, the following three research questions have been formulated:

RQ1. To what extent has modular and platform-based product development in a process-industrial context previously been covered in academia and what are the major findings of these studies?

RQ2. How, if possible, can existing product platform development concepts and principles from discrete manufacturing industry be leveraged in the process industry to efficiently deliver derivative product variants?

RQ3. What are the potentials of applying modular and platform-based product development principles in the process industry across a company's value chain?

CHAPTER 5. RESEARCH DESIGN

The purpose of this section is two-fold: to present the research design and methodology adopted for this PhD project as well as evaluate the quality of the research performed. This is done by first introducing the research framework and methodology followed by the research methods and a quality evaluation thereof.

Researchers may adopt different worldviews, which constitute a "*set of beliefs*" (Creswell, 2009, p. 3) that guide decisions regarding design of research projects. These worldviews range from the post-positivistic, which is what is typically associated with traditional sciences, to the application-oriented pragmatistic worldview, which is concerned with suitability and finding solutions to problems (Creswell, 2009). Pragmatism is furthermore method-agnostic in that it does not subscribe strictly to either qualitative or quantitative research methods (Creswell, 2009). Rather, methods are selected for their fit to a given situation and may involve a combination of both qualitative and quantitative methods – i.e., mixed methods research (Creswell, 2009) – resulting in a flexible and pragmatic perspective on research.

The structure and rationale of the research design for this PhD project is based on a three-step logical progression. This research design can, to some extent, be compared to the construction process of a building, as visualized in Figure 3.

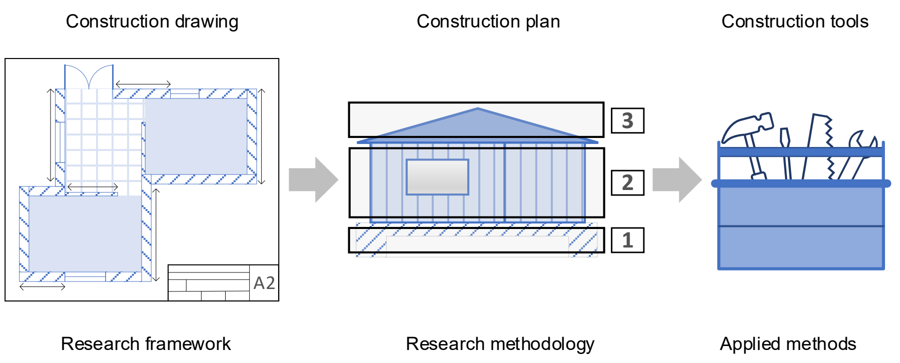

Figure 3: The research design explained through an analogy to construction projects.

The first step in a construction project is the commissioning of a building, which seeks to solve some problem or offer a better solution to an existing problem. For example, a building may be constructed to improve the quality of living in case of a residential building or provide more sustainable energy in case of a hydropower plant. Before construction can commence technical drawings must be made, which provide an overview of what the structure is comprised of. This is akin to the research framework introduced in Section 5.1, which shows the components and their relations in a design science research (DSR) project. From the construction drawings, a construction plan can be formulated, informing builders in which order the structure should be put together. Similarly, the research methodology described in Section 5.2 informs researchers about the structure of the research project, the activities to perform, and in what general order they occur. Lastly, to raise a structure, builders have a multitude of tools available to them, which are suited to specific tasks or scenarios. In a similar way, work methods available to perform research are numerous, and researchers are faced with a similar decision of which "tools" to apply in each situation. The work methods adopted in this PhD project are described in Section 5.3.

5.1. RESEARCH FRAMEWORK

Like pragmatism, design science is application oriented (A. R. Hevner et al., 2004; Johannesson & Perjons, 2014). Whereas traditional sciences are concerned mainly with describing, explaining, and predicting naturally occurring phenomena (Dresch et al., 2015; Johannesson & Perjons, 2014), design science is focused on what could be – solutions to problems or improved situations – thereby providing value to people (A. Hevner & Chatterjee, 2010). It achieves this through design of novel artifacts (A. R. Hevner et al., 2004), hence the name. However, "design" makes up only half the name of the paradigm. The "science" aspect relates to the other important element: the rigor of the artifact developed (A. R. Hevner et al., 2004), and by extension the underlying method and ensuing results. Hevner and Chatterjee (2010, p. 5) define DSR as:

> *"a research paradigm in which a designer answers questions relevant to human problems via the creation of innovative artifacts, thereby contributing new knowledge to the body of scientific evidence. The designed artifacts are both useful and fundamental in understanding that problem."*

From this general introduction to DSR combined with the scope of this PhD project, DSR is considered a suitable framework to structure the research activities around. Grounding of this PhD project in the practical challenges experienced by the industrial partner, introduced in Section 1.2, makes the application-forward perspective of DSR well-suited to address this problem.

The relation between identifying the relevant questions, designing the artifact, and ensuring the value of the latter in both industry and research is documented in the DSR framework, illustrated in Figure 4. Each of the major elements of the framework are addressed in the following subsections.

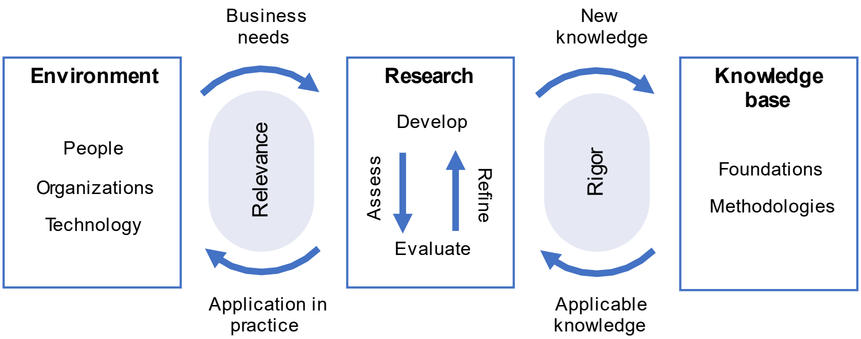

Figure 4: The design science research framework. Adapted from A. R. Hevner et al. (2004).

5.1.1. PRACTICAL PROBLEMS

The left-hand side of Figure 4 represents the environment in which the problem resides. The problem may be related to humans, the organizations they are part of, or the technology that support their actions or organizations (A. R. Hevner et al., 2004). Regardless of the problem at hand, the fundamental criterion is that it is grounded in practice (A. Hevner & Chatterjee, 2010; A. R. Hevner et al., 2004; Johannesson & Perjons, 2014). In engineering and management applications, such problems are typically related to identified gaps in business performance (A. Hevner & Chatterjee, 2010). According to Johannesson and Perjons (2014), two types of problems exist in DSR: (1) situations where the current state is considered undesirable and the desired state neutral – i.e., no additional benefit is gained from solving the problem, and (2) situations where the current state is considered neutral, and the desirable state is positive – i.e., solving the problem is perceived as providing additional benefits. The latter type of problems is relevant to the case company in that potential benefits reported for discrete manufacturing industry products are considered a desirable state to aim for. Section 1.2 indicates the practical problems experienced by the industrial partner, and together with the background and state-of-the-art we can deduce the relation between research questions and these practical problems:

- **Practical problem 1** (R/T RQ1): Given a preliminary finding that methods for modular and platform-based product development are lacking for the process industry, the practical problem relates to identifying what knowledge exists on the topic to inform both researchers and practitioners who seek to undertake such development projects.

- **Practical problem 2** (R/T RQ2): Again, preliminary findings and anecdotal evidence suggest a potential in adapting design methods from discrete industry. Achieving this would allow companies to utilize existing knowledge to some extent and build on a more established knowledge base.

- **Practical problem 3** (R/T RQ3): From Section 2.2.2 it is evident that companies in discrete industry have achieved significant business results from platform-based product development approaches. Naturally, the industrial partner as well as other researchers and practitioners interested in pursuing platform-based approaches in the process industry would be interested in indications of potential benefits.

Irrespective of the nature of the problem at hand, the complexity of the environment within which most problems exist results in most DSR projects taking outset in simplified representations of the problem (A. R. Hevner et al., 2004). Since platform-based product development requires input from many stakeholders, simplifications of reality, such as by focusing on a limited portion of the product portfolio, may prove advantageous to the research effort.

5.1.2. ARTIFACT DESIGN

The practical problem provides researchers with the requirements or needs of the business (A. R. Hevner et al., 2004), forming the basis for subsequent artifact design. Nevertheless, as illustrated in Figure 4, design of the artifact is also impacted by established theories, models, methods, analysis techniques, etc. which form the knowledge base. The outcome of applying these various types of codified knowledge to the solving of a problem are artifacts generated by researchers (A. R. Hevner et al., 2004). We generally distinguish between four types of artifacts (A. R. Hevner et al., 2004; Johannesson & Perjons, 2014), which Hevner et al. (2004) so precisely summarize as (emphasis added by author):

> *"**constructs** by which to think about [problems], **models** by which to represent and explore them, **methods** by which to analyze or optimize them, and **instantiations** that demonstrate how to affect them."*

Johannesson and Perjons (2014) note that a frequent response to practical problems is the identification of a partial solution. These proposed solutions – in the form of one of the above-referenced artifact types – are subsequently assessed for their relevance to the intended application area and the rigor of their design. Findings of the assessment may lead to revisions of the artifact, and the cycle repeats. Indeed, Hevner et al. (2004) note that design science research is iterative by nature.

The outcome of DSR, as applied in this project, is documented by the publications presented in Chapter 6. From a research design perspective, the papers represent two different phases of this project: a discovery phase and a synthesis phase, as illustrated in Figure 5.

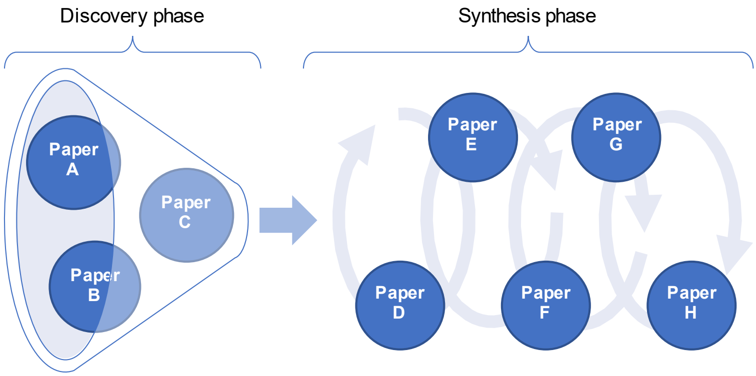

Figure 5: The two research phases of discovery and synthesis, and their relation to the papers included.

The discovery phase includes papers A-C and investigates the issue of high product variety and complexity management in the process industry from different perspectives. The synthesis phase takes outset in findings from these first three papers, particularly paper B and paper C. Through an iterative process of investigating multiple aspects of MFD, the synthesis phase also produced several artifacts which are documented in papers D-H. An overview of the types of artifacts produced is provided in Table 3.

Table 3: An overview of designed artifacts and their corresponding research papers.

	Construct	Model	Method	Instantiation
Paper A				X
Paper B		X	X	X
Paper C	Review paper			
Paper D			X	X
Paper E	X			X
Paper F		X	X	X
Paper G		X		
Paper H	X	X	X	X

As shown in Table 3, the designed artifacts relate mostly to instantiations followed by contributions regarding models and methods. Constructs are least represented in the works generated throughout this PhD project.

5.1.3. ARTIFACT EVALUATION

Assessment of an artifact may be performed according to several evaluation methods whether they are analytical, experimental, simulations, etc. (A. R. Hevner et al., 2004). Regardless, complete evaluation of an artifact requires consideration of how business needs have been addressed as well as how available knowledge have been applied to arrive at the artifact design (A. R. Hevner et al., 2004; Johannesson & Perjons, 2014). These two evaluation parameters are termed relevance and rigor, respectively (A. R. Hevner et al., 2004). Although the ultimate evaluation of artifacts is their implementation in practice, they often serve as proof-of-concepts, partial solutions, or references for full-scale system designs rather than implementation-ready solutions (A. R. Hevner et al., 2004). Specifically, from a research perspective there are four main types of research contributions:

1. The artifact's ability to solve previously unsolved problems.
2. Demonstration of creative development of an artifact that advances the design-science knowledge base.
3. Creative development and use of evaluation methods. (A. R. Hevner et al., 2004)
4. Design of a novel use case for an existing artifact – i.e., exaptation (Johannesson & Perjons, 2014).

When evaluating DSR research, generalizability of findings is important although it should never be at the expense of the practical relevance of the artifact (A. R. Hevner et al., 2004). Indeed, this application forward perspective is also emphasized by Dresch et al. (2015) who note that optimality of solutions is not an objective of DSR, rather DSR embraces the English aphorism "perfect is the enemy of good."

5.1.4. BUSINESS AND RESEARCH RESULTS

The output of DSR can take either of two forms: knowledge of application of artifacts in the appropriate environment or additions to the knowledge base (A. R. Hevner et al., 2004). Furthermore, good practice in DSR emphasizes communication of results obtained to both research and practice communities (Johannesson & Perjons, 2014), which is achieved through two main streams in this PhD project: (1) research relevant results are communicated primarily through publications and presentations at conferences, and (2) practitioner-relevant results are likewise included in publications as well as this PhD thesis, while most of the knowledge dissemination to practice is achieved through workshops and project collaborations with the case company.

5.2. RESEARCH METHODOLOGY

The operational structure of a research project can take many forms (Jørgensen, 2000), and the same can be argued for DSR projects. For the major research projects undertaken throughout this PhD project, the generic research and development project structure proposed by Jørgensen (2000), see Figure 6, is adopted. The project structure is consistent with the DSR framework, in that it takes outset in problem solving, which is followed by design and evaluation activities. Figure 6 furthermore details relations between the sequential activities in Jørgensen's generic project structure and the environment and knowledge base elements of the DSR framework.

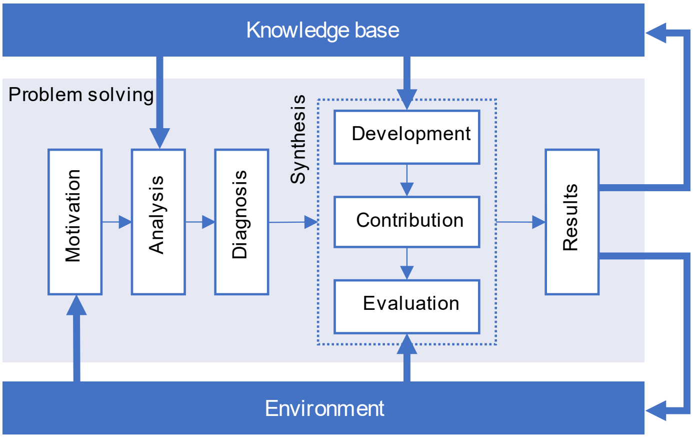

Figure 6: Relating the design science research framework to the generic research project structure by Jørgensen (2000).

As noted earlier, the primary motivation for research projects based on DSR is found in problems experienced in practice, for which reason the problem solving takes input from the environment for its first activity. Analysis is primarily supported by information contained in the knowledge base which, in connection with the identified problem, helps clarify the problem through diagnosis. These preliminary activities form the basis for design, or synthesis, of a solution. During the synthesis phase, both the knowledge base and environment provide valuable input to the artifact design. This may be in terms of e.g., constraints imposed by the specific environment or relevant existing methodologies to support solving of the problem. Furthermore, the knowledge base provides a crucial reference for defining the scientific contribution of the artifact while input from the environment is imperative for evaluation of the designed artifact in relation to the practical problem it is intended to solve. Finally, an essential part of solving any research problem based on DSR is communication of results to both practitioners and the scientific community alike.

5.3. RESEARCH METHODS

The applied methods used to perform research in this project include a combination of literature reviews and case studies, which have supported the design of novel artifacts aimed at solving problems of practical relevance in the case company. The following subsections elaborate on the motivation for choosing specific work methods.

5.3.1. LITERATURE REVIEWS

Performing a review of existing literature is acknowledged as an effective means of advancing the knowledge of a given topic (Hart, 1998; Levy & Ellis, 2006; Snyder, 2019). Literature reviews achieve this by comprehensively covering relevant knowledge within a given research field to gain a broad understanding of the topic (Hart, 1998) as well as patterns and gaps existing within this field of study, which relates directly to RQ1. Performing a literature review is thus an effective way of ensuring that the research activity undertaken is indeed not already covered extensively in literature. Literature reviews also provide researchers with guidance towards what relevant research projects might be pursued in the future. Different types of literature reviews exist (Snyder, 2019), varying typically by how rigorously they adhere to a predefined procedure as well as the scope of their search. Literature reviews have been applied in different capacities throughout all papers presented as part of this PhD project. These reviews have typically served to demonstrate the lack of suitable solutions to an identified problem (cf. paper B and papers E-F) or to investigate the extent to which a field of study has been applied within the process industry, as is the case for paper A and paper C.

Specific to literature reviews, Snyder (2019) presents several guidelines to assess the quality of such research. The guidelines are categorized into four phases covering design, conducting, data analysis, and reporting the literature review (Snyder, 2019, fig. 4). While the guidelines are presented as ex-post evaluation criteria, reformulating them allow researchers to apply them as ex-ante evaluation parameters to ensure quality of their literature review. The major literature review performed in this PhD project (see paper C) was designed as a systematic literature review. This approach is particularly concerned with rigor and transparency of the review method, thereby accommodating related criteria throughout all four phases. The remaining criteria concerning the fit of the method towards answering the research questions posed are accommodated through comprehensive motivation of the research topic and method. For literature reviews performed in the remaining papers of this PhD project, many of the same principles and methods from paper C have been applied to ensure rigor of these studies despite obvious differences in scope of the literature reviews performed.

5.3.2. CASE STUDIES

Case study research is characterized by typically focusing on one instance, which provides researchers the ability to gain in-depth knowledge of a phenomenon in its natural setting (Yin, 2018) by use of multiple research methods and sources of data. Although the most prevalent form of case studies focuses on a single instance, they can vary along multiple dimensions such as duration or period, number of instances, or purposes (Johannesson & Perjons, 2014).

High-quality case study research should follow a clear methodology (Yin, 2018), yet not be too rigid as one of the main benefits of case study research is the inherent flexibility of this approach in comparison to other research methods e.g., questionnaires (Voss et al., 2002). For this PhD project, the overall case is determined by the nature of the research being done in collaboration with an industrial partner. Nevertheless, the choice of specific instances of interest within the company allowed for greater flexibility, and each of the case study-based papers (see papers A-B, papers D-F, and paper H) produced as part of this PhD project has their individual unit of analysis described in the respective paper.

The relevance of case study research to this PhD project stems from the suitability of case study research to answer research questions focusing on the "how" and "why" of a phenomenon (Voss et al., 2002; Yin, 2018), which relate directly to RQ2. Furthermore, Voss et al. (2002) note that case study research is useful not only for explorative phases of research, but also for development, testing and refinement of theories or ideas. These qualities are of relevance to the overall research objective of this PhD project and further supports the application of case study research in answering part of the research questions posed.

Judging the quality of case study research can be done according to four criteria focusing on aspects of operationalization of concepts, generalizability, causal relations, and reliability (Yin, 2018). Concerning the first criteria (construct validity) multiple sources of evidence has been applied to support and confirm research findings, for example by first analyzing archival records and interviewing company experts about their perceived validity of the findings. In other situations, multiple company representatives have been interviewed to achieve consensus about a given topic. Ensuring generalizability of case study research findings is considered a challenge (Johannesson & Perjons, 2014). In case study research, generalization may be achieved not through the sample (case) selected – or statistical generalizability – but rather through analytic generalizability, which refers to the application of established theory to allow researchers to generalize findings from a specific case study to a broader class (Yin, 2018). In the context of this PhD project, the specific cases studied have been selected as they share several of the characteristics associated with the process industry, as described in Section 2.1. Furthermore, the product family which forms the unit of analysis in the case studies in paper B, papers D-F, and paper H embodies many of the characteristics considered important for adopting platform-based development approaches in the discrete manufacturing industry. Another aspect, which may impact the case studies is the often-active participation of the researcher in several of the internal projects carried out in the case company, thereby blurring the line between case study research and action research. The latter research strategy is characterized by the researcher addressing "*practical problems that appear* *in real-world settings*” (Johannesson & Perjons, 2014). This is evident from two aspects: the first is related to generating scientific results from research projects, while the second aspect is related to imparting new knowledge into the organization, which may impact methods and approaches to particularly product development activities.

CHAPTER 6. FINDINGS

This section summarizes the contributions of the PhD project as documented through the eight papers forming the content of this section. Each paper is described using a four-part structure resembling an extended abstract, including research purpose, methodology, findings, and implications. The research implications part is further sub-divided by implications relating to this PhD project, the research field, and practice.

6.1. PAPER A: CHANGEABLE MANUFACTURING IN THE PROCESS INDUSTRY

Purpose

Mass customization and the resulting increase in potential product variants impose requirements on production systems in both discrete and process manufacturing industry. Nevertheless, examples of changeable production systems are sparse in the process industry despite the concept being industry-agnostic. This study, therefore, concerns itself with the investigation of this apparent discrepancy.

Methodology

The study combines an initial review of available literature on changeable manufacturing in the process industry with a case study from the same industry. The case study took outset in the production system at the case company and the five production levels and types of changeability.

Findings

There is relatively limited research on changeable manufacturing in the process industry as well as a lack of industrial scale examples of such production systems. Associated operational and business effects are likewise scarce.

Production planning and control research in relation to changeability is most prevalent among the studies reviewed, which is in alignment with the finding that most research identified was concentrated at the higher abstraction levels in the changeability taxonomy.

In terms of challenges, this study found that a combination of product development practices, rigid material transport infrastructure, and heuristic production planning approaches impeded increased changeability from a production perspective. However, a potential for improving production changeability through application of single-minute exchange of die approaches was identified at the case company.

Implications

Project	• The findings of this study assisted in deciding the scope of the overall research project.
Research	• This study contributed to research literature by providing an overview of concepts of changeable manufacturing in the context of the process industry. • The study identified a need for further research into designing utilities backbone systems that can support efficient system reconfigurations in process industry production systems.
Practice	• This study is relevant to practitioners as it identifies several distinct challenges towards increased changeability in the process industry. • It is noted that the presence of a discretization point may further complicate production system design due to the need to cover methods and tools related to both discrete and process industry production systems.

6.2. PAPER B: IDENTIFYING COMPLEXITY DRIVERS

Purpose

Within the field of complexity management, the initial identification of the drivers of complexity is a crucial task, as knowledge of such drivers allow decision makers to focus resources within organizations. Despite the importance of this activity in complexity management, there is a lack of concrete and practitioner-oriented methods to support this discovery phase. The objective of this paper is, therefore, to present a framework to assist practitioners in identifying complexity drivers in manufacturing companies.

Methodology

Based on an initial literature search, related research was reviewed and identified methods were evaluated regarding their repeatability and generalizability.

The proposed framework consists of two elements: 1) a multi-dimensional matrix forming the structure of the framework and 2) the associated process to follow for successful application of the framework in practice. The framework matrix combines a generic value chain with a generic product structure as the axes of the matrix and denote the perceived static and dynamic complexity at each intersection. The framework process is structured around multiple workshops involving all primary organizational functions and cover the phases of complexity rating and complexity driver elaboration.

Findings

Previous methods generally lack sufficiently detailed descriptions to facilitate successful repetition or are too narrow in scope to be of general use.

Applying the framework in the case company resulted in workshop participants identifying 53 different complexity drivers. From a product structure perspective, it was found that bottles and recipes were perceived as equally complex while labels were perceived as incurring the least complexity-related costs. From a value chain perspective, the highest perceived complexity was concentrated in logistics and production activities.

Implications

Project	• The findings of this study assisted in narrowing the scope of the overall research project.
Research	• Presents a structured, generic, and value-chain wide framework for complexity driver identification; the use and functioning of which is verified in the case company.
Practice	• Through documentation of both functioning and process, the framework presents a viable option for early-phase complexity management tools aimed at practitioners.

6.3. PAPER C: REVIEW OF PRODUCT PLATFORM LITERATURE IN PROCESS INDUSTRY

Purpose

Due to a lack of evidence on platform-based products in the process industry compared to discrete manufacturing industry products – despite these industries experiencing similar market trends – this paper identifies, and reviews literature related to platform-based product development in the process industry.

Methodology

This study is based on an extensive systematic literature review that utilized both block search and forwards/backwards searches in multiple databases. A delimitation process consisting of progressively more detailed reviews reduced an initial 4277 publications to 62.

For the subsequent analyses, inspiration was found in literature focusing on discrete manufacturing industry. Categorization and analysis of drivers of platform-based product development are based on the primary categories: cost reduction, productivity of product development, and development lead time reduction as proposed by Muffatto (1999). Approaches and methods identified were grouped according to their fit to the 12 fundamental concepts and approaches covering the three stages front-end, design and development, and back-end issues used by Pirmoradi et al. (2014).

Findings

The bibliometric analysis found that despite sparse literature on the subject, the past two decades has shown an almost exponential growth in publications.

Identified definitions of key concepts demonstrated considerable similarity to their counterparts in discrete manufacturing industry.

Cost reduction and productivity of product development was found to be the most frequent drivers of platform-based product development. Most papers utilizing modular designs were found to be primarily concerned with cost reductions, while increased product variety were of lower importance.

Among the publications identified, there is a significantly higher focus on design and development issues compared to market or manufacturing and supply chain issues.

Examples of platform-based development from industry are based mostly on empirical evidence and anecdotes, with most of these relating to food, beverage, and electronics manufacturing. Furthermore, despite the prevalence of chemistry-focused studies, industry cases and examples of these are lacking.

Overall, the findings from this study suggest a potential for pursing application of existing methods for platform-based product development of process industry products.

Implications

Project	• This study contributes to RQ1 by extensively reviewing existing literature on the topic and establishing the main findings in relation to platform-based product development in the process industry.
Research	• The study provides researchers with a consolidated overview of what definitions, drivers, and methods and approaches have been applied in previous studies. • Several potential avenues of further research are identified to advance the knowledge of this topic in the process industry.

Practice	
	• The study found significant similarities in key constructs applied in both discrete and process industry, thereby suggesting potentials for applying existing methods in a process industrial context.

6.4. PAPER D: INVESTIGATING MFD IN THE PROCESS INDUSTRY

Purpose

The comparatively sparse evidence on adoption of modular and platform-based product development in the process industry, and disputes on the applicability of these principles to the process industry, calls for further investigation into whether existing methods for platform-based or modular product design are feasible.

Emphasizing practical efficacy and business orientation, the modular function deployment (MFD) method is analyzed for its applicability to the process industry.

Methodology

The paper combines review and analysis of literature related to the five individual steps of the MFD methodology with insights from the case company and general anecdotal evidence from the process industry.

Findings

It was found that quality function deployment has been applied in the process industry and that an industry-adapted method exists. Case insights indicated that the modified quality function deployment version by Erixon (1998) combined with the customer value rating matrix by Borjesson (2014) would allow for the necessary detail.

The often-simpler structure of process industry products makes the use of structured methods less critical for proper functional decomposition. This is likewise the case for identifying module concepts through the module indication matrix. Furthermore, case insights showed that functional interdependence is present, potentially impacting the ability to achieve good modular product designs. Evaluation of technical solutions as per the MFD method appears applicable although changes to the criteria are expected.

Several of the module drivers proposed by Erixon (1998) were found to be potentially applicable in the case company. Even so, the category of "After sales" drivers were found to be less relevant in a process industry context.

Interfaces discussed by Erixon (1998) appear heavily influenced by mechanical product design due to reliance on geometry and movement which are generally of limited applicability for process industry products. Furthermore, the metrics for the module evaluation chart are, like module drivers, not uniformly applicable with some being directly useable (carryover, share of purchased modules, number of modules), while others are deemed questionable (interface complexity and material purity).

References to application of Design-for-X methods in process industry has been identified, providing credence to their applicability.

Implications

Project	• This study contributes to RQ2 by investigating applicability of the MFD method in a process industry context.
Research	• A thorough investigation of all steps of the MFD method and their individual potentials and challenges in a process industry context is provided.
Practice	• The study suggests that MFD may prove an interesting point of departure for practitioners seeking adoption of platform-based product development principles for process industry products.

6.5. PAPER E: LIMITED DEMONSTRATION OF MFD IN THE PROCESS INDUSTRY

Purpose

This study applies the MFD method in a limited scope in the case company to demonstrate how selected elements of this method can be applied for non-assembled products.

Methodology

This study presents a limited application of MFD, focusing on elements from selection of technical solutions to generation and evaluation of module concepts. The MFD method was simplified in several aspects to fit the context, such as by adopting a binary scoring system for the module indication matrix and comparative analysis of products.

Findings

Functional decomposition revealed some ingredient categories did not aid in the primary function yet are included as differentiating elements in the product.

The study presented context specific definitions of modules, as either a base onto which other modules or ingredients could be added or as a collection of ingredients that could be added to the mixing process at a later stage in production. Moreover, seven of the 12 original module drivers were found relevant for the case, excluding “After sales” module drivers entirely.

Several ingredient categories, where it would be expected to identify module candidates from, were identified. Likewise, it was found that isolating technical solutions related to fulfilment of allergen and environmental labelling requirements would be infeasible as these are generally product-level requirements rather than ingredient level requirements.

Comparative analysis of two recipe pairs showed mixed results. In the first case, the proposed module concepts were considered infeasible as ingredients were not isolated to a single process step. In the second case, high commonality of ingredients during early stages of production suggested a potential for use of a common recipe base.

Implications

Project	• This study contributes to RQ2 and RQ3 by demonstrating a limited application of MFD in a case company manufacturing consumer chemicals. In relation to RQ3, evaluation results suggest a potential for utilizing common recipe bases.
Research	• Provides the first documented application of elements of the MFD method for chemical products.
Practice	• The study can act as a preliminary frame of reference for practitioners and present specific challenges from an industry perspective when seeking to apply MFD.

6.6. PAPER F: IMPROVED MODULE DRIVER ANALYSIS

Purpose

This paper seeks to reduce the influence of analytical bias and competence gaps when identifying relevant module drivers and their potential relevance in modular product designs by exploring how available company data can facilitate quantification of module drivers as a means of decision support.

Methodology

The 12 module driver descriptions were analyzed with respect to key terms and potentially quantifiable dimensions. Next, these dimensions were compared against data available in the company's IT systems. Based on the available data, module driver metrics were proposed. Results were then structured in a two-dimensional matrix comprising module drivers and product part groups.

Findings

It was found that the importance of quantifiable dimensions towards enabling data-based analysis is directly proportional to the number of module drivers that share them. Even so, quantifiable dimensions with one-to-one relations to a module driver may be essential to quantification of that specific driver.

The study found that only the case company's enterprise resource planning system provided data of appropriate structure and quality for the purpose of this study, despite investigating several IT systems within the case company.

Adaptation of existing metrics from literature were found to provide indices for some module drivers, while new metrics are needed for other module drivers. In total, seven metrics are proposed covering all product life cycle aspects, although not all module drivers.

Despite the data-based approach presented in this paper considering strategic suppliers irrelevant, reviewing the results with company stakeholders revealed potentials, not visible from the data. This demonstrates the importance of involving stakeholders in reviewing and evaluating results.

Implications

Project	• By exploring data-based evaluation of module drivers, this study contributes to RQ3. • Demonstration in a case company from the process industry provides insights into potentials of modular and platform-based development, thereby contributing to RQ3.
Research	• Metrics and indices are proposed for the module drivers proposed by Erixon (1998).
Practice	• This study provides a point of departure for evaluating the potential of modularizing product structures based on readily available data in a production company.

6.7. PAPER G: OVERVIEW OF MODULE DRIVERS

Purpose

Despite the importance of module drivers in MFD, previous literature demonstrates only scattered research on module drivers, with most studies relying on the original 12 drivers. Adherence to the original drivers only may result in foregoing potentially beneficial design concepts inspired by other module drivers. This paper addresses this issue by presenting a comprehensive and generic set of module drivers for use in modular product development.

Methodology

This paper takes outset in a literature review on module drivers followed by mapping and synthesis of extracted data. A four-step method is developed and followed to arrive at a comprehensive and generic set of module drivers based on a hierarchical presentation of these with a generic value chain as highest-order grouping.

Findings

The study found that module drivers are unevenly distributed across the value chain steps, with "Product development"-related module drivers being most frequent. Surprisingly, "After sales"-related drivers represent the second most frequent category. In total, 68 module drivers are identified and categorized into 29 module driver categories spanning 6 value chain steps.

Compared to the original module drivers and categories proposed by Erixon, the "Product development" and "After sales" steps have seen the greatest increase in number of new module drivers over the period analyzed.

Implications

Project	• The comprehensive set of module drivers identified in this study contribute in part to RQ3 by providing a broader overview of the potential benefits attainable from modularizing products.
Research	• This study contributes to research by providing a comprehensive overview of 63 different module drivers across 6 generic value chain steps. • Based on the extensive set of module drivers, motivation for further research into developing a method to support an efficient preliminary delimitation of these is presented.
Practice	• From a practitioner perspective, this set of module drivers can assist product development teams by ensuring that most potential benefits from modularizing products are uncovered.

6.8. PAPER H: EXTENDED MFD FOR THE PROCESS INDUSTRY

Purpose

This paper builds on previous findings of both potential benefits and challenges of applying MFD in a process industry context and seeks to adapt and extend the method by developing practitioner-oriented tools to support aspects of MFD for which these are lacking.

Methodology

The paper is based on a design science research approach, where the adapted MFD method is developed through an iterative process in the case company.

An additional step for the MFD method is proposed to establish common terminology in the design team prior to embarking on a development project. Furthermore, a more elaborate and process for identification and selection of technical solutions i.e., step 2 of MFD, is proposed including development of new tools to support practitioners. Step 3 is likewise modified to allow for greater adaptation to different contexts by proposing module generation approaches based on dimensions of knowledge level and product complexity. The modified Step 3 also introduce improved support for practitioners to the prior tasks of selecting module drivers as well as the subsequent task of pre-evaluating module concepts. Lastly, a systems impact perspective on the effects of module concepts is introduced for the evaluation of these in Step 4.

Findings

Literature on MFD was found to focus mostly on steps 2-4 as these constitute product design elements, which represent significant departure from regular product design activities.

To establish common terminology and understanding of modular and platform-based design principles, the everyday product example of a pizza was found to be suitable common grounds for communicating core concepts relevant to the development project.

In step 2, it was found that reframing and expanding the process for identification and evaluation of technical solutions was considered an improvement over earlier approaches.

For the module concept identification and generation step, it was found that use of questionnaires was suitable for module driver rating. The application of the compound metric identified six module candidates, of which two – an individualization and an integration candidate – were evaluated as promising for further investigation.

A product/process analysis demonstrated an architecture resembling elements from both a “hamburger” and “base part” assembly. Furthermore, analyzing the system level impact of the selected module concepts suggested significant improvements concerning economies of scale and production lead time reductions. However, several potential drawbacks were also noted for the module concepts.

Implications

Project	• This study has contributed to RQ2 and RQ3 by demonstrating the feasibility and potential of applying a modified MFD method in the process industry.
Research	• The method and tools designed to support analysis efforts in Steps 2-4 address neglected areas of MFD. • The representation of a process industry product/process architecture using the interface matrix provides credence to the application of existing methods in the process industry.
Practice	• The close collaboration with the industrial partner in the modification of MFD has resulted in several tools designed to be practically viable and support development projects in industry.

CHAPTER 7. DISCUSSION

In this section, aspects of the methodology applied and presented findings, which may be of interest to discuss, are elaborated on to provide nuance to the research conducted and potentials and limitations thereof. In particular, the issue of defining the process industry and the generalizability of the industrial case used are discussed.

The introduction and background of this thesis first presented the general distinction of manufactured products as belonging to either discrete or process industry. While these industries do indeed differ along several dimensions, they also share certain characteristics, blurring the line between what is process industry and what is not. Moreover, Section 2.1 noted that the definition of what constitutes the process industry is very dependent upon the specific perspective adopted, further blurring the distinction between these two fundamental types of manufacturing industry. The adoption of a specific definition of the process industry as presented by e.g., the American Production and Inventory Control Society (APICS) is popular among several studies (see e.g., Dennis & Meredith, 2000; Flapper et al., 2002; Lager, 2017; Lyons et al., 2013) reviewed throughout this PhD project. Although the APICS definition (Dennis & Meredith, 2000 citing Wallace, 1992) is targeted at production processes, it can be re-written to take the perspective of the product: "*[products] made by mixing, separating, forming, and/or chemical reactions [in] either batch or continuous mode*". While such a specific definition would appear to clarify the boundaries of what is considered part of the process industry and what is not, it does not aid sufficiently in sharpening the distinction between the two types of industry. Let us consider two examples: A sheet metal products manufacturer and a muesli manufacturer. According to the APICS-derived definition, both examples would qualify as belonging to the process industry. The sheet metal products are made by forming and/or shaping processes and the muesli products are made by mixing various cereals, dried fruits, and other adjuncts. However, while both the finished products and semi-manufactures of the muesli producer has a limited shelf life, there are no practical shelf-life constraints imposed on the sheet metal products. Moreover, while the sheet metal products manufacturer will have some scrap metal i.e., by-products, from its process, this will not necessarily apply to the muesli manufacturer if production is pure mixing. Certainly, additional comparisons can be made between the two hypothetical manufacturing companies, their products, and the typical process industry characteristics listed in Table 1. Thus, while definitions of the process industry can be formulated, clearly distinguishing between the two industries is difficult in practice and have likewise challenged the delimitation of the research performed throughout this PhD project.

The industrial partner for this project, as introduced in Section 1.2, inherits many of the characteristics distinctive of a process industry company. Nevertheless, not all characteristics listed in Table 1 apply to this company. For example, while the company uses both batch and continuous mixing equipment to make its products, few chemical reactions occur during production, and the process is more about mixing different ingredients and homogenizing these. Thus, the product flow is more akin to a convergent rather than divergent flow. The products and production process furthermore do not result in the formation of co- or by-products except for residual heat generated by some chemical reactions. Several additional comparisons could be made between typical characteristics of the process industry and how they do or do not apply to the products and processes of the industrial partner. The lacking coverage of some of the process industry characteristics in the case company naturally implies that concrete evidence about the applicability of platform-based development techniques for such products have not been possible to produce in the cases covered in this project. Nevertheless, the extensive literature review presented in paper C covers the process industry from a broader perspective and include findings to support the general application of the principles and methods, thereby demonstrating potential for analytic generalization (Yin, 2018). Furthermore, some of the research performed (see paper B and papers F-G) is applicable beyond the process industry, as aspects of complexity management and modular product design is argued to be generic in nature. Regardless, DSR recognizes that designed artifacts typically require further modification to be feasible in practice and that problems tend to be context-specific (Dresch et al., 2015). This specificity of designed solutions often adds to the difficulty of evaluating the artifacts produced (A. Hevner & Chatterjee, 2010) and some level of adaptation is, therefore, expected to fit other cases.

CHAPTER 8. CONCLUSION

This final chapter of the thesis conclude on the PhD project with outset in the overall research objective. Subsequently, conclusions related to each of the three supporting research questions are elaborated on.

8.1. OVERALL RESEARCH OBJECTIVE

> *"To develop and validate methods and concepts to assist researchers and practitioners in designing platform-based and modular products in a process-industrial context."*

From the "Discover" phase of the project, a potential was identified concerning adaptation of existing methods from discrete industry to application in the process industry (Andersen et al., 2022d). In the following "Synthesis" phase, the Modular function deployment (MFD) method for modular and platform-based product development was identified as suitable – subject to adaptations to the process industry context – due to its practitioner-oriented approach (Andersen et al., 2021). The "Synthesis" phase then demonstrated limited application of aspects of MFD in the industrial case (Mogensen et al., 2022). Learnings from this study prompted further analysis and development of several aspects of MFD, focusing on identifying module drivers in general (Andersen et al., 2022c) and in a specific case (Andersen et al., 2022a) before developing and validating an extended and adapted version of MFD in the industrial partner company (Andersen et al., 2022b).

The research undertaken in this project, relating mainly to exploring and adapting the MFD method in a process industry context, has produced multiple tools and methods to support researchers and practitioners in the development of modular and platform-based products. While these artifacts are first and foremost developed with the process industry in mind, several are applicable in discrete industry as well.

8.2. RESEARCH QUESTION 1

> *"To what extent has modular and platform-based product development in a process-industrial context previously been covered in academia and what are the major findings of these studies?"*

An extensive review of relevant literature formed the basis for answering this question. It was found that while the amount of literature is generally scarce – especially in comparison to the discrete industry – there has been a marked rise in the number of publications over the past two decades (Andersen et al., 2022d). Despite some disagreements among authors on the subject constructs and models, originally from the discrete industry, have been used several times in a process industry context. Indeed, it was found that the first major publication in this area (see Meyer & Dalal, 2002) takes outset in the same constructs presented in the seminal book (Meyer & Lehnerd, 1997) co-written by Marc Meyer. Regardless, evidence from literature led to the conclusion that methods from discrete industry could potentially be applied in the process industry, though with some adaptations needed.

8.3. RESEARCH QUESTION 2

> *"How, if possible, can existing product platform development concepts and principles from discrete manufacturing industry be leveraged in the process industry to efficiently deliver derivative product variants?"*

Taking outset in MFD, as an existing method from discrete industry, several artifacts were designed to solve practical problems experienced by the industrial partner related to aspects of this method. These modifications and extensions to the original method in combination with validation in the case company demonstrate how the concept of modular and platform-based product development can be utilized in a process industry context.

Mogensen et al. (2022) proposed definitions for modules applicable to the case company. Different module types were identified relating to product customization as well as product commonality (Andersen et al., 2022b). On the contrary, it can be concluded that since many process industry products are consumables (e.g., cleaning agents, food and beverages, or pharmaceuticals) or homogeneous (e.g., metals, ceramics or wood products) the "After sales" category of module drivers (i.e., upgrading, maintenance, recycling) were found mostly irrelevant to the case studied due to the nature of the products (see e.g., Andersen et al., 2021; Mogensen et al., 2022).

Some of the artifacts developed are argued to be industry-agnostic and would apply equally well to discrete and process industries. The feasibility of applying these methods is affected more by company-specific aspects not necessarily related to the industry of origin, such as the company's IT systems (Andersen et al., 2022a) or their familiarity with the topic (Andersen et al., 2022b). This is the case for the complexity mapping framework (Andersen et al., 2019), the module driver exploration method (Andersen et al., 2022a), and the technical solution exploration method in Andersen et al. (2022b).

Regardless of industry, it can be concluded that while MFD is oriented towards practitioners, the original method proposed by Erixon (1998) benefits from the addition of concrete tools to solve some of the practical problems experienced by companies following this approach.

8.4. RESEARCH QUESTION 3

> *"What are the potentials of applying modular and platform-based product development principles in the process industry across a company's value chain?"*

Evidence and indications of potential benefits from adopting concepts and principles related to modular and platform-based product development in the process industry relate to three different aspects: (1) evidence from industry and pilot cases, (2) synthetic results from laboratory experiments and simulations, and (3) analytical results.

Little concrete evidence of the effects of platform-based products are found in literature. Nevertheless, from the evidence presented, platform-based products in the process industry offer several of the same impacts reported for discrete industry products based on platforms. This includes lower average product development costs, higher return on investment (Meyer & Dalal, 2002), and lower inventory costs (van Kampen & van Donk, 2014).

Several laboratory experiments point to the potential of achieving lower product costs through more efficient product designs as well as reduced development time and cost obtained from modular and platform-based product designs (Andersen et al., 2022d). Simulations show increased ability to customize products to individual customers (Siiskonen et al., 2020). Similar results are reported from studies of the industrial partner case, where multiple module concepts were found to fit specific customer needs at comparably lower costs as well as reduce product cost through improved economies of scale and reduced production lead times (Andersen et al., 2022b).

Other potential benefits include improved ability to identify module drivers across organizational functions (Andersen et al., 2022c) and applicability of platform-based design principles across product families (Andersen et al., 2022b).

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