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Developing Manufacturing System Platforms

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Curriculum Vitae

Daniel G.H. Sørensen

Daniel G.H. Sørensen was born in Silkeborg, Denmark. From 2011, he studied mechanical engineering at Aalborg University, receiving his B.Sc. in 2014, followed by a M.Sc. in manufacturing technology in 2016. Since September 2016, he has been a Ph.D. fellow at Aalborg University's Department of Materials and Production as part of the Mass Customization research group. During his Ph.D. studies, he stayed for three months as a visiting researcher at the Intelligent Manufacturing Systems Centre (IMSC) at the University of Windsor in Canada. His research on manufacturing system platforms, their nature, development, documentation, and utilisation is part of the Manufacturing Academy of Denmark (MADE), funded by the Innovation Fund Denmark.

Abstract

Platforms have long since proven their worth for managing the ever-increasing variety of products, a trend experienced across the globe. As collections of standardised assets, forming a structure from which a stream of derivative systems can be developed, platforms dictate which features of a product or system can be changed to achieve the desired variety and function. For manufacturers, manufacturing system platforms are a way to achieve manufacturing systems capable of changing according their needs, accelerating new product introduction and development of new manufacturing systems. Developing and implementing these manufacturing system platforms remains a challenging task for manufacturers, and a relatively immature field of research.

To address these issues with manufacturing system platform development, this Ph.D. project employs a framework for design science in information systems research. It combines design science and behavioural science, taking both a reactive and proactive approach to development of new and application of existing vocabulary, classifications, models, methods, and instantiations. Inspiration is taken from product development, software architecture, and system engineering, using concepts from all three to grow the knowledge base on manufacturing system platforms, applying existing and new concepts in an industrial context.

The contributions of this research are documented in six appended papers, summarised in the thesis. In a multi-case study, an iterative approach—employing concepts from software architecture and systems engineering—was used to guide the platform development process and vocabulary. Several challenges appeared, highlighting issues to be addressed. This lead to the development of a classification scheme for production processes and a summation of challenges related to manufacturing system platform development, based on an evolving case study carried out over three years. This case study made the need for tools and objectivity clear, thus a classification coding scheme was developed, capturing key characteristics of manufacturing systems. A method for brownfield platform development involving identification of potential platforms based on existing systems was proposed, and the classification coding scheme was demonstrated for this purpose.

Keywords: *Manufacturing; Platforms; Classification; Reconfigurable; Modularity; Reuse*

Dansk Resumé

Platforme har forlængst bevist deres værd når det kommer til at håndtere den stadigt stigende mængde af produktvarianter, en tendens der mærkes over hele kloden. Som samlinger af standardiserede enheder, der danner en struktur hvorfra afledte systemer kan udvikles, dikterer platforme hvilke funktioner i et produkt eller system der kan ændres på for at opnå den ønskede variation og funktion. For producenter er platforme en måde at opnå produktionssystemer, der kan ændres efter behov, accelerere introduktion af nye produkter, og udvikling af nye produktionssystemer. Udvikling af disse produktionssystemplatforme er stadig en udfordring for producenter og et relativt umodent forskningsområde.

For at addressere disse problemer med udvikling af produktionssystemplatforme anvender dette Ph.D.-projekt et "framework for design science in information systems research". Det kombinere designvidenskab og adfærdsvidenskab og tager derved en reaktiv og proaktiv tilgang til udvikling af nye, og anvendelse af eksisterende, klassifikationer, modeller, metoder, og instantieringer. Inspiration hentes fra produktudvikling, softwarearkitektur, og system engineering, hvor koncepter fra alle tre bruges til at udvide vidensbasen om udvikling af produktionssystemplatforme ved at anvende eksisterende og nye koncepter i en industriel kontekst.

Forskningsbidragene er dokumenteret i seks vedlagte artikler og sammenfattet i denne afhandling. I et multi case study blev en iterativ tilgang anvendt til at guide platformsudvikling ved brug af koncepter fra softwarearktitektur og system engineering. Undervejs dukkede adskillige udfordringer op, og fremhævede problemer der måtte addresseres. Dette førte til udvikling af et klassificeringssystem for produktionsprocesser, og en opsummering af udfordringer relateret til udvikling af produktionssystemplatforme baseret på et case study udført over tre år. Dette case study tydeliggjorde behovet for objektive værktøjer, hvorfor et klassificeringskodningssystem, som beskriver nøgleegenskaber for produktionssystemer, blev udviklet. En metode til brownfield-udvikling af platforme, der involverede identifikation af potentielle platforme baseret på eksisterende systemer, blev dernæst foreslået og klassificeringskodningssystemet blev demonstreret til dette formål.

Nøgleord: *Produktion; Platforme; Klassificering; Rekonfigurering; Modularitet; Genbrug*

Dissertation Details

Dissertation Title: Developing Manufacturing System Platforms

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Ph.D. Supervisors: Thomas Ditlev Brunø, Assoc. Prof.
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The main body of this thesis consist of the following papers.

A D. G. H. Sorensen, J. Bossen, M. Bejlegaard, T. D. Brunoe and K. Nielsen (2018a). 'Production Platform Development through the Four Loops of Concern'. In: *Customization 4.0. Proceedings of the 9th World Mass Customization & Personalization Conference (MCPC 2017), Aachen, Germany, November 20th-21st, 2017*. Mass Customization & Personalization Conference (MCPC2017) (20th–21st Nov. 2017). Ed. by S. Hankammer, K. Nielsen, F. T. Piller, G. Schuh and N. Wang. Aachen, Germany: Springer International Publishing, pp. 479–493. DOI: `10.1007/978-3-319-77556-2_30`

B D. G. H. Sorensen, T. D. Brunoe and K. Nielsen (2018b). 'A classification scheme for production system processes'. In: *Procedia CIRP* 72. 51st CIRP Conference on Manufacturing Systems, pp. 609–614. ISSN: 2212-8271. DOI: `10.1016/j.procir.2018.03.021`

C D. G. H. Sorensen, T. D. Brunoe and K. Nielsen (2018c). 'Challenges in Production and Manufacturing Systems Platform Development for Changeable Manufacturing'. In: *Advances in Production Management Systems. Production Management for Data-Driven, Intelligent, Collaborative, and Sustainable Manufacturing. IFIP WG 5.7 International Conference, APMS 2018, Seoul, Korea, August 26-30, 2018, Proceedings, Part I*. ed. by I. Moon, G. M. Lee, J. Park, D. Kiritsis and G. von Cieminski. Cham: Springer International Publishing, pp. 312–319. ISBN: 978-3-319-99704-9. DOI: `10.1007/978-3-319-99704-9_38`

D D. G. H. Sorensen, H. A. ElMaraghy, T. D. Brunoe and K. Nielsen (2019b). 'Classification Coding of Production Systems for Identification of Platform Candidates'.

In: *CIRP Journal of Manufacturing Science and Technology*. Ed. by J. Vancza. CIRPJ-D-18-00193. ISSN: 1755-5817. In second review

E D. G. H. Sorensen, T. D. Brunoe and K. Nielsen (2019a). 'Brownfield Development of Platforms for Changeable Manufacturing'. In: *Procedia CIRP* 81. 52nd CIRP Conference on Manufacturing Systems (CMS), Ljubljana, Slovenia, June 12-14, 2019, pp. 986–991. ISSN: 2212-8271. DOI: 10.1016/j.procir.2019.03.239

F D. G. H. Sorensen, H. A. ElMaraghy, T. D. Brunoe and K. Nielsen (2019c). 'Identification of Platform Candidates through Production System Classification Coding'. In: *Advances in Production Management Systems. Production Management for the Factory of the Future. Production Management for the Factory of the Future*. Ed. by F. Ameri, K. E. Stecke, G. von Cieminski and D. Kiritsis. Vol. 566. IFIP Advances in Information and Communication Technology. Cham: Springer International Publishing. Chap. 50, pp. 400–407. ISBN: 978-3-030-30000-5. DOI: 10.1007/978-3-030-30000-5_50

In addition to the main papers, smaller contributions to the following publications have also been made.

[1] T. D. Brunoe, D. G. H. Sørensen, A.-L. Andersen and K. Nielsen (2018b). 'Framework for Integrating Production System Models and Product Family Models'. In: *Procedia CIRP* 72. 51st CIRP Conference on Manufacturing Systems, pp. 592–597. ISSN: 2212-8271. DOI: 10.1016/j.procir.2018.03.020

[2] T. D. Brunoe, D. G. H. Sorensen, M. Bejlegaard, A.-L. Andersen and K. Nielsen (2018a). 'Product-Process Modelling as an Enabler of Manufacturing Changeability'. In: *Advances in Production Management Systems. Production Management for Data-Driven, Intelligent, Collaborative, and Sustainable Manufacturing*. Ed. by I. Moon, G. M. Lee, J. Park, D. Kiritsis and G. von Cieminski. Cham: Springer International Publishing, pp. 328–335. ISBN: 978-3-319-99704-9. DOI: 10.1007/978-3-319-99704-9_40

[3] T. D. Brunoe, A.-L. Andersen, D. G. H. Sorensen, K. Nielsen and M. Bejlegaard (2019). 'Integrated product-process modelling for platform-based co-development'. In: *International Journal of Production Research*. Manuscript submitted for publication. DOI: 10.1080/00207543.2019.1671628

This thesis has been submitted for assessment in partial fulfillment of the Ph.D. degree. The thesis is based on the submitted or published scientific papers which are listed above. Parts of the papers are used directly or indirectly in the extended summary of the thesis. As part of the assessment, co-author statements have been made available to the assessment committee and are also available at the Faculty.

Contents

Preface

If you've ever read the preface and acknowledgements section of a Ph.D. thesis before, you already know what's coming in this one. They always talk about the amount of work being put into the thesis, the personal achievement it is to finish a work such as this, the many hours spent alone doing research, writing papers and finally the thesis. Often, they will also talk about the author's motivation for starting this gruelling process, because what actually does motivate a person to go through this voluntarily? We'll get back to that in a second.

The preface, acknowledgements or equivalent will *always* talk about and thank a lot of people for their direct or indirect help with the thesis, the project and the papers. In many ways, this preface will be no different. But this is definitely a section I have been looking forward to writing. I have been looking forward to putting the finishing touches on my thesis, of course, and thanking all the people who helped me along the way. Credit where credit's due.

Having spent countless hours pouring over minor details just in the layout and setup of the thesis template, it has been a joy seeing the pages fill—sometimes slowly, sometimes fast—and everything just working. But part of it, is also that I consider this one section of my thesis to be sort of a free space; a place where I can just write (almost) what comes to mind. And truth be told, that is incredibly refreshing. If you've read or written academic papers or theses before, you'll know that the language used in these kinds of things is something quite its own. In this free space, I'm slightly less bound by scientific customs, terms and formality. I can speak more directly to you.

Let's get back to the bit about motivation. I started at Aalborg University in 2011, choosing mechanical engineering because it sounded right up my alley, and Aalborg University seemed like a perfect fit. Lots of work in groups, projects focused on solving actual problems and applying actual solutions. It wasn't easy by any means, but I liked it a lot—the subjects, the people and the university. I didn't really find *my* area of interest until the second semester of my Master's degree in 2015 where I had the first project on platforms. It just clicked. This was something I was good at, something I understood, something that interested me, and I was not about to let it go. So for the following two last semesters, I kept working with platforms. Building up more knowledge, coming up with new ideas for things to work on in relation to platforms. By the end of it, I was worn out—a Master's thesis is not easy to write either. Truth be told, the last thing I was considering at that point in time was doing a Ph.D. I decided I was done with the university and had to get out, at least for a little bit. But then I was asked whether I wanted to do a Ph.D., and after carefully considering it for a few months as I defended my Master's thesis and watched my friends do the same, I decided this was something I couldn't turn down.

And I do not regret it in the least. Of course it didn't turn out exactly the way I'd imagined it, I don't think it ever really does, but it has definitely been an experience I wouldn't have been without. I've met so many amazing people along the way, travelled to new places, learned so much and I've become a better person for it.

So if you come across this thesis—whether it is in your search for knowledge, out of obligation because someone handed you a copy, if you find it buried on some shelf somewhere, or simply blindly grabbing *something* to read—I hope you find it useful, interesting or at the very least, a way to kill a few hours. Because all things considered and despite the bad times, I have had a blast working on this thesis and I *am* proud of my work, this thesis being one of my bigger personal achievements so far. And with that, before we head into the actual thesis, I have a few people I want to thank.

Acknowledgements

Firstly, my supervisors Assoc. Prof. Thomas D. Brunø and Assoc. Prof. Kjeld Nielsen. You believed in me enough to give me this opportunity, and for that I am forever grateful. The support, guidance, and inspiration you have given me over the last three years have been invaluable. And to my colleagues in the Mass Customization research group, I couldn't have dreamed of a better environment to work these past three years.

My gratitude goes out to Prof. Hoda A. ElMaraghy and Prof. Waguih ElMaraghy. Thank you for welcoming me at the Intelligent Manufacturing System Centre at University of Windsor and sharing your knowledge with me. It has been my honour to work with you, and your insight contributed significantly to the progress of my research. In the same breath, I would like to thank the researchers at the Intelligent Manufacturing Systems Lab. You helped make my stay enjoyable.

I would also like to thank Bjørn Langeland, chief engineer, for taking part in and helping me conduct this research with the industry. We've had many long discussions throughout the years this research has taken place. My acknowledgement also goes out to the Manufacturing Academy of Denmark (MADE) for giving me the opportunity to conduct this research.

Finally, I owe my family and friends more than words can express. I would not have made it through this process without your support and help. A special mention and my heartfelt gratitude to Sofie Bech and Nikolai Øllegaard. Thank you for being there for me through all of this. For sharing my joy when things went right, for pulling me back up when I was down, and distracting me when I needed it. I know I haven't always been easy to deal with, but you were always there for me. Thank you for all the good times, and for everything that's come.

Daniel G.H. Sørensen
Aalborg University, August 31st, 2019

Reader's Guide

This Ph.D. thesis takes the form of an extended summary covering a collection of papers structured into chapters 1 to 4. References follow the author-year format, and are set in regular brackets, like so (Sorensen et al. 2018a). In the electronic version of the document, the entire citation acts as a hyperlink to the bibliography on page 53. The bibliography itself contains the page number of each page a reference has been used. Appended papers each have their own bibliography. An index specifying several terms used in this thesis can be found on page 51.

Internal cross-references between sections, pages, figures, and tables also act as hyperlinks to their corresponding parts of the thesis. Figures and tables are numbered according to section in which they appear.

This document was written in LaTeX using SublimeText 3, typeset with Garamond and Arial, compiled using LuaTeX. A public repository of the source files is available at GitHub[1]. It complies with the guidelines set by Aalborg University, and follows a template developed by the author. All figures were created in Microsoft Visio. Appended papers follow templates for their corresponding journal or proceedings, but have been cropped and scaled to fit the pages of this thesis.

[1] github.com/Firebrazer/DevelopingManufacturingSystemPlatforms

List of Figures

List of Tables

1

Introduction

At the threshold of the fourth industrial revolution, an era of increased digitalisation, variety, and personalisation in manufacturing is at hand. Manufacturers are presented with countless new opportunities and challenges. Their ability to remain competitive is critically dependent on managing these changes within the industry—a task that has proven momentous for many companies (ElMaraghy et al. 2013).

At its core, manufacture in an industrial setting is the making or producing of wares, goods, and products from one or more other materials or parts through manufacturing processes. These manufacturing processes change (or transform) the original product or material in a number of ways, e.g. by removing material, joining it to another material, or modifying it's properties. The manufacturing process, or in more general terms the transformation process, is essentially a series of effects carried out on a product or material in its initial state to transform it into a desired state. A transformation process does not stand on its own, but is part of a transformation system containing also the execution system performing the transformation process, and the active environment influencing the process (Hubka and Eder 1988). The execution system itself consists of the technical system, containing machinery and tools carrying out the actual transformation process, and the human system, containing any needed human operators for the machinery. A diagram of the transformation system and its elements is shown on Figure 1.1.

When people speak of manufacturing systems, it is typically the combined human and technical system within the transformation system. Sometimes, parts or all of the active environment for the manufacturing system are considered part of the system itself. But such transformation processes and systems exist everywhere and may be both intentional and unintentional, desirable and undesirable in relation to human needs. So while a manufacturing system can be considered a transformation system, a more precise designation is that of a technical system which, along with a human system, executes technical processes rather than transformation processes. This distinction is important, since a technical process is a specific type of transformation process where humans use technical systems as artificially created tools, while transformation systems also cover naturally occurring phenomenons (Hubka and Eder 1988), e.g. biological or environmental processes. Often, the terms production system and manufacturing system are used interchangeably. This thesis will primarily use the term manufacturing system as described above, i.e. the technical system, and use the term production in a wider

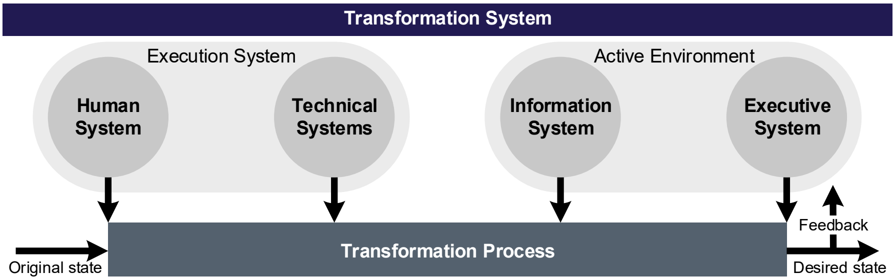

Figure 1.1: Diagram of the transformation system, adapted from Hubka and Eder (1988). The active environment also includes influences outside the trasnformation system itself such as time and space (not pictured). The executive system can also be considered the management and goal system, while the information system is a storage medium and source. For the sake of simplicity, ecosystems and all factors not included in the human system, technical systems, and transformation process are collected in the active environment.

sense, covering the manufacturing system as well as logistics, planning, and control, i.e. the broader transformation system

One of the earliest and most well-known examples of the modern manufacturing system is the Ford Model-T mass production line, rapidly producing thousands of near-identical cars. Since before the Ford Model-T, the evolution of manufacturing has been driven by manufacturers seeking to minimise costs while increasing quality, reliability, and profit. To enable this, and manufacture increasingly complex products, new materials and processing techniques have continuously been introduced, advancing production technology and shaping the manufacturing industry as a whole (ElMaraghy 2019). A currently ongoing change is the transition from mass production towards mass customisation and personalisation; a direction that does not seem to be changing soon (Salvador et al. 2009). The trend towards increasing product variety and shortening product development life cycles is causing a misalignment between products and the manufacturing systems that produce them (ElMaraghy and Wiendahl 2009). Dedicated manufacturing systems, manufacturing only a very limited number of product variants (like the Ford Model-T systems), tend to outlive the life cycles of the product generations they manufacture. As a result of the increased demand for variety, manufacturing systems must be able to manufacture multiple generations and variants of products, pushing manufacturers in the direction of changeable manufacturing, e.g. flexible, reconfigurable manufacturing systems (ElMaraghy et al. 2013; Wiendahl et al. 2007)—a manufacturing paradigm shift, as illustrated on Figure 1.2. Manufacturing systems and the industry itself will continue to evolve.

Amidst the fourth industrial revolution heading towards Industry 4.0, enabling technologies are also evolving and advancing. To mention a few, information processing speeds are becoming faster, sensors are becoming more sophisticated, machine learning and artificial intelligence are gaining ground, all while technology costs and availability are improving. All of these and more are leading to more available data and more sophisticated analysis supporting effective and efficient decision-making in manufacturing companies. These advances in technology enable improved communication both between systems

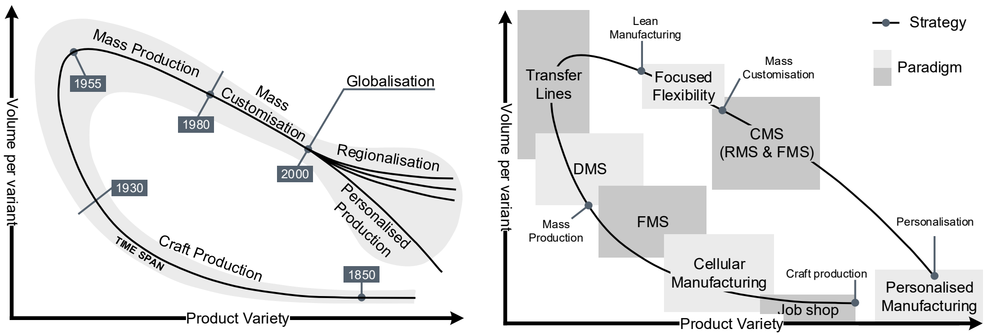

Figure 1.2: Left: Evolution of the manufacturing paradigm, from craft production to mass production, mass customisation and mass personalisation. Adapted from Koren (2010). Right: Evolution of the manufacturing systems paradigms. Adapted from ElMaraghy et al. (2013). FMS (Flexible Manufacturing System), DMS (Dedicated Manufacturing System), CMS (Changeable Manufacturing System), RMS (Reconfigurable Manufacturing System).

within a company and elements of individual systems, leading to increased digitalisation, data exchange, and analytics (Jeschke et al. 2017). Concepts related to Industry 4.0, such as the Industrial Internet of Things (IIoT) and Internet of Production (IoP), employ these new technologies and strategies to lay the foundation for quicker and more knowledge-based decision-making when it comes to reconfiguring or changing a manufacturing system (ElMaraghy 2019).

Achieving manufacturing systems capable of reconfiguration and change remains a challenge for many manufacturers. To address the adversity posed by increasing variety and complications implementing changeable manufacturing, manufacturing system platforms, platform-based co-development, and co-platforming are gaining traction in research (Abbas and ElMaraghy 2018; ElMaraghy and Abbas 2015; Michaelis and Johannesson 2012; Sorensen et al. 2018a). The following sections define several terms used throughout this thesis, all of which are summarised in the index on page 51. They furthermore provide a state-of-the-art for manufacturing system platforms, their background, nature, and connection to related subjects. Finally, what has been attempted in the present effort is outlined, followed by a description of this thesis' structure.

1.1 On Platforms

Platforms are a way to manage variety by allowing certain areas or features of a product or system to be changed, while standardising and effectively "locking" other features. They are essentially a collection of decisions on certain aspects of a system, which designers and developers must adhere to when creating a new system. These decisions can be made for various purposes, e.g. to ensure compatibility between system generations, speed up the system design process, ensure system robustness, ease integration of new technology, or guarantee manufacturability, to mention a few. Standardisation of physical and non-physical assets, as well as the sharing of these assets or characteristics, i.e. commonality, is the core of platforms. In this way, new system variants and generations can relatively quickly be created by designers and developers utilising platforms. As such, platforms are the result of answering two essential questions with regards to a system (Sorensen et al. 2018a):

- What may change and what may not?
- Where is variety acceptable and where is it not?

One area where platforms have seen significant success is in product design and development, where they have been successfully adopted to manage an increasing number of product variants (Simpson 2004). While various definitions pertaining to platforms exist, this thesis subscribes to the definition proposed by Meyer and Lehnerd (1997).

> **Definition of platform:**
> a collection of elements and interfaces forming a common structure, from which a stream of derivative products can be efficiently developed (Meyer and Lehnerd 1997)

This makes the platform itself distinct from another commonly used term in product design and development; product family. Where a platform is a collection of entities from which products are built, a product family is a collection of products sharing certain common characteristics, which may have been built on a platform. The definition above was originally aimed towards products (i.e. product platforms), but it is also considered pertinent when discussing manufacturing systems, as these are considered the product of a targeted design and development process, and a technical product can generally be considered a system. Research in the development, implementation, and utilisation of manufacturing system platforms is sparse and examples are few (Bossen et al. 2015; Sorensen et al. 2018c), but several well-known aspects of product platforms can be applied to manufacturing system platforms as well. Among these are the core concepts of architecture, modules, interactions, and interfaces.

1.1.1 Architecture

The concept of system architecture is similar to that of platforms, and the two terms are often used interchangeably despite significant differences between the two. In system design and development, regardless of whether these systems are products or manufacturing systems, an architecture is essentially a description of a system or system of systems. It captures both the functional and physical elements of a system, how they relate to each other, and how the system interacts with its environment. Where a platform contains the standardised elements or features upon which systems can be or are built, the architecture contains all elements and relations of a system, including those that are not standardised (Harlou and Mortensen 2006). As such, a platform can be considered a subset of an architecture. However, while all systems exhibit an architecture (explicit and intentionally developed or otherwise), not all systems exhibit platforms. Architectures are commonly used within systems engineering and software development (INCOSE 2015; ISO et al.

Figure 1.3: Three common types of modularity. Redrawn from Ulrich and Eppinger (2012).

2011). This thesis aligns itself with a slightly modified definition of architecture by Ulrich and Eppinger (2012), relying on the notion of modules discussed in the following section.

> **Definition of architecture:**
> the architecture of a system is the scheme by which the functional elements of the system are arranged into modules and by which the modules interact

1.1.2 Modules

Platforms and modules are closely related, but remain distinct concepts (Brunoe et al. 2015). A module is an entity designed to implement one or more well-defined functions, with well-defined interfaces connecting one module to another. Examples of various common types of modularity are shown on Figure 1.3. This aligns with the core purposes of a platform, since modules are essentially standardised assets, functions, and interfaces. Platforms are characterised by a particular type of modularity, as the constituents of a platform are elements with low variety and high reusability (Baldwin and Woodard 2009), making platforms modular by nature. Systems based on platforms will typically be constructed from these platform modules of low variety and high reusability, combined with a number of modules with high variety and low reusability in order to create the desired variety of the system. There can be a number of reasons for why a module exists or why a particular set of functions are encapsulated in a single module. These are generally dubbed module drivers, and represent different criteria behind modularisation (Erixon et al. 1996). Although the module drivers were originally defined for product design and development, Brunoe et al. (2015) identified several drivers applicable within production and manufacturing system design, as outlined in Table 1.1.

1.1.3 Interfaces & Interactions

To describe how systems and their elements interact and are influenced by each other and the environment, the terms interaction and interface will be used. An interaction is some effect that occurs between at least two objects, while an interface is how said effect is transferred from one object to another. The distinction between these two is often overlooked, as the focus is typically on interfaces, which tend to cover both terms in one. It is, however, an important distinction to make when it comes to platform development in order to identify similar interactions carried out over different interfaces.

Table 1.1: Relevant drivers for modular production. Adapted from (Brunoe et al. 2015).

Category	Driver	Description
System Development	Geometric Integration and Precision	Careful alignment of parts and manufacturing assets.
	Function Sharing	Two or more manufacturing assets sharing a common function.
	Portability of Interfaces	Ease of connecting two manufacturing assets via an interface.
Localization of Changes	Module Carryover	Functions not expected to change in the future.
	Technology Evolution	Changes expected due to implementation of new manufacturing technology.
	Planned Product Changes	Planned changes due to product/production planning.
Variety and Standardisation	Common Unit	Function required by several different manufacturing assets.
	Different Specification	Function required for localised differentiation.
Production of Manufacturing equipment	Vendor Capabilities	Outsourced functions.
Service and Recycling	Service and Maintenance	Frequently used functions subject to wear.

Definition of interaction:
a mutual or reciprocal action occurring as a result of two or more objects influencing each other

Definition of interface:
a point of contact between two or more objects, at and/or through which an interaction occurs

Interactions are further classified into four generic types; spatial, energy, information, and material (Pimmler and Eppinger 1994). A spatial interaction calls for adjacency, orientation, or alignment, e.g. two parts oriented for assembly, or a gripper being adjacent to the end of an articulated robot. An energy interaction describes a need for energy transfer, e.g. the transfer of heat from a processor to a heatsink, or power from a power supply to components in a control system. An information interaction identifies a need for information, data, or signal exchange, e.g. exchange of information between a sensor and a control system or processor. A material interaction calls for material exchange, e.g.

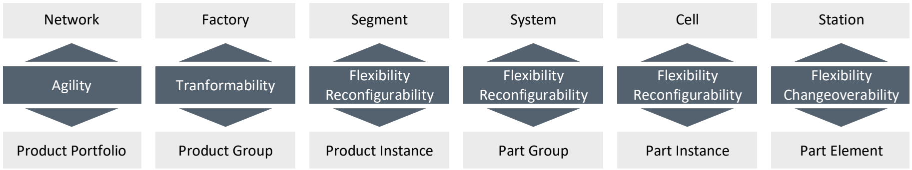

Figure 1.4: The six levels of a factory (top), with their corresponding changeability class (mid), and the equivalent product level (bottom). Adopted from ElMaraghy and Wiendahl (2009).

airflow over a heatsink or water from a pump to a pipe system. Individual interfaces can facilitate multiple interactions depending on the level of detail being considered. In the case of the interaction between the heatsink and processor described above, there is also a need for a physical contact and alignment (i.e. a spatial interaction) between the two components. Such interactions between heatsink and processor can be realised in various manners. Screws and pins can be used to align the two components, while a thermal interface material (such as cooling paste) can be used to facilitate the transfer of heat and absorb tolerances from spatial alignment. Fans attached to the heatsink can then provide an increased airflow for a material interaction, and the processor can be connected to a sensor and power supply through wires or pins on a motherboard for energy, information, and spatial interactions.

1.1.4 Manufacturing System Platforms and Changeable Manufacturing

Development and utilisation of platforms in manufacturing is an enabler for changeable manufacturing; a way to improve variety management in manufacturing systems. Changeable manufacturing is a manufacturing paradigm based on the concept of changeability, i.e. the characteristics giving manufacturing systems the capability to accommodate to change in an economical manner by making adjustments at all levels of a factory (ElMaraghy and Wiendahl 2009). It is an umbrella term encapsulating a number of so-called changeability classes, each relating to specific levels within a factory, as shown on Figure 1.4. Each level, when broken down, consists of one or more instances on the lower level, e.g. a network consisting of multiple factories, a factory consisting of multiple segments, and a segment consisting of multiple manufacturing systems. The five changeability classes are briefly outlined below (ElMaraghy and Wiendahl 2009):

- **Agility:** strategic ability of a company to respond to volatile market conditions, e.g. by pursuing new markets, services, products, or manufacturing systems.
- **Transformability:** tactical ability of a factory to switch between a variety of product groups or families.
- **Reconfigurability:** ability of a production area to, through a physical change, switch between similar product groups or families with relative ease and speed.
- **Flexibility:** operative ability of a production system to, without a physical change, switch between variants within a predefined product family quickly and effortlessly.

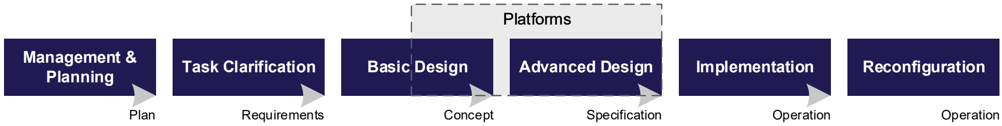

Figure 1.5: Simplified generic reconfigurable manufacturing system design approach by Andersen et al. (2017). A dashed box has been highlighted to during which stages utilisation of platforms provide the largest benefit (Sorensen et al. 2019a).

- **Changeoverability:** operative ability of a workstation to perform specific operations without effort and delay.

Traditional dedicated manufacturing systems (DMS), lacking the characteristics facilitating change, are unable to keep up with the rapid introduction of new technologies, products, and variants. Changeable manufacturing systems (CMS)—i.e. manufacturing systems possessing characteristics giving them the capability to accommodate change—and in particular reconfigurable manufacturing systems (RMS) are becoming increasingly relevant to manufacturers. One of the key characteristics of RMS is modularity (ElMaraghy and Wiendahl 2009; Koren 2006). The modular nature of both platforms and RMS implies a connection between the two. In fact, the utilisation of platforms to design an RMS can be considered part of the basic and advanced design phases of RMS design. Following Andersen et al.'s (2017) generic method for RMS design, platforms can play into the basic design phase when realisation of reconfigurability and functionality is determined, interfaces identified and specified, and system elements are decided upon. A simplified illustration of the design approach is shown on Figure 1.5, with highlights added to illustrate when platforms can provide a benefit. For the advanced design phase, the platform plays into the detailing of system modules, system interfaces, and detailed manufacturing equipment design. These functional elements, enablers, interactions, interfaces, and modules are all things a platform should include.

With the development, implementation, and utilisation of manufacturing system platforms remaining a relatively immature field of research, attempts at drawing inspiration, concepts, and methods from other areas where maturity is higher and platforms are more common have previously been made, especially borrowing from software architecture and development (Benkamoun et al. 2014; Bossen et al. 2017; Jepsen et al. 2014; Sorensen et al. 2018a). Having both a product and manufacturing system platform available could greatly limit the effects of introducing a new product variant or generation, preventing these changes from propagating throughout a manufacturing company. Utilising both types of platforms in conjunction facilitates co-development of new solutions across departments in a manufacturing company.

1.2 Co-Development & Co-Platforming

Co-development in systems engineering, product, and production design refers to the simultaneous development or design of two or more systems with some required or anticipated mutual effect on each other, e.g. a product and the manufacturing system producing it.

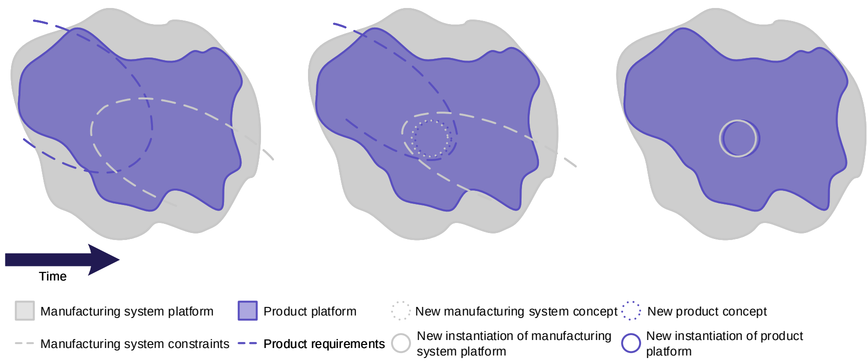

Figure 1.6: Platform-based co-development with new instantiations of the product and manufacturing system platform being developed alongside each other to ensure alignment and compatibility. Adapted from Michaelis and Johannesson (2012).

Co-development, along with the related concept co-platforming, has been gaining footing in research on platforms and reconfigurable manufacturing in particular (ElMaraghy and Abbas 2015; Michaelis and Johannesson 2012). The end-goal of co-development of products and manufacturing systems, as outlined by Michaelis and Johannesson (2012) and shown on Figure 1.6, is to achieve platform-based co-development, wherein aligned instantiations of the platforms are simultaneously created as explicit configurations of products and their corresponding manufacturing system.

Inconsistencies and lack of communication with regards to platform development as well as misalignment between platforms have proven massive challenges for manufacturers (Sorensen et al. 2018c). To address this, and generally improve the synergy between product and manufacturing system development, various approaches to integrate and align the two areas are appearing, such as integrated product and production modelling (Brunoe et al. 2018a; b; Michaelis et al. 2015), resource modelling and capability matchmaking (Dhungana et al. 2018; Järvenpää et al. 2018; 2016), and set-based concurrent engineering utilising platforms (Landahl et al. 2016; Levandowski et al. 2014a; b). Such approaches provide support for a formal way to integrate the work of product and production development teams, ensuring their alignment and compatibility by making it clear which product functions and features are needed, which manufacturing capabilities are available, and how these can be matched, thus facilitating co-development of solutions.

1.3 Supporting Independent Development of Platforms

In summation, the rising demand for new products, new technologies, and options for personalisation all play a part in increasing the variety manufacturers must be able to handle in order to remain competitive. Product platforms have successfully been employed to manage this variety in products, but dealing with variety and frequent product changes is straining the capabilities of existing manufacturing systems. New manufacturing paradigms and the coming fourth industrial revolution present manufacturers with new opportunities to manage variety and improve the capabilities of their manufacturing systems. Manufacturing system platforms and changeable manufacturing in conjunction with product platforms are seemingly attractive choices to achieve the desired variety and capability of both product and production.

Present effort is a step towards arming manufacturing companies with the necessary background, methods, and tools to independently develop manufacturing system platforms. Few tools and methods exist aimed explicitly at assisting manufacturers in developing manufacturing system platforms. Through the studies, projects, and research gathered and presented in this thesis, strides have been made to address this, by gaining inspiration and applying concepts, methods, and tools from various other fields dealing with systems engineering in general.

1.3.1 Thesis Structure

This thesis is structured into four chapters and an appendix with six appended papers. The core purpose and content of each of the four chapters is described below:

1 **Introduction:** Sets the stage for the thesis, introducing its primary subject and context. Defines a number of important terms and provides state-of-the-art for manufacturing system platforms, linking it to other relevant research areas.

2 **Research Approach:** Outlines the research approach, covering methodological background and introduces the industrial case. Lists research objective, questions and sub-questions addressed through the Ph.D. project.

3 **Developing Manufacturing System Platforms:** Describes the contributions made within the research field through the Ph.D. project, based off the six appended papers. Provides an extended abstract for each paper and summarises the implications of the contribution.

4 **Concluding Remarks:** Sums up the main findings of the Ph.D. project and addresses research objectives and questions. Discusses findings and applications, and outlines future research.

2

Research Approach

A central aspect of this thesis is the creation of new knowledge on manufacturing system platforms with both theoretical uses and practical applications. With the limited existing research in the field and continuing difficulties in developing and utilising manufacturing system platforms in companies, new theories, concepts, methods, models, and tools contributing to the state-of-the-art are needed. In particular, the steps and tools required in going from realising platforms, modules, and changeable manufacturing are needed, to identifying, developing, and documenting these for future use. Thus, considering the above and the state-of-the-art presented in Chapter 1, the overall objective of this thesis can be formulated as below.

> **Research Objective**
> Create and apply methods and tools for identifying, developing, and documenting manufacturing system platforms through commonality and standardisation of assets

The focus on creation of new knowledge and its application in companies calls for a research approach centred around this. It should be an approach that can be employed for research on both manufacturing systems, products, and systems engineering as a whole, in order to account for future co-development and the necessary alignment between these departments in a company. In the following sections, the applied design science research approach is outlined, the industrial case presented, and finally the research objective is framed by individual research questions and sub-questions.

2.1 Design Science Research

Hevner et al.'s (2004) framework for design science in information systems (IS) research emphasises creation of new knowledge, and its application in real world scenarios. It is a conceptual framework for conducting research on information systems by combining design science and behavioural science, i.e. the search for utility (effective artefacts) and the search for truth (justified theory), respectively (Hevner et al. 2004). An effective artefact is, for the purposes of the research framework, a concrete entity addressing and facilitating

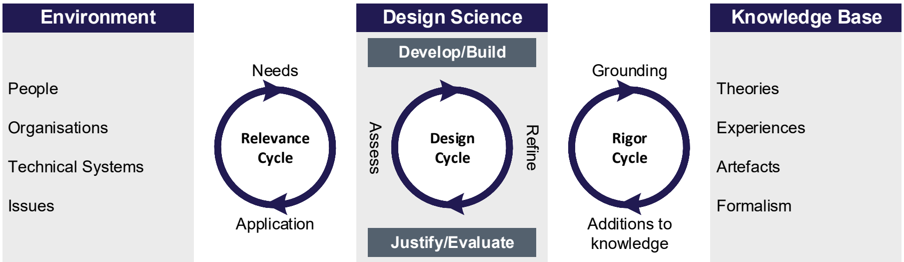

Figure 2.1: Hevner's (2007) information systems framework and design science research cycles.

understanding of problems. Hevner et al. (2004) describes four type of artefacts: "*constructs* (vocabulary and symbols), *models* (abstractions and representations), *methods* (algorithms and practices), and *instantiations* (implemented and prototype systems)". In the design science framework, development of artefacts is initiated by problems or needs in an environment. Using applicable knowledge, e.g. theories, frameworks, or existing artefacts, new artefacts are built or designed and consistently evaluated in order to justify their existence and continued development. Finished and justified artefacts are applied and tested in an appropriate environment, and subsequently added to a knowledge base along with any newly acquired experiences and developed theories.

Hevner (2007) introduced the notion of design science research cycles to the original research framework, resulting in the iteration shown on Figure 2.1. The *relevance cycle* provides a context for application of the design science research results, along with a specification of the requirements and determination of acceptance criteria for evaluating the outcome of the research. It connects the design activities to the overall context for the research project. Needs are defined in the environment, i.e. the problem space, and provide an input to be processed by design science activities. Every artefact developed based on the needs from the environment is applied within the context of the environment, and field tested to determine the artefact's utility. Through the *rigor cycle*, the design activities are founded in scientific theories, experiences, and existing artefacts in a knowledge base while newly developed artefacts, theories, experiences, and potential extensions to already existing entries are fed back to the knowledge base. Central to the design activities and project is the *design cycle* itself. In this cycle, the two core design activities of building (developing) and evaluating (justifying) are carried out iteratively. Artefacts are built, evaluated, and refined until a satisfactory result is achieved. The requirements upon which the evaluation is based are input from the relevance cycle, while the evaluation, development, and refinement methods are all pulled from the rigor cycle. As Hevner (2007) put it, "it is important to understand the dependencies of the design cycle on the other two cycles while appreciating its relative independence during the actual execution of research."

The four types of artefacts are all highly relevant to the development of manufacturing system platforms. Construct artefacts, defined as vocabulary and symbols, is essentially the language and manner in which problems and solutions are communicated and defined. While the platforms are discussed increasingly frequently in research and within companies, there are still several individual understandings and opinions of e.g. what constitutes a platform, how a module is defined, what a manufacturing process or manufacturing system is (Sorensen et al. 2018a; Sorensen et al. 2018c). Developing constructs, e.g. in the shape of employee handbooks, classification schemes, and modelling formalisms, makes communication during platform projects easier and helps avoid misunderstandings. They also function as templates and forms for documenting platforms and their development. Model artefacts use the vocabulary defined in constructs to represent the problem, solution, environment, and the link between them. They are tools to be used during platform development, e.g. to represent the functional structure of a platform in development, highlight how requirements are realised in the modules of a platform, or ways of representing entire manufacturing systems and their characteristics. Abstracting various aspects of platforms in this manner is useful to manage the complexity of the development process.

Method artefacts are processes or procedures guiding problem solving and decision-making. An informal method can be a simple text, describing how a manufacturing process is carried out, or how a model is built and used. Method artefacts can also be formal mathematical algorithms, e.g. providing a measure of the commonality between two systems, or a recommendation on which platforms to develop. Instantiation artefacts are artefacts implemented to solve a problem in an environment. This can, for instance, be the actual decision of selecting a potential platform based on an algorithm applied to a classification coding scheme. An instantiation artefact may also be an implemented manufacturing system platform. Examples of these are few and far between, but remain critical to the continued research within the field as a way to demonstrate the feasibility of both the platforms and the artefacts, theories, and experiences that helped create them.

The design science in information systems research framework outlined above is an appropriate fit for research on manufacturing system platforms since it is, as discussed in Section 1.1.4, a field of relative immaturity. Thus, the notion of employing knowledge bases aligns with, as others have suggested, gaining inspiration and applying concepts from other fields of research, thereby contributing to the knowledge base on manufacturing system platforms with new experiences and artefacts. Further, with its focus on application of artefacts to solve real-world problems within a defined environment context, it lends itself well to case-studies, where new tools and methods are developed, or existing tools and methods are applied in a new context. Another reason for choosing this framework, is that it is both proactive and reactive with respect to technology (Hevner et al. 2004). Proactive, in the sense that design science focuses on creating and evaluating technology and artefacts, allowing the industry to address their needs through the artefacts. Reactive, as behavioural science focuses on developing and justifying theories related to the implementation and use of technology and artefacts. Research on platforms should be developed and evaluated in a collaborative context between academia and the industry.

2.2 Industrial Case

This Ph.D. project is affiliated with, and partly funded by, the national research initiative, Manufacturing Academy of Denmark (MADE), specifically the first iteration, MADE SPIR (Strategic Platform for Innovation and Research) in work package 2 (WP2) on modular production platforms[1]. MADE is essentially a collaboration of Danish universities, companies, and technology institutes working towards addressing issues in the Danish manufacturing industry and keeping Danish manufacturers competitive on a global scale.

The primary collaborator for this Ph.D. project is a large, Danish-founded manufacturer of discrete products for both domestic and industrial applications. Currently, the company employs over 19,000 people, distributed across several factories and sales offices in more than 50 countries, with their main headquarters and the majority of their factories located in Denmark, as summarised in Table 2.1. Every year, hundreds of manufacturing systems produce millions of complete products, packed and ready for sale to private or industrial customers, as well as components, sub-assemblies, and custom solutions to industrial partners. With in-house final assembly and production of components and sub-assemblies, the company is essentially horizontally integrated. Many of the case company's manufacturing systems are largely contracted designs by a variety of system integrators, while some systems include manufacturing equipment designed entirely in-house. Thereby resulting in a high variety of the manufacturing systems themselves, with manufacturing equipment from a wide range of suppliers and system integrators.

Recently, the case company has been seeing a high demand for rapid introduction of new products, an upswing in product variety, and an accelerated time-to-market, along with a continuous pressure to increase productivity and lower costs. This has lead to a need for an accelerated product and production development process, which in turn lead to the realisation that the case company must introduce the capability to efficiently accommodate change through standardisation—thus, changeability through platforms.

Stakeholders within the case company have been working towards increased modularity and standardisation in products and production for several years. Development and support truly picked up speed in 2014 with participation in MADE SPIR, thereby acquiring additional resources in the shape of collaboration with researchers from Aalborg University. The first large platform co-development project was initiated in 2015, intended to kick-start development of a product platform and a manufacturing system platform for a specific set of products and related production systems. It involved designers, developers, experts, and stakeholders from both product and production as well as Ph.D. and M.Sc. students from two Danish universities. Focus for this project was essentially to design the first iteration of a platform-based product and production architecture, intended to be the foundation of any future new products and manufacturing systems within the scoped product and production segment. Additional details on platform projects with the primary collaborator, the challenges that appeared, and recommendations on how to address these have been outlined in (Sorensen et al. 2018c).

As a result of an increased focus on platforms and standardisation, various initiatives related to big data have been initiated within the company, including the formation of a new department whose task is to gather and standardise production data. Data on manufacturing systems has proven crucial in the continued development of platforms within the case company, and the required data has historically been inadequate or completely missing. A seemingly simple question such as "how many manufacturing systems do we have?" has turned out difficult to answer, due to varying definitions and opinions on what exactly constitutes a manufacturing system. Outside the immediate intended benefits

[1] `http://made.dk/spir`

Table 2.1: Overview of the industrial case. The first four rows refer to the company as a whole, while the remaining rows refer only to the selected production segment.

Characteristic	Value
Company Size	Large $> 19,000$ employees
Industry	Private and industrial mechatronic products
Manufacturing Paradigm	Mass production
Manufacturing System Paradigm	Dedicated manufacturing
Production Context	Mechatronic sub-assembly
Location	4 factories in 4 different countries
Production Volume	5k–2mil annually
Product Variety	24 product architectures
Production Variety	20 production architectures
Production Planning	Make-to-stock
Automation	Manual, semi-automated and fully-automated
Cycle time	9s–90s

of utilising platforms, e.g. accelerated time-to-market, increased process robustness, and simplified variety management, a number of other related benefits are expected as an indirect result of platform development, as outlined in the concluding remarks, Chapter 4.

For the purposes of this Ph.D. project, a segment of the case company's production has been selected to act as primary production context. The selected production segment is the assembly of a mechatronic sub-assembly, covering a wide range of production processes and automation degrees ranging from manual through semi-automated to fully automated. This production segment consists of 20 manufacturing systems, producing 24 product architectures, covering both high-runner products with an annual volume over 2 million, and specialised products numbering 5,000 annually. Size, mass, shape, and functionality also vary greatly across product architectures. Table 2.1 summarises the case company and the segment of their production covered in this research. Characteristics below the second line refer only to the production segment covered in this study.

2.3 Research Questions

In order to further frame this thesis and elaborate on the research objective listed in the beginning of this chapter, three overall research questions have been formulated. Each research question is addressed through one or more sub-questions from six research tasks, documented in the six appended papers. While the overall research approach is the design science research framework described in Section 2.1, a number of other methods have also been used for the individual appended papers. For each sub-question, the paper it originates from is listed along with the selected research methods.

> **Research Question 1:**
> How can manufacturing system platforms be developed and documented using well-known concepts from software systems engineering and architecture, and which challenges arise during this process?

RQ1.1 How can production platforms be developed and documented with the aid of concepts and constructs from the field of software systems architecture? (Paper A; multi case study)

RQ1.2 Which challenges arise during manufacturing system platform development, and how can these be addressed? (Paper A; multi case study)

Research Question 2:
How can commonality in processes across manufacturing systems be classified and used to identify candidates for manufacturing system platforms?

RQ2.1 How can processes during production of discrete products be classified independently of the means facilitating the process? (Paper B; literature review, iterative search and consolidation)

RQ2.2 What are the essential aspects of manufacturing systems that must be captured in order to classify them? (Paper D; design science research, classification, analysis, development and refinement of artefacts and knowledge)

RQ2.3 What is the best form/structure of a coding scheme that captures and classifies essential manufacturing system aspects/characteristics? (Paper D; design science research, classification, analysis, development and refinement of artefacts and knowledge)

RQ2.4 How can a production system classification coding scheme be used to identify candidates for a manufacturing system platform? (Paper F; design science research, single case study, application in environment)

Research Question 3:
How can manufacturing system platforms be developed in a brownfield approach taking into account a manufacturer's existing production landscape and which challenges arise over time as platform development progresses?

RQ3.1 Which challenges do mature manufacturers face over time, when developing manufacturing system platforms? (Paper C; design science research, evolving case study)

RQ3.2 What steps should a manufacturer take to develop platforms of standardised assets based on existing manufacturing systems and environments? (Paper E; conceptual research, evolving case study)

3

Developing Manufacturing System Platforms

In order to demonstrate the progress made within the field of manufacturing system platforms, this chapter accounts for the scientific contribution of each of the six appended, peer-reviewed papers. To illustrate the progress and development of the research as it was carried out, the papers are organised in chronological order of writing. As outlined in Section 2.3, each paper covers one or more sub-questions, each contributing to addressing the three main research questions for this thesis.

The following sections are based on the six appended papers, and will include an extended abstract for each paper. As such, some level of similarity and repetition of certain results, arguments, figures, and phrasings is to be expected.

3.1 Platform Development Through The Four Loops of Concern

Paper A is entitled 'Production Platform Development through the Four Loops of Concern', written for and presented at the 9th Mass Customization & Personalization Conference (MCPC2017) in 2017. It relates to and addresses RQ1 by answering the following two sub-questions:

RQ1.1 How can production platforms be developed and documented with the aid of concepts and constructs from the field of software systems architecture?

RQ1.2 Which challenges arise during manufacturing system platform development, and how can these be addressed?

It was carried out as a multi case study in close collaboration with two industrial collaborators, one of which is the main industrial collaborator for this project. The main purpose of the paper was to document a platform development method created through the first platform and co-development projects in both companies. It is inspired by the conceptual model for manufacturing system platforms presented by Bossen et al. (2017), using concepts and methods from software architecture to guide the process and vocabulary, specifically the notion of architecture descriptions, views, and viewpoints from ISO/IEC/IEEE 42010:2011(E) (from here on ISO 42010) (ISO et al. 2011).

3.1.1 Extended Abstract

Introduction & Background

Platforms, based around commonality and standardisation (Baldwin and Woodard 2009), can target a variety of assets within a company, each standardised according to various objectives, e.g. products (Simpson 2004), processes (Jiao et al. 2007), technologies (Alblas and Wortmann 2014), and manufacturing systems (Michaelis et al. 2015). Without aligning these platforms, which can exist concurrently in a company, companies run the risk of sub-optimising their product and manufacturing system platforms. Taking a more holistic approach, i.e. seeing the bigger picture, can help create this alignment between the platforms, and avoid sub-optimal solutions that are not compatible with or ideal for the rest of a company's production landscape. Co-development, co-platforming, and integrated platform development are all examples of more holistic approaches to platform and platform-based development (ElMaraghy and Abbas 2015; Levandowski et al. 2014a; Michaelis and Johannesson 2012).

To ease the adoption, development, and documentation of platforms, efforts have been made to employ applicable concepts, methods, and tools from outside the manufacturing industry (Benkamoun et al. 2014; Bossen et al. 2017; Jepsen et al. 2014). This effort is continued by adopting the concept of architecture descriptions from ISO 42010, which is originally a way to structure the development of software architecture (ISO et al. 2011). Architecture descriptions are a concrete way of expressing the otherwise abstract architecture exhibited by a system. A core aspect of architecture descriptions is the notion of viewpoints and views, both of which are building blocks of an architecture description. Viewpoints are a way to look at systems, comparable to construct and method artefacts from design science research in information systems (Hevner and Chatterjee 2010). They provide a set of tools for developers (or system architects) to use, and guide the usage of said tools. Views are the results of applying specific viewpoints to a system, similarly to model and instantiation artefacts. Employing a "functional viewpoint" creates a "functional view" addressing stakeholder concerns related a system's function. Translating this to platforms, and considering platforms a standardised subset of an architecture, platform viewpoints and platform views can be used to create platform descriptions, describing platforms within a company. Adopting viewpoints and views in product and manufacturing system development allows companies to utilise the vast, existing knowledge base on software architecture, for instance the catalogue of viewpoints and concerns by Rozanski and Woods (2011).

In order to create a platform description, a collection of viewpoints that sufficiently frame stakeholder concerns should be identified. One of the case companies employed an existing model for product platforms in a separate department within the company, see Figure 3.1 (left). Building on this model and the aforementioned viewpoint catalogue, a revised model was created to cover both product and manufacturing system platforms, while introducing the concept of viewpoints and views, Figure 3.1 (right). The six viewpoints for product and manufacturing system, and the views created from them, constitute the product and manufacturing system architecture description, while the four viewpoints below the line represent the platform description for either system. Each of the views resulting from using a corresponding viewpoint can be explained briefly as:

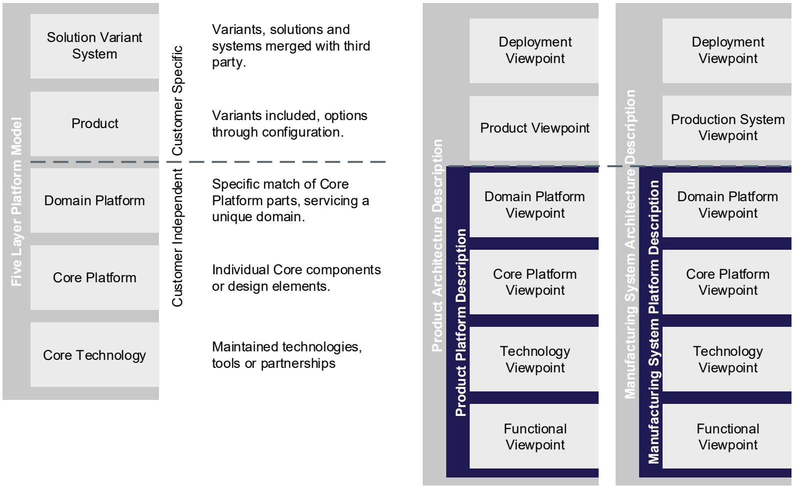

Figure 3.1: Initial five layer product platform model from one of the case companies (left) alongside the revised platform model (right) using viewpoints for both product and manufacturing system platforms (Sorensen et al. 2018a).

- **Functional view:** functional structure of the manufacturing system, the elements and their primary interactions, interfaces, and responsibilities.
- **Technology view:** fundamental technologies employed by the company, how they are maintained and developed.
- **Core platform view:** available components, design elements, equipment, etc. within the platform.
- **Domain platform view:** how core platforms are used within a specific area of application.
- **System view:** the instantiated system developed from an internal development process using available platforms.
- **Deployment view:** deployment and operation of the instantiated system within its immediate environment.

The Four Loops

Four Loops of Concern (FLC) is a method guiding the standardisation of tangible and intangible assets for platform development, leaving out the two non-platform viewpoints on Figure 3.1 (system and deployment). It consists of four loops, progressing from intangible (functions and technologies) towards tangible (components and instantiations), illustrated as a spiral on Figure 3.2—a common visual for iterative methods in software development (Maier and Rechtin 2000). Each loop consists of four basic steps:

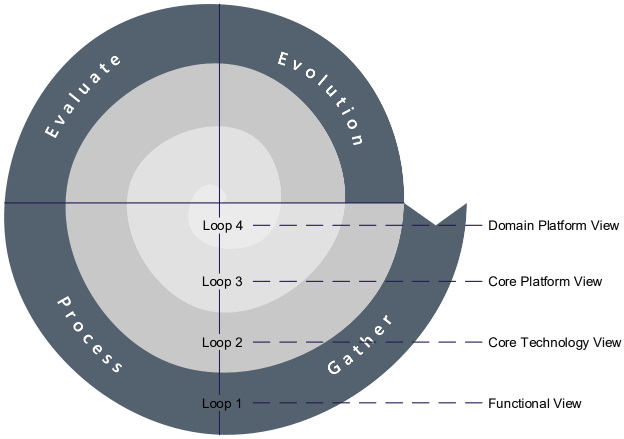

Figure 3.2: The Four Loops of Concern (FLC) for developing and documenting platforms. Redrawn from (Sorensen et al. 2018a).

1. **Gather:** collection of data/information required for a given loop, e.g. production layouts and schematics.
2. **Process:** application of tools, methods, and models to refine and structure data, e.g. function-means trees.
3. **Evaluate:** synthesis of information based on refined data, e.g. mapping of functions to technologies.
4. **Evolution:** decisions made regarding the next steps in development, e.g. discontinuation of old technology and implementation of new.

Going through all four steps for all four loops results in the creation of four views describing a platform. The output for each loop can be summarised as: (loop 1) functional elements and (loop 2) technologies to be supported in the future, (loop 3) a catalogue of platforms (components, equipment and modules), and (loop 4) guidelines on when and how to use specific platforms. Completing all four loops ensures that a view is created for each platform viewpoint shown on Figure 3.1.

Findings

FLC was applied in two separate case companies with separate participants. Both case studies covered one production segment with multiple manufacturing systems. In both studies, the main sources of information were system experts, ERP systems, and data collected manually from the manufacturing systems. As a result of applying FLC, a book was created by each company, containing the resulting information and decisions from the platform development process. The books represent the first iteration of a collection of platform descriptions for each company. They did not cover all elements identified during the development process in detail, but described them briefly, detailed a smaller number of platforms, and set up guiding principles for future development.

Numerous challenges appeared during the case studies. Many of these were related to the lack of objective tools and measures for identifying potential platforms and commonality across manufacturing systems. Most of the available data was based on knowledge from system experts and stakeholders, including design drivers, system characteristics, and functions, making this data subjective in nature. Specifically, a classification scheme for processes or functions in manufacturing systems would be beneficial to the data gathering phase, and facilitate a more objective comparison of manufacturing system characteristics. Further, the vocabulary, and need to consider principles rather than moving directly to physical concepts and solutions, proved difficult. In an effort to accommodate issues with the vocabulary, words like "viewpoint" and "view" were not used in the primary project group, but the concepts remained relevant.

Conclusions

The Four Loops of Concern is an iterative approach to develop and document platforms through standardisation of tangible and intangible elements of a system. It is based on concepts and methods from software architecture development, and has been applied in two separate case studies. While FLC was applied successfully in both cases, there is a need for more objectivity and for making the method and vocabulary more consistent and easily relatable to developers, designers, and stakeholders.

3.1.2 Implications

The paper summarised above describes the first platform development project within each company, and the first case study of this Ph.D. project. As such, it set the stage and direction for much of the research to follow. During the case study and work on the paper, it became clear that consistent communication and a relatable vocabulary was key to getting designers and developers motivated and involved in the platform development process. Too many new and foreign concepts were introduced rather quickly during the case study. The purpose of the development project and the new concepts was not made sufficiently clear early on in the project. With much of the project relying heavily on subjective information from experts and stakeholders, their individual understanding of these concepts and purposes greatly influenced the outcomes of the case study, and highlighted the need for more consistency, coherency, and objectivity during the development process. The outcome and contributions of the paper can be summarised as:

1. An iterative method to platform development and documentation.
2. Experiences in platform development added to the knowledge base.
3. Successful application and an increased understanding of ISO 42010 concepts and tools to advance platform development.
4. A direction for future research on tools and methods to address the challenges encountered during the project.

3.2 Classification of Production Processes

Paper B is entitled 'A classification scheme for production system processes', written for and presented at the 51st CIRP Conference on Manufacturing Systems (CMS2018) in 2018. It relates to and addresses RQ2 by answering the following sub-question:

RQ2.1 How can processes during production of discrete products be classified independently of the means facilitating the process?

The study was carried out as a literature review of production and manufacturing processes. Through an iterative search and consolidation process, a classification scheme on production processes was created by consolidating existing classification schemes. The purpose of this was to lay the foundation for making a quantitative and more objective comparison of manufacturing systems, in order to identify potential platform candidates.

3.2.1 Extended Abstract

Introduction & Method

Simultaneous development of products and manufacturing systems based on co-existing platforms of standardised assets has been gaining traction (ElMaraghy and Abbas 2015; Michaelis and Johannesson 2012). However, development of manufacturing system platforms remains a difficult task (Bossen et al. 2015), with many inherent challenges. One such challenge is the identification of potential platforms, i.e. platform candidates, based on a company's existing manufacturing systems. To properly identify platform candidates, a way to consistently identify common processes across manufacturing systems is needed. This can be achieved through a classification scheme for production processes. Using the common vocabulary and definitions in a classification scheme, processes, and thus process commonality between systems, can be identified consistently in a standardised manner. Consistency and standardisation are key aspects of platforms.

Various classification schemes for manufacturing processes or material handling processes exist, and a few include test and inspection processes, but no single classification scheme has been found to incorporate all of these. Such a consolidated classification scheme could greatly benefit the manufacturing system platform development task by, easing both the collection of data and the identification of commonality in manufacturing systems. Focus for the consolidated process classification scheme presented in the following is on discrete manufacturing. While it may have applications outside discrete manufacturing, creating a classification scheme for the process industry poses different challenges, partly due to a prevalence of shapeless materials.

In order to structure the creation of the classification scheme, the study employed an iterative approach switching between searching for and consolidating classification schemes, taxonomies, or ontologies for manufacturing processes and material handling processes. It is essentially a simplified adaption of the design science research cycles (Hevner 2007). The first part of the approach was a simple search on a number of keyword combinations followed by pearl-growing. The consolidation step was focused on grouping processes, process discrepancies (e.g. included/excluded processes), and how well the classification schemes fit the following criteria:

- include both manufacturing and handling processes
- clearly differentiable levels
- manageable amount of levels
- function-based processes

Following these criteria, the intention was to create a comprehensive classification scheme that was easily navigable, and consisted of processes independent of the means or equipment performing the processes. Function-based processes make it easier to identify alternatives to existing solutions, and compare production systems that may not have much similarity in terms of equipment, but rather in the processes they carry out.

Classifications & Taxonomies

As a basis for categorising manufacturing and material handling processes, this study subscribes to the notion of added *utility* rather than added value (Apple 1972; Kay 2012). Material handling processes add "time" and "place" utility, by ensuring workpieces are in the right place at the right time, and manufacturing processes add "form" utility by changing the shape and composition of a workpiece. Traditionally, material handling processes are considered non-value-adding processes, but they are still necessary for many value-adding processes to be successful.

To create the consolidated classification scheme, several classifications, taxonomies, and ontologies were reviewed. Six key schemes form the main influencers of the consolidated classification scheme; four for manufacturing processes (Ashby 2011; DIN 2003; Kalpakjian and Schmid 2009; Todd et al. 1994) and two for material handling processes (Kay 2012; VDI 1990). None of the six key classification schemes, or any of the additional reviewed schemes, fulfil the first criteria on including both manufacturing and material handling processes, but the consolidated classification scheme does.

A common aspect of the reviewed classification schemes is, that the primary way to categorise manufacturing processes whether they are shaping or non-shaping (Ashby 2011; DIN 2003; Kalpakjian and Schmid 2009; Todd et al. 1994), i.e. whether they change the shape of an object or not. Following this first differentiation, there are a number of ways to categories manufacturing processes. Todd et al. (1994) group processes in up to eight levels, making the distinction clear, but difficult to manage in terms of levels. DIN 8580:2009–09 (henceforth DIN 8580) groups processes according to material state and whether the process creates, reduces, or preserves the coherence of a given workpiece. This incorporates shaping/non-shaping implicitly, rather than explicitly. Ashby (2011) initially groups processes depending on when they occur, i.e. primary shaping for creating the initial shape of the workpiece, secondary processes for adding features, joining for assembly, and surface treatment for finishing. Subsequently, the processes are grouped hierarchically into four levels (universe, family, class, and subclass). Kalpakjian and Schmid (2009) have six families of processes with three levels each, grouping each

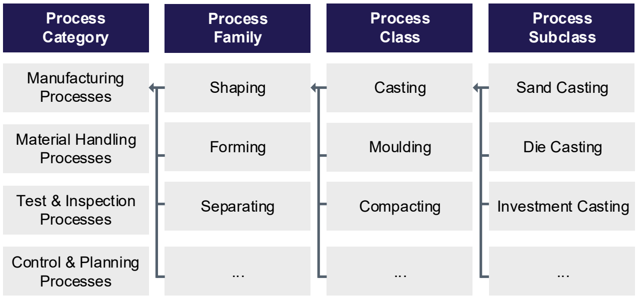

Figure 3.3: Partially expanded consolidated overview of the classification scheme, focusing on the "shaping" process family and "casting" process class. Adapted from (Sorensen et al. 2018b).

process' corresponding description according to the material they are applicable to. In general, as the level of detail increases, the classification of processes becomes more dependent on the means/equipment used to perform the process.

The reviewed material handling classifications are largely equipment-based and defined by the four primary material handling functions described by Chu et al. (1995); transport, positioning, unit load formation, and storage. Kay (2012) adds "identification and control" as a fifth category. VDI 2860:1990–05 (henceforth VDI 2860) breaks material handling into three groups focusing on the "handling" processes, and references other standards for the two remaining groups ("transport" and "storage(hold)") (VDI 1990). "Handling" is broken down an additional two times, reaching elementary functions (e.g. "rotate") and composite functions (e.g. "allocate") at the lowest level. VDI 2860 also introduces a set of symbols for creating flow charts based on the standard, and is independent of equipment and means.

Results

An overview of the consolidated classification scheme is presented on Figure 3.3, with a partially expanded view of the "manufacturing process" category. It consists of four levels (category, family, class, and subclass), adopting a structure similar to the one presented by Ashby (2011). The classification scheme has been modelled using Protégé (Musen and the Protégé Team 2015) and made available as an OWL file[1]. In total, the covered categories, families, classes, and subclasses comes to:

- 4 process categories
- 16 process families
- 53 process classes
- 232 process subclasses

[1] github.com/Firebrazer/ProdProcClass

Manufacturing processes add "form" utility to workpieces, changing their shape or make-up. It consists of six process families: shaping, forming, separating, change material properties, joining, and surface treatment. Each process family is broken down another two times, each containing six to nine process classes, and each class listing up to ten subclasses.

Material handling processes add "time" and "place" utility by making sure a workpiece is at a specified location at the right time. The material handling category consists of four process families: transport, storage(hold), handling, and unit load formation. Focusing on processes occurring within the manufacturing system themselves, the transport and storage(hold) families were omitted from the study, as they occur between or outside manufacturing systems. The handling and unit load formation families each consist of four classes with up to nine subclasses per class.

Focus for the study is on manufacturing and material handling processes, as such, the two remaining process categories (control & planning and test & inspection) have been left relatively unexplored during the study. Control and planning processes manage, balance, and facilitate the utility provided by other processes, but does not strictly provide "form", "time" or "place" utility. It contains three process families: business planning and control, manufacturing operations and control, and line control.

On the basis that the test and inspection processes provide a form of "information" utility rather than "time" and "place", they are separated from material handling and given their own category instead. They capture and communicate various types of information related to workpieces. This category is broken down into three families: inspection, functional test, and performance test.

Conclusions

Based on a review and consolidation of production process classifications, taxonomies, and ontologies, a consolidated production process classification scheme has been created. It groups processes into four categories based on the type of utility they add to a workpiece, further breaking down the categories into families, classes, and subclasses based on the characteristics of each process. The process classification scheme is intended to facilitate consistent data collection on, and comparison of, existing manufacturing systems within a company. This is done with the express purpose of identifying commonality and platform candidates across manufacturing systems to enable platform development and standardisation of assets.

3.2.2 Implications

The classification scheme can be used to describe manufacturing systems based on the processes they perform in a consistent manner. With a consistent and coherent classification of processes carried out by manufacturing systems, there is a potential for application of optimisation methods and algorithms to identify platform candidates, similarly to how Kashkoush and ElMaraghy (2016) form product families. Using the individually distinguishable symbols presented in VDI 2860 to map or describe manufacturing systems can also facilitate rapid digitalisation of manually collected data, and generally speed up the process of comparing multiple manufacturing systems.

The classification scheme is expandable, as additional classes and subclasses can be added, should it prove necessary. This may be needed when it comes to functional and performance tests, as some companies can have very specific tests that do not make sense to include or break down in a generic process classification scheme, e.g. a "final test" process covering a number of very specific tests. To recap, the outcome and contributions of the paper are:

1. A consolidated process classification scheme covering manufacturing, material handling, planning, control, test, and inspection processes.

2. A foundation upon which commonality can be identified across manufacturing systems, independently of physical means and solutions.

3. An increased understanding of production processes and technology enabling them.

3.3 Challenges in Manufacturing System Platform Development

Paper C is entitled 'Challenges in Production and Manufacturing Systems Platform Development for Changeable Manufacturing', written for and presented at the 2018 conference on Advances in Production Management Systems (APMS2018). It relates to and addresses RQ3 by answering the following sub-question:

RQ3.1 Which challenges do mature manufacturers face over time, when developing manufacturing system platforms?

The study documented in Paper C was carried out with a design science research approach through an evolving case study with the industrial collaborator. Its purpose was to sum up and outline the challenges encountered during three years of manufacturing system platform development projects with the industry. This was done to set the stage for research into areas of manufacturing system platform development benefitting manufacturers, and advancing the field as a whole.

3.3.1 Extended Abstract

Introduction & Method

Incorporating changeability into manufacturing systems appears to be a logical choice to managing variety in products (ElMaraghy et al. 2013; ElMaraghy and Wiendahl 2009) However, achieving this remains a difficult process despite research into platforms, co-development (Michaelis and Johannesson 2012), and co-platforming (ElMaraghy and Abbas 2015) paving the way for using manufacturing system platforms during manufacturing system design (Andersen et al. 2017; Bossen et al. 2015). With these collaborative approaches and integrated modelling gaining traction (Landahl et al. 2016; Michaelis et al. 2015), the need for co-existing product and manufacturing system platforms seems clear.

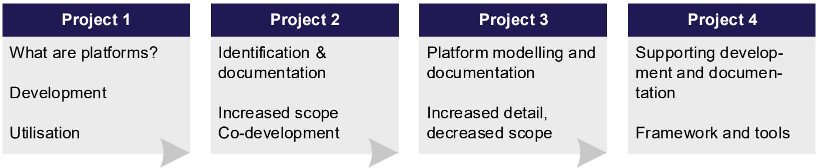

Figure 3.4: The four projects in the evolving case study. Adapted from (Sorensen et al. 2018c).

To highlight these challenges, and frame them for future research, this study presents a number of challenges, lessons, and experiences on development of manufacturing systems, based on an evolving case study spanning four projects and three years.

The evolving case study is structured based on the framework for design science research in information systems by Hevner et al. (2004). This framework is focused on developing new artefacts, new theories, and making new experiences, applying them all in an appropriate environment, and recording them in a knowledge base. The knowledge base itself essentially acts as a platform, as resources can be pulled from it and applied to a specific context, with the results being used to update the knowledge base, making it more comprehensive. Artefacts are used to communicate, represent, and solve problems (construct, model, and method artefacts respectively) as well as demonstrating the feasibility of both artefacts and solutions (instantiations). They can be considered somewhat analogous to the concepts of viewpoints (constructs and methods) and views (models and instantiations) from software architecture (ISO et al. 2011).

The Case

For the evolving case study, the case company is a large Danish manufacturer of discrete consumer and OEM products. The case study covers a number of different factories and systems both in Denmark and other countries, manufacturing both mechatronic and purely mechanical components and products. As the case study evolved, the scope was gradually changed to reflect the progress of development and the number of participants, as well as considering the timing of parallel projects and the company's internal roadmaps. As the knowledge base on manufacturing system platforms was somewhat limited prior to initiation of the evolving case study, applicable theories and artefacts from software architecture and product platforms were employed. The application environment for new artefacts and theories was provided by the case study environment, including the people, organisations, and technologies relevant to the case company.

Results

The evolving case study consists of four sequential projects, each with their own purpose, scope, and group of participants. An overview of the four projects is shown on Figure 3.4. Certain challenges appeared throughout the four projects; some repeatedly, while others were unique to the specific project. All of them are outlined in the following.

One challenge was prevalent during all four projects, but was especially an issue during the first project. This was the focus on product platforms in literature and the general lack of research on manufacturing system platforms. Knowledge on platforms among the participants of the project was sparse, so questions related to the nature and utilisation of platforms dominated the project. The ambition for initiating the platform projects was to design an RMS which, through platforms, achieved an improved level of utilisation and robustness. Because of this, there was also a need for clarifying the connection between RMS, changeability, and platforms. Five manufacturing systems in the same production segment, producing five product variants within the same product family, were scoped for the first project. Based on these five systems and product variants, a first iteration of an extractive platform development approach was created to show platforms could be developed based on existing manufacturing systems, and, through a workshop, how the platform could be used to design an RMS and its various configurations for the company.

For the second project, the scope was increased to cover 23 manufacturing systems and 25 corresponding product architectures. With this, both the scope and number of project participants increased greatly. Here, alignment of participant knowledge on both platforms and project purpose was key; especially with participants coming from multiple departments within the company, each with their own specific goals for participation. The focus for this project was on making knowledge on platforms more accessible throughout the company, by identifying, developing, and documenting potential platforms, thereby creating concrete examples of manufacturing system platforms that could be communicated in the various departments. It was also an attempt at breaking down the "silos" in which individual departments isolate themselves. Overall, the project was carried out according to the Four Loops of Concern (FLC) as outlined in (Sorensen et al. 2018a). As such, the project was an evaluation of the FLC, both its vocabulary and its use as a platform development method. Several model and instantiation artefacts were created during the project using e.g. function-means trees, generic organ diagrams, interface diagrams, radar diagrams, technical drawings, etc. Finally, the project resulted in the creation of an initial format for documenting product and manufacturing system platforms.

In the third project, the scope was drastically decreased to focus on a single key process carried out by all 23 manufacturing systems covered in the second project. The intention for this project was to increase the level of detail while continuing work on a documentation format or system for platforms, as the documentation system prior to the third project was still reliant on individual text documents, static figures, and tables. To better accommodate individual stakeholder concerns, a back end model for generating customised documentation containing only the requested information was developed. The intention was to have all available information on a given platform collected in one model, and then generate documentation specifically for various stakeholders in order to avoid information overload. Using a modelling formalism was also intended to promote consistency in terms of how platforms were described, documented, and communicated. It was based on the configurable component framework (CCF) because of its integration of both product and manufacturing system platforms (Claesson 2006; Michaelis et al. 2015). The selected process was documented as a platform, with all current and planned future configurations documented as configurable components with interactions, interfaces, constraints, requirements, and design solutions.

The fourth project is, at the time of writing, still on-going. Its purpose is to create a comprehensive platform framework supporting the development, documentation, and utilisation of manufacturing system platforms. The framework itself will be based around the conceptual model by Bossen et al. (2017) and the ISO 42010 standard on architecture descriptions (ISO et al. 2011), thus employing concepts, tools, and methods from software architecture and systems engineering. This is further an attempt at addressing both the lack of research on manufacturing system platforms, as well as the lack of concrete tools assisting manufacturers in their platform development process. Sorensen et al.'s (2018b) classification scheme is one concrete part of this framework, which, along side a manufacturing system classification code, is intended to help manufacturers structure and standardise their information and data collection on existing manufacturing systems, so these systems can form the base for development of new platforms.

Conclusions

As the case company progressed through the four projects outlined above, all participants' knowledge on platforms grew significantly. A multitude of approaches and tools were tested under a variety of circumstances and project scopes. The main challenges encountered during this evolving case study can be summarised as follows:

- Little to no consistency and coherency in vocabulary and development process.
- Participant knowledge on platforms and project scope was not aligned.
- Frequent miscommunication between departments in the case company.
- Very few available examples of platform documentation.
- Minimal available research and tools for manufacturing system platforms.

3.3.2 Implications

In concretising several challenges on manufacturing system platforms and particularly their development and documentation, the paper outlined above sets the stage for research on addressing these challenges and concerns. Particularly the vocabulary proved inconsistent and problematic as scope and project participants changed. This, coupled with a persistent need to collect more information on existing manufacturing systems, calls for a structured approach and tool if platforms are to be developed based on existing systems. The outcome is summarised as:

1. A list of frequent challenges related to manufacturing system development.
2. Suggestions on how to address these frequent challenges.
3. Sets the stage for research on concrete tools for manufacturing system platform development.
4. Feeds back experiences to the knowledge base on manufacturing system platforms.

3.4 Classification Coding of Manufacturing Systems

Paper D is entitled 'Classification Coding of Production Systems for Identification of Platform Candidates', written for and submitted to a journal in 2018, currently undergoing a second round of review. It relates to and addresses RQ2 by answering the following sub-questions:

RQ2.2 What are the essential aspects of manufacturing systems that must be captured in order to classify them?

RQ2.3 What is the best form/structure of a coding scheme that captures and classifies essential manufacturing system aspects/characteristics?

Taking a design science research approach, this study presents several new artefacts for describing manufacturing systems; their design, structure, processes, and enablers. It does so through a classification coding scheme with several digits, each representing a unique aspect of a manufacturing system. Using this classification coding scheme, manufacturers can ensure consistent and standardised descriptions of their manufacturing systems as lines of digits, uniquely identifying each manufacturing system and facilitating objective comparison of manufacturing systems across departments. Consistent and objective comparison and analysis of manufacturing systems enables identification of commonality and a variety of other characteristics and implications of design choices, that are not immediately obvious and can be beneficial to manufacturers.

3.4.1 Extended Abstract

Introduction

Manufacturing systems have continuously evolved since their introduction during the first industrial revolution. Changes in demand, technology, materials, and strategy keep pushing manufacturing systems forward in the search for improved performance and profits. With the increasing performance of computing and sensing technology, data and advanced analytics are becoming available to manufacturers, facilitating timely decisions on when and which changes to make in manufacturing systems, thus enabling reconfigurable and changeable manufacturing (ElMaraghy 2019). Manufacturing systems capable of accommodating change (i.e. changeable manufacturing systems) are still difficult to design and implement, although concepts and approaches based on the co-existence of product and manufacturing system platforms are becoming more popular (Abbas and ElMaraghy 2018; ElMaraghy and Abbas 2015; Michaelis and Johannesson 2012). However, development of platforms is no trivial matter either (Andersen et al. 2017; Bossen et al. 2015).

A key early step in the development of platforms is the identification of which assets to standardise and include in the platform, i.e. platform candidates. Often, the primary source of platform candidates is the tacit knowledge and intuition of system experts who have years of experience designing, maintaining, or working with the system (Sorensen et al. 2018a). This does lead to the identification of platform candidates, but the process could be improved with more objective decision support, helping system experts justify their decisions and identify platform candidates that would otherwise been missed.

Classification Systems & Coding

Commonality between products have long been used to identify assets to include in a platform or product family (Fixson 2007; Schuh et al. 2014; Thevenot and Simpson 2006). One approach to forming these families is through group technology and coding, an approach for classifying and grouping assets based on their properties and similarities, whatever these may be (Shunk 1985). Several coding schemes exist (Jung and Ahluwalia 1991), with the OPITZ scheme (Opitz and Wiendahl 1971) being one of the more widely known schemes for parts and components, but few such schemes exist for manufacturing systems (ElMaraghy 2006; ElMaraghy et al. 2014; 2010). Based on the results of group technology and coding, manufacturing can be rearranged to improve performance, e.g. a reduction in material handling and work-in-progress. Group and classification coding schemes are often customised to fit a specific company or industry in order to achieve the best possible results in terms of efficiency and benefits, contributing to the fact that no parts classification and coding scheme has been universally adopted yet (Groover 2015).

Coding schemes are typically numeric, consisting of a string of digits, each with a number of potential values. Each of these values have a distinct interpretation. In hierarchical codes, the interpretation of a value depends on the value of preceding digits, while the values in chain codes can be interpreted independently of preceding digits. Usually, chain codes will require more digits in order to contain the same information as a hierarchical code, but it will be easier to interpret (Groover 2015). Hybrid codes combine these two types of codes, allowing a more flexible, but also potentially complicated, coding scheme. Regardless of its type, a completed code will only ever have one clear interpretation.

Identifying commonality between manufacturing systems require that these be described in a consistent manner, for instance through a classification scheme, taxonomy, or ontology. McCarthy (1995) created a dendogram classifying manufacturing systems based on their operational objectives and characteristics, with McCarthy and Ridgway (2000) later developing a cladogram of automotive manufacturing systems, capturing their history based on 54 attributes. Manufacturing systems have also been classified according to their ability to make adjustments, i.e. according to their changeability (ElMaraghy et al. 2013; Wiendahl et al. 2007). Sorensen et al. (2018b) presented a consolidated process classification scheme for classifying manufacturing systems according to the processes they perform. Agarwal et al. (1994) proposes a similar process classification, albeit limited to manufacturing processes, in their coding scheme for parts and components. Järvenpää et al. (2018) use an ontology to model the capabilities of manufacturing equipment, with each piece of equipment having a number of assorted capabilities, interfaces, and variables used to describe that specific equipment. These resources and capabilities could be linked to a product model through a process taxonomy (Brunoe et al. 2018b).

Classification and coding systems were initially developed for manufactured components and parts. No equivalent system existed for manufacturing systems until the manufacturing structural classification coding (SCC) by ElMaraghy (2006). It was introduced to classify equipment in a manufacturing system and the layout of these. The SCC consists of two sub-codes—a layout classification code and an equipment classification code—with the equipment classification code itself capable of classifying three types of equipment; machines, transporters, and buffers. While the first few digits of the equipment classification code vary depending on the equipment type, the remaining digits, describing control, programmability, and operation characteristics, are the same for all types of equipment. The layout classification code describes the layout of the system, how it is controlled, programmed, and operated. SCC is a chain code, with the value of each digit depending on the complexity of the corresponding entities; the higher the value, the higher the complexity. Later, a classification coding scheme for assembly systems was developed by ElMaraghy et al. (2010), extending the original SCC to include assembly-specific features and equipment. Both these classification codes are useful for comparing manufacturing systems and identifying commonality, as well as determining their complexity (Samy and ElMaraghy 2012).

Method

To structure development of the production system classification code (PSCC), Hevner et al.'s (2004) information systems research framework was adopted. With the framework's focus on development and justification of new artefacts—in this case, the sub-codes, digits, and their interpretations—it lends itself well to the development of a classification coding scheme. Each digit must have an individual justification for existing in the coding scheme, they should address a specific need, be applied in an appropriate environment, and added to the growing knowledge base. The iterative nature of the method and its internal design cycle were key to selection of the method and the design of the resulting coding scheme (Hevner 2007). New digits, values, and interpretations were suggested during each design cycle, and their justification for inclusion was evaluated based on the need and relevance of the knowledge they added to the coding scheme. Several internal design cycles were carried out, followed by an application of the coding scheme to a number manufacturing systems. This resulted in additional design cycles and an evaluation with an industrial partner.

In contrast to the aforementioned manufacturing and assembly system classification and coding schemes (ElMaraghy 2006; Samy and ElMaraghy 2012), PSCC does not attempt to define nor calculate the complexity of systems, but does capture both physical (tangible) and logical (intangible) characteristics of manufacturing systems. They capture *why* and *what* a system is, *what* it does and *how* it does it. Certain digits in the coding scheme are inspired by and have been adopted from existing coding schemes, i.e. they come from the knowledge base on manufacturing system and product coding.

Classification Coding Scheme

An overview of the PSCC is shown on Figure 3.5. It consists of four sub-codes (bottom right), each consisting of four to ten digits. These sub-codes describe and capture different aspects of the system-of-interest at various levels of abstraction. Two sub-codes (system design driver classification code (DCC) and layout classification code (LCC)) are on a system level, and thus consider the manufacturing system as a whole. The other two sub-codes (process classification code (PCC) and enabler classification code (ECC)) are on a cell/station level, and thus relate to individual elements of the manufacturing system. DCC and PCC capture logical (intangible) characteristics of the system, while LCC and

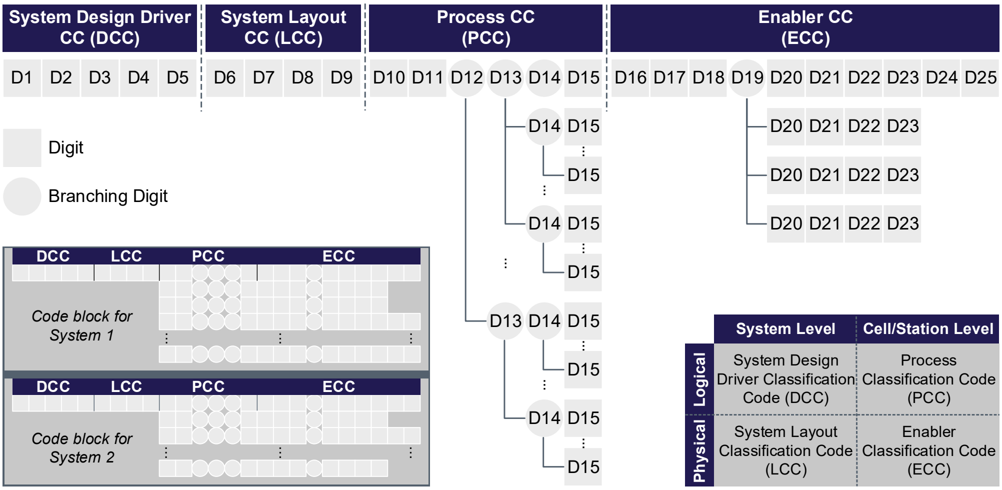

Figure 3.5: Top: the structure of the production system classification code (PSCC). Bottom left: manufacturing systems described through blocks of code consisting of one DCC, one LCC and several PCC and ECC sub-codes. Bottom right: overview of the PSCC's four sub-codes.

ECC capture physical (tangible) characteristics. Physical characteristics are those that can be observed and collected directly from the system during observation, while logical characteristics require a deeper understanding of the system. DCC (digits D1–D5) captures the rationale, reasoning, and drivers behind the design choices of a system, while the LCC (digits D6–D9) describes the layout of the system; PCC (D10–D15) captures all processes performed by the system, and ECC (D16–D25) describes the enablers carrying out the processes. In this study, *enabler* refers to the physical manufacturing equipment enabling production processes and the logical tools enabling planning and control of manufacturing systems. The PSCC deals with the fundamental building blocks of manufacturing systems, the code strings being similar to biological DNA identifiers. As such, it can be applied to any kind of manufacturing system, regardless of size, manufacturing paradigm, physical structure, or configuration. Tables 3.1 and 3.2 elaborate on the 25 digits of the PSCC, providing a brief description of the characteristic captured by each.

System design drivers captured in the DCC are the main reasons for a particular system's design, e.g. product size, which drives the width of a conveyor, or production volume making manual processes infeasible. These are typically documented in the system requirements or remain undocumented as tacit knowledge to system designers and experts. This type of knowledge provides insight into why two seemingly similar systems have different physical instantiations. Most of the digits in the DCC require customisation to the specific company. The listed drivers are examples of common or generic drivers for system design.

Capturing the layout of the manufacturing system, the LCC captures physical characteristics unrelated to the operation of the system, but is more concerned with its location, shape, automation level, and material flow. Location plays a part in determining an appropriate level of automation, depending on the specific country it is located in, and

Table 3.1: Digits and description for the DCC, SCC and PCC sub-codes in the PSCC (Sorensen et al. 2019b).

#	DCC	Description
1	Primary driver	Main reason for a specific system design.
2	Product size	Relative size of the manufactured product.
3	Production volume	Relative annual production volume.
4	Variety	Degree of variety of the manufactured products.
5	Paradigm	How the system accommodates change.
#	SCC	Description
6	Location	Physical, geographical location.
7	Shape	Physical shape of the system.
8	Automation	Overall level of automation.
9	Flow direction	Direction of material flow.
#	PCC	Description
10	Core	Core process are used on all manufactured variants.
11	Position	Position in sequence of processes.
12	Category	Process category.
13	Family	Decomposition of category.
14	Class	Decomposition of family.
15	Subclass	Decomposition of class.

with a sufficiently detailed location parameter, it may directly influence design through floorspace or features that must be considered. Shape and flow is useful in describing the way material flows, and can be combined with the position digits (D10 and D16 in PCC and ECC respectively) to link layout, processes, and enablers, also capturing cases where two processes are carried out by the same enabler at different points in the overall process.

In the PCC, the processes carried out by the system are captured and classified according to a consolidated process classification scheme (Sorensen et al. 2018b), but currently leaving out the control and planning processes. It also captures the position of each process in the material flow, and notes whether a process is used for all variants manufactured by the system or only specific variants. All of this can be used to better understand the function of a manufacturing system, and how the product is transformed through the system, with the position digit being useful in potentially generating process flow diagrams.

The ECC consist of five common digits (digits D16–D20), with digit D19 creating four branches of the sub-code; one for each type of enabler (machine, handling, buffer, or fixture). For each enabler, a position, structure, sourcing, category, and type is needed to describe the enabler on a high level, tying it to a specific location on a production layout (via the position digit D16), and linking it to a specific process. The three to five remaining digits describe the specific features of the enabler, so differences and similarities in their physical instantiations can be captured and analysed.

Table 3.2: Digits and description for the ECC sub-code in the PSCC (Sorensen et al. 2019b).

#	ECC	Description
16	Position	Position in sequence of processes.
17	Structure	Degree to which the enabler accommodates change.
18	Sourcing	In-house or contracted design of enabler.
19	Category	Enabler category.
20	Type	Specifies enabler type based on category.
#	Machine ECC	Description
21	Spindles	Number of rotary axes moving parts/tools.
22	Work heads	Number of work heads carrying out operations.
23	Axes of Motion	Number of axes of motion enabler can move along.
24	Tools	Degree to which tools can be changed.
25	Fixture	Degree to which fixture can be changed.
#	Handling ECC	Description
21	Path	Degree to which path of enabler can be changed.
22	Power	Whether the enabler requires power to function.
23	Part Types	Capability to handle one or more part types.
#	Buffer ECC	Description
21	Access	Order in which parts are accessed by enablers using buffer.
22	Location	Relative location to enabler using buffer.
23	Part Types	Number of different parts stored by enabler.
#	Fixture ECC	Description
21	Key Contact Points	Number of key contact points between fixture and part.
22	Fixing method	How a part is fixed/held by fixture.
23	Part Types	Capability to handle one or more part types.

Case Study & Applications

To illustrate potential applications of the PSCC, a case study was conducted at a large Danish manufacturer of discrete products. Nine manufacturing systems were selected, manufacturing products of the same type, but with various sizes and features. One code-block was created for each manufacturing system, consisting of one DCC and LCC as well as 12–34 PCC and ECC. This resulted in a total of 190 lines of the PSCC in an spreadsheet made for the case study. Afterwards, the populated codes were visualised, analysed, and simple comparisons were made on the nine systems based on a few select digits.

A visualisation of an interactive dashboard in PowerBI is shown on Figure 3.6 to summarise the results of the case study. (A) shows a count of process subclasses across the nine systems (the bars) and how large a portion of the systems the process appears in (prevalence, yellow line). (C) shows the split of manufacturing, material handling, and test & inspection processes across the systems, while (D) lists enablers by type, how often they are used, for what, and in which systems. (B) is a data slicer for filtering visualisations. The visualisation on Figure 3.6 uses only five code digits (D2: product size, D3: production volume, D12: process category, D15: process subclass, D20: enabler type) and a system

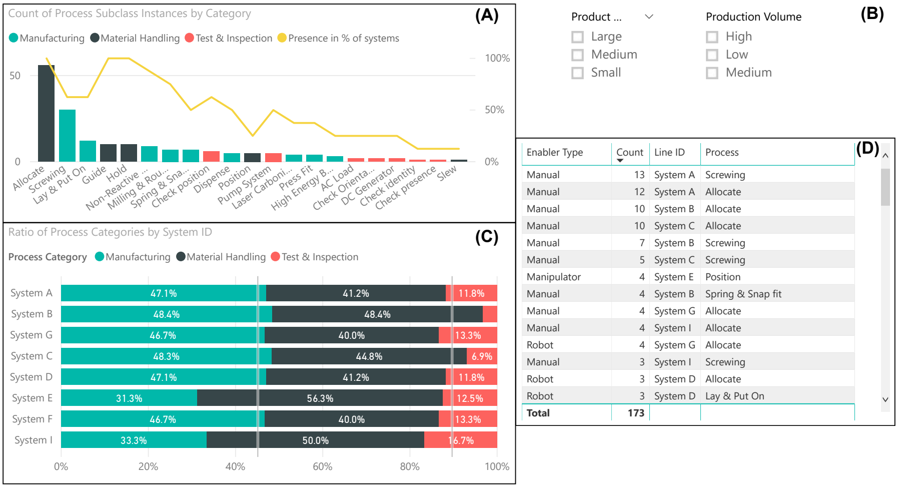

Figure 3.6: Example interactive dashboard created from the populated code of nine manufacturing systems (Sorensen et al. 2019b).

identifier. Based on these five digits alone, a multitude of analysis and visualisations of the scoped manufacturing systems can be made, with an increasing level of detail and additional analysis as more digits are considered. For instance, the allocate process (creation of a partial quantity and movement of said quantity to a specific location) occurs over 50 times and across all nine systems, while the screwing process occurs 30 times but only in 55% of the systems, with 13 of these instances occurring in a single system.

Using the code presented above, manufacturing systems can be compared to identify commonality. It can help make the existing manufacturing capabilities and structure clear, so solutions can be reused for new purposes. An algorithm can be applied to recommended specific platform candidates based on the company's requirements and the commonality highlighted by the code. Recommendations based on the code could be further strengthened by adding supplementary information on the manufacturing systems, such as their cost and performance. This could also further enable a multitude of comparisons and analysis. Simple and general comparisons between manufacturing systems can also be carried out, e.g. based on D1–D9, providing a simple measure of similarity. This measure, along with the recommendations for platform candidates, can be expanded with weighted factors and additional digits, allowing manufacturers to fine-tune the decision support tool according to their purposes and experiences. Such measures can also be used to form manufacturing system families, providing benefits similar to product families, for instance by developing a solution for one system in a manufacturing system family and using it for other systems within the same family.

With its modular nature, the PSCC can also be used to capture and document the arrangement and connections of enablers, thus forming configurations (Hu et al. 2011) that can be saved and used for future reference. This can be beneficial both for design of new systems and reconfiguration of existing systems, as a database can be searched for previous or existing similar configurations, making use of any experience with these configurations. It could also be used, alongside a modelling framework such as the one suggested by Brunoe et al. (2018b), for determining the manufacturability of new products, and potentially suggesting changes or reconfigurations to the manufacturing system to improve manufacturability.

Conclusions

The presented production systems classification code is intended to facilitate comparison of manufacturing systems within a manufacturing company, by standardising the manner in which these manufacturing systems are described, and outlining the data needed for this comparison. It captures both physical and logical system characteristics on a system and cell/station level through a hybrid-code consisting of up to 25 digits grouped into four sub-codes, inspired by and incorporating digits from existing classification coding schemes. The PSCC acts as a decision support tool, customisable and applicable to manufacturing systems regardless of the size of the company. Even through analysis of relatively few systems and a partly populated code, the PSCC can provide value as shown during the case study, and with increased focus on big data and supplementary information such as performance and cost, the PSCC can be a powerful tool for a manufacturing company. There are several potential applications outside the identification of platform candidates presented in this study, and the PSCC can be customised and expanded further to include more or different characteristics of manufacturing systems, including applications in the food, chemicals, and pharmaceuticals industry.

3.4.2 Implications

With development of the the production system classification code (PSCC) presented above, groundwork has been laid for standardising the description of manufacturing systems. Their characteristics can be captured in a standardised format and subjected to numerous analysis providing value to various stakeholders within the company. It fills a gap within the case company itself, describing the structure and functions of their existing manufacturing systems, which has historically been missing. This also enables manufacturers to link their standardised descriptions of manufacturing systems with their respective performance and cost data, providing valuable knowledge of their manufacturing systems across departments and factories. For a manufacturer such as the case company, a manufacturing system platform represents a consolidation of their existing facilities and the definitive place to start when a new manufacturing development task is to be initiated. In summation, the outcome of the study is:

1. A classification coding scheme describing key aspects of manufacturing systems in a standardised format.

2. Facilitation of an objective comparison of manufacturing systems across departments in a company.

3. Groundwork enabling a variety of analysis approaches to determining why a system is performing well or poorly.

4. A new classification coding scheme, numerous new digits, and experiences added to the knowledge base on classification coding and manufacturing system platform development.

3.5 Brownfield Platform Development

Paper E is entitled 'Brownfield Development of Platforms for Changeable Manufacturing', written for and presented at the 52nd CIRP Conference on Manufacturing Systems (CMS2019) in 2019. It relates to and addresses RQ3 by answering the follow sub-question:

RQ3.2 What steps should a manufacturer take to develop platforms of standardised assets based on existing manufacturing systems and environments?

Through an evolving case study spanning multiple years, this paper presents seven recommended steps manufacturers can take to develop manufacturing system platforms based on an existing production landscape. While greenfield approaches to development of platforms and changeable manufacturing exist, there are few explicit brownfield approaches manufacturers can use. The brownfield approach presented in the following is intended to lower the barrier of entry for manufacturers looking to achieve changeable manufacturing.

3.5.1 Extended Abstract

Introduction & Background

Manufacturers looking to achieve changeable manufacturing in order to manage an increasing variety will often have existing product portfolios, manufacturing systems, and potentially platforms scattered throughout the company. This existing production landscape represents a large investment by the company, and is not something that can simply be scrapped for all new systems. Rather than designing new changeable systems and products from scratch, considering and reusing elements of the existing production landscape could lower the barrier of entry for manufacturers looking to adopt changeable manufacturing.

Through greenfield approaches, systems are developed outside the constraints of prior work, existing systems, or ongoing projects. Platform approaches typically do consider existing systems, but focus on development of new platforms, modules, and solutions (Joergensen et al. 2014; Sorensen et al. 2018a). Similarly, design of RMS and CMS usually employ greenfield approaches while still taking a manufacturer's requirements for changeability into account (Andersen et al. 2017; 2018). Performing an internal evaluation of existing systems and their potential for change is, however, always recommended prior to or during design of CMS (ElMaraghy 2005).

In contrast, through brownfield approaches systems are developed within the constraints of prior work, in this case, the existing production landscape. Employing such an approach, platforms can be developed from existing solutions, essentially elevating them and preparing them for reuse rather than developing all new solutions and platforms. To do so requires that the most likely platform candidates are identified, and as many of their characteristics as possible are standardised and documented, determining which characteristics may change, and which may not. Thus, designers and developers can free up development time by solving frequent processes or functions with robust modules and equipment already present within the platform, allowing them to spend more time on less frequent tasks, new technologies, and efficiency improvements.

Manufacturing system platforms have an inherent connection with reconfigurable and changeable manufacturing, and while certain methods for RMS design do mention platforms, their role in the design of changeable manufacturing is rarely stated explicitly. Based on the generic RMS design method by Andersen et al. (2017), platforms are essentially applicable by and beneficial to designers during the later stages of the basic design phase (phase 3) and throughout the advanced design phase (phase 4). The prior planning (phase 1) and task clarification (phase 2) phases set the scope and requirements for the design phase, while basic design (phase 3) use these to define system elements, interfaces, and modules for the system being designed. In advanced design (phase 4), the concept from basic design is transformed into a detailed design representing the physical design and construction of the system. Following the design phases, the system is implemented and subsequently operated and reconfigured as needed. Having a platform consisting of standardised solutions with well-defined functions and interfaces could significantly ease the basic and advanced design phases.

Method

The stage-gate approach presented in the following was developed as a result of an evolving case study, consisting of four consecutive platform projects, with an industrial partner. Focus and the group of participants varied from project to project, with project one focusing on the nature, development, and utilisation of platforms, project two on the identification and documentation of platforms, project three on modelling and increasing the level of details, while project four is ongoing and focused on creating a framework and tools supporting platform development. Additional details on the evolving case study and the four constituent projects are available in (Sorensen et al. 2018c).

A Stage-Gate Approach

The suggested brownfield platform development approach is a systematic stage-gate approach consisting of the seven stages listed below. It is inspired by systematic design (Pahl et al. 2007), going through the same four design phases, from planning and clarification (stage 1 and 2) to conceptual (stage 3), embodiment (4 and 5), and detail design (stage 6). Stage 7, dealing with governance and maintenance of platforms, is outside these four basic phases of design, but is necessary for the continued life and function of platforms. The seven stages are operational guidelines, and should generally be carried out in the listed order, although there is some need for flexibility in the approach. It may also be necessary to complete multiple iterations of the approach for a satisfactory result.

1. Assess changeability requirements
2. Identify platform candidates
3. Define essential functions
4. Establish principal structure
5. Define physical enablers
6. Document platform
7. Govern and maintain platforms

Stages 1 and 2 are performed once per iteration, while stages 3–6 are performed for each identified platform candidate, and stage 7 continues throughout the entire life cycle of the platforms. After each stage, the continued development of the relevant subject (i.e. platform candidate) must be justified. If no justification for continued development can be found, the remaining stages should be skipped and the decision regarding the platform candidate is noted for future reference. Stages 1 and 7 are considered more related to an overarching platform framework than actual platform development. Thus, this study focuses on stages 2–6, covering stages 1 and 7 only briefly.

A prerequisite for any development related to changeability, including platform development, is the assessment of a company's changeability requirement (stage 1). This sets the scope for all subsequent stages of platform development by screening a company's need for changeability, determining change drivers, recommending type and degree of changeability, and estimating potential benefits. One way to perform this assessment is through the participatory method proposed by Andersen et al. (2018) considering existing products, manufacturing systems, and facilities, subsequently recommending a path to changeability to individual companies.

Identification of platform candidates (stage 2) represents the identification of the essential functions, processes, equipment, or knowledge with the potential to become platforms. Initially, existing manufacturing systems should be grouped and classified in order to create a map of a company's production landscape. This should be done in a standardised way facilitating comparison and identification of commonality across the systems. Group technology and classification coding is one example of how this can be achieved, although few coding schemes exist for manufacturing systems (ElMaraghy 2006; ElMaraghy et al. 2010). Decision algorithms and criteria can then be applied to the classified manufacturing systems, returning a recommendation of which processes or equipment should be investigated further based on the company's specific changeability requirements. Each of the identified platforms should be further developed, either in individual projects or as part of projects intended to make use of the specific platform.

As essential functions are defined (stage 3), the function of a particular platform candidate becomes clear. They are the functions a candidate must carry out for it to fulfil its purpose. Standardising these functions means standardising the functional capability of a system. Initially, top-level functions must be identified and subsequently broken down into sub-functions. A function sequence should be used to represent each platform candidate, thus describing exactly what functions the platform candidate is supposed to

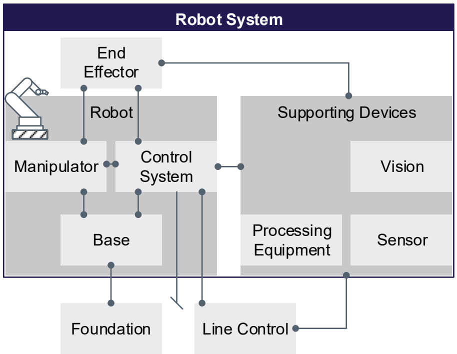

Figure 3.7: A robot, an end effector, and optional supporting devices form the principal structure of a robot system. The foundation and line control elements are outside the robot system. Adapted from (Sorensen et al. 2019a).

perform. Should a candidate be capable of carrying out multiple top-level functions, such as a robot capable of performing both material handling and assembly, a function sequence should be created for each.

Establishing the principal structure (stage 4) of a platform candidate, refers to the creation of a structure describing the interactions between elements of a platform candidate and its environment; essentially a simple view of a platform candidate's architecture, illustrated on Figure 3.7. While interactions and corresponding interfaces are not fully specified at this stage, they should be identified and assigned a corresponding type, i.e. spatial, energy, information, or material (Pimmler and Eppinger 1994). A close examination of existing physical instantiations of the platform candidate can help establish the principal structure. On Figure 3.7, the principal structure for a robot system is shown, with the robot itself consisting of a manipulator, control system, and a base. The robot system further consists of an end effector connected to the robot's manipulator, and a number of supporting devices.

Defining the physical enablers (stage 5) for a platform candidate is essentially the act of selecting the future physical instantiations of a candidate. It means specifying a few well-defined solutions spanning a range of applications, rather than creating or selecting a single solution to deal with all potential applications. A variety of physical enablers are available for each element shown on Figure 3.7. To distinguish enablers and select an appropriate one for a given application, a set of requirements must be defined for all enablers, forming a basis for comparison and selection. These could be e.g. accuracy, reach, and load for the robot on Figure 3.7. Such requirements can then be used to form areas of application, under which each existing enabler can be grouped. A decision can then be made, based on the performance and characteristics of enablers, on which enablers should continue to exist and be used within a given area of application. All enablers, whose continued existence is justified, have their principal structure detailed into a physical structure, including further specification of elements, interfaces, and interactions.

Platform documentation (stage 6) is a crucial yet oft-overlooked part of platforms. They are necessary for platforms to be widely adopted within a company. The documentation for a platform should include all requirements, models, decisions, reasoning, etc. from the previous stages, and make them accessible to relevant stakeholders. ISO 42010, providing a standard for architecture descriptions, presents a way to accomplish this and customise the documentation to specific stakeholder concerns (ISO et al. 2011). Some recommended sections of the platform documentation are: (a) vocabulary, (b) scope, (c) requirements, (d) essential functions, (e) principal structure, (f) physical enablers and interfaces, (g) detailed enablers, and (h) further reading.

Platform governance and maintenance (stage 7) is the infrastructure in a company facilitating the continued use of platforms. Use of platforms in a company requires commitment from all levels of the company; both the goal of using them as well as their existence must be clear at all levels of the organisation. Responsibilities and procedures to be followed should be set and become an integral part of new development projects. Information on the platforms themselves must be easily available to all who need the information. Platforms must also regularly be maintained, ensuring that the design, decisions, and reasoning from previous iterations still hold, redesigning or scrapping the platform if needed. Emerging technologies or changing requirements must be considered in this process. Stage 7 does not truly end as long as a company is committed to using platforms.

Conclusions

The stage-gate approach for brownfield platform development presented above outlines seven stages to the platform development process. These stages take companies through an assessment of changeability requirements, through identification of platform candidates and development of these, to the documentation and governance of the final platform. It is an alternative to the more prevalent greenfield approaches in the field of platform development, as it bases development on a company's existing production landscape, potentially speeding up the design and implementation of changeable manufacturing. Can no suitable brownfield solution be found, a greenfield approach can be employed to develop a new solution.

3.5.2 Implications

In the study presented above, an attempt at transitioning from greenfield to brownfield development of platforms have been made. It describes a number of generic recommendations for companies to follow on their path to changeable manufacturing through platforms, building on the experiences and challenges faced during the evolving case study (Sorensen et al. 2018c). The seven stages are operational guidelines in a recommended order of execution, but there is room for flexibility. Certain steps can be skipped or saved for later, if the need arises. As with any generic approach, some tailoring to the individual company is to be expected, since differences in circumstances, environment, and organisational structure etc. will play a part in the tools and approaches a company should utilise. The outcome of the paper can be summarised as follows:

1. A stage-gate approach to brownfield platform development.

2. Potentially a lowered barrier of entry for designing and implementing changeable manufacturing through platforms.

3. Recommendations for how to approach certain aspects of platform utilisation related to documentation, governance, and maintenance.

3.6 Platform Candidate Identification

Paper F is entitled 'Identification of Platform Candidates through Production System Classification Coding', written for and to be presented at the 2019 conference on Advances in Production Management Systems (APMS2019) in September 2019. It relates to and addresses RQ2 by answering the following sub-question:

RQ2.4 How can a production system classification coding scheme be used to identify candidates for a manufacturing system platform?

This case study applies the classification coding scheme presented by Sorensen et al. (2019b) in an industrial context at the case company. A classification code is created for a number of manufacturing systems, followed by a comparison and analysis of the resulting code in order to identify potential platform candidates, based on a set of simple drivers and criteria.

3.6.1 Extended Abstract

Introduction

A key aspect of platforms is standardisation of assets. Standardising tangible and intangible assets of products and manufacturing systems bring platforms their utility in managing variety. One of the first steps to successful development of manufacturing system platforms is the identification of which assets should or should not be included in a platform (Sorensen et al. 2019a). Previously, one of the primary sources of platform candidates is the tacit knowledge of system experts, who have built up an inherent knowledge on the system of interest (Sorensen et al. 2018c). Decisions based on tacit and inherent knowledge can be difficult to communicate and justify to system stakeholders. A more objective approach to identification of platform candidates can help back up the decisions of system experts.

Commonality is frequently the starting point for developing modules and platforms (Fixson 2007; Thevenot and Simpson 2006), but whether similar shapes (Cardone et al. 2003) or shared assets (Kashkoush and ElMaraghy 2016), commonality can be difficult to find across large, complex systems. Some progress has been made towards identifying commonality through classification of processes (Sorensen et al. 2018b) along with generic and tailored ontologies for integrated product and manufacturing modelling (Brunoe et al. 2018b). This study builds on top of the classification approach to identifying commonality.

System Level									Cell/Station Level															
Design Driver					Layout				Processes						Enablers									
D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D13	D14	D15	D16	D17	D18	D19	D20	D21	D22	D23	D24	D25
Primary driver	Product size	Production Volume	Degree of variety	Manufacturing Paradigm	Production Location	System Shape	Level of Automation	Flow Direction	Core	Position	Category	Family	Class	Sub-class	Position	Structure	Sourcing	Category	Type	First characteristic	Second characteristic	Third characteristic	Fourth characteristic	Fifth characteristic

Figure 3.8: Overview of the production system classification coding (PSCC) scheme. Adapted from (Sorensen et al. 2019c).

Method

A production system classification code (PSCC) (Sorensen et al. 2019b) is applied to create a standardised digital representation of the scoped manufacturing systems. PSCC is a hybrid-code scheme including system design driving requirements, layout, processes and enablers, based on Sorensen et al.'s (2018b) process classification and ElMaraghy's (2006) manufacturing system complexity coding and classification scheme. It consists of the 25 digits shown on Figure 3.8 and is used to create a digital map of a company's production landscape by classifying their existing manufacturing systems. Digits D1–D9 are filled out once per manufacturing system, while digits D10–D25 are filled out once per process or enabler. As the code is populated, each digit is given an alphanumeric value with a unique meaning for the specific manufacturing system. Manufacturing systems are thus represented as grouped strings of alphanumeric values.

The populated code for the scoped manufacturing systems will be analysed based on three drivers for platform candidate identification: (1) frequency, number of instances of a particular process or enabler; (2) prevalence, ratio between number of systems a process or enabler appears in, and the total number of scoped systems; (3) enabler/process ratio, number of different enablers per process and vice versa. These drivers are examples of reasons why a process or enabler should be a platform candidate, and can be determined by the information captured by the PSCC.

Results

To demonstrate the PSCC and how it can be used to identify platform candidates, a case study was carried out with a large Danish manufacturer of discrete products. Nine distinct manufacturing systems were covered, spanning two departments. Some systems manufacture components and sub-assemblies for internal use, and others manufacture complete OEM product. The characteristics of the systems (e.g. automation level and cycle time) vary greatly, and so do the characteristics of the products (e.g. product size and features), despite them sharing the same primary function. All nine systems were surveyed as part of previous projects and case studies, the data from which was used to classify the systems according to the PSCC.

Table 3.3: Excerpt of the process subclasses ranked by drivers, sorted by total rank (Sorensen et al. 2019c)

Process	Frequency	Frequency rank	Prevalence	Prevalence rank	Enabler ratio	Enabler ratio rank	Total score	Total rank
Allocate	56	1	1.000	1	0.089	2	4	1
Screwing	30	2	0.556	7	0.067	1	10	2
Guide	10	4	1.00	1	0.300	7	12	3
Hold	10	4	1.00	1	0.300	7	12	3
Milling & Routing	7	7	0.778	4	0.286	6	17	5
…								

Table 3.4: Excerpt of the enabler types ranked by drivers, sorted by total rank (Sorensen et al. 2019c)

Process	Frequency	Frequency rank	Prevalence	Prevalence rank	Process ratio	Process ratio rank	Enabler ratio	Enabler ratio rank	Total score	Total rank
Manuel	89	1	1.000	1	0.067	1	0.067	1	4	1
Conveyor	11	3	1.000	1	0.182	5	0.273	4	13	2
Pallet	10	4	1.000	1	0.100	2	0.300	7	14	3
Robot	23	2	0.667	6	0.174	4	0.261	3	15	4
Mill	7	6	0.778	5	0.143	3	0.286	5	19	5
Tester	9	5	1.000	1	0.333	9	0.333	8	23	6
…										

Tables 3.3 and 3.4 shows the top five process subclasses and top six enabler types ranked according to the previously mentioned platform candidate identification drivers. 21 different process subclasses and 12 different enabler types were covered in the study.

The top ranked process in Table 3.3, allocate, is a material handling process defined as the creation of a defined partial quantity of parts and the movement of the same quantity to a target location (Sorensen et al. 2018b). With an apparent low variety of enablers and high prevalence and frequency, a platform for the allocate process likely already exists, or there is an agreed upon way to carry out the process. If the former is the case, the platform should be documented, and in the case of the latter, a platform should be developed. In either case, the process is a clear platform candidate.

The second highest ranked process, screwing, is a manufacturing process. While it ranks low in terms of prevalence (rank 7), it has a low variety and high frequency. Once again, the classification and analysis indicates that a standardised way to carry out the process exists, and that it should be developed and formally described as a platform.

As for enablers, manual is ranked first by quite a margin. The manual enabler represents an operator in the system being the impetus behind a process. Alongside the conveyor, pallet and tester, it appears in all scoped systems. Due to their high prevalence (1.000), all four show potential for platform development, while both the pallet, and tester also show room for improved standardisation with a relatively high enabler ratio for their prevalence (0.300 and 0.333 respectively). Lastly, the robot enabler is a clear candidate, ranking second in frequency and performing four different processes using six distinct enablers.

Conclusions

Nine previously surveyed manufacturing systems were classified according to a production system classification coding scheme, with the intention of comparing the manufacturing systems to identify commonality and thus potential platform candidates. The classification coding scheme captures key characteristics of the manufacturing systems, including its driving requirements, structure, and functions. Based on this, potential platform candidates in the form of processes and enablers can be identified and ranked according to a number of drivers indicating their suitability for platform development. Both the PSCC and ensuing comparison of the populated code act as decision support tools for manufacturers looking towards brownfield platform development.

3.6.2 Implications

The study presented above takes the next step in supporting platform development by demonstrating how a decision support tool can be used to identify new platform candidates. Implementation of the classification coding scheme within a company remains a challenge, and there is a need for a concrete, dedicated application facilitating creation of the code in an intuitive manner.

Several changes can be made to strengthen the platform identification approach based on the PSCC. An obvious way to do so, is to include additional drivers and digits for ranking the various processes and enablers, for instance using digit D10 to determine how many instances of a process are considered "core" to the manufacturer. Performance and cost data can also be included to help separate "good" and "bad" solutions, i.e. solutions with good performance and low cost versus bad performance and high costs. This could also potentially let manufacturers determine a correlation between characteristics of a system or enabler and its cost and performance. Summing up, the contributions made through the study are listed below:

1. Applies Sorensen et al.'s (2019b) classification coding scheme to show its feasibility.
2. Highlights the difficulty inherent to implementing a classification coding scheme in an industrial context.
3. Demonstrates how potential platform candidates can be identified using a classification coding scheme.

4

Concluding Remarks

As stated in Chapter 2 and repeated below, the objective for this research was to create knowledge on manufacturing system platforms. Specifically on their development and documentation by creating and applying both new and existing methods and tools.

> **Research Objective**
> Create and apply methods and tools for identifying, developing, and documenting manufacturing system platforms through commonality and standardisation of assets

To achieve this, a design science research framework was employed to create new artefacts based on existing, related knowledge bases, and to apply these artefacts in appropriate environments—in this case, an industrial context within a case company. Thus, knowledge and experience on manufacturing system platforms is fed back to the corresponding knowledge base, effectively expanding it as these contributions are documented and disseminated. The following sections summarise the contributions of this Ph.D. project and proposes avenues for future research related to manufacturing system platform development.

4.1 Research Contributions & Implications

In Section 2.3, three main research questions were listed to frame the research objective repeated above. This research objective and the three research questions have been addressed based on the contributions documented in Papers A to F.

RQ1: How can manufacturing system platforms be developed and documented using well-known concepts from software systems engineering and architecture, and which challenges arise during this process? Through the Four Loops of Concern, presented in Paper A and summarised in Section 3.1, key concepts from software architecture and systems engineering was introduced to the manufacturing system platform development process. Four Loops of Concern outlines the platform development process from the initial gathering of data on manufacturing systems, to the identification of potential platforms, and subsequent development and documentation of said platforms. In particular, the identification and documentation phases are not widely covered in previous research. The Four Loops of Concern is an iterative, generic approach that can be applied by manufacturing companies looking to develop manufacturing system platforms, regardless of their size and maturity. It emphasises function and technology as distinct assets to be standardised, promoting a search for alternative solutions as function and technology are combined to address specific stakeholder needs. As iterations of the approach were completed, several issues were brought to light, commonly related to the complicatedness and abstractedness of terms and concepts being introduced, as well as the subjective nature of the available data. These challenges heavily influenced the continued direction of this research.

RQ2: How can commonality in processes across manufacturing systems be classified and used to identify candidates for manufacturing system platforms? Commonality in manufacturing can be many things, but the outset for this research was the common functions shared across manufacturing systems, i.e. the processes. To base manufacturing system platform development on process commonality, a classification of these processes was necessary. Thus, a consolidated classification scheme was presented in Paper B and summarised in Section 3.2. The classification scheme is based on a review of several existing classification schemes, and includes both manufacturing, material handling, control, planning, test, and inspection processes—unlike the reviewed classifications, which include only one or two of these categories. This makes the consolidated process classification scheme useful in classifying a large variety of processes in a coherent manner, using an easily navigable structure with room for addition of more processes as needed. It is also useful for simply structuring, describing, and explaining characteristics of processes occurring through production systems.

While function and process commonality is an important factor in manufacturing system platform development, it is necessary to know more about the manufacturing systems. How the systems differ, and why these differences exist, are key to deciding where to focus development. To capture these characteristics and make them clear to system stakeholders, experts, and designers, a production system classification code was presented in Paper D, summarised in Section 3.4. It is based on existing classification coding schemes and the consolidated process classification scheme, and captures both explicit and tacit characteristics of manufacturing systems. Thus, manufacturing systems can be described as strings of alphanumeric digits, essentially representing the DNA of the manufacturing system. The code itself is expandable and customisable, making it tailorable to individual companies in various industries, regardless of their size and maturity.

Through research and work on manufacturing system platforms, identification of potential platforms was found to be key. In Paper F, summarised in Section 3.6, the production system classification code was demonstrated as a means to identify platform candidates based on commonality across manufacturing systems. From an analysis of nine manufacturing systems encoded in accordance with the production system classification code, platform candidates were recommended on the basis of three generic platform drivers. This effectively strengthens the process of identifying potential platforms, making it more objective, and helps system experts defend their decisions on where to focus the platform development process.

RQ3: How can manufacturing system platforms be developed in a brownfield approach taking into account a manufacturer's existing production landscape and which challenges arise over time as platform development progresses? Throughout this Ph.D. project, and preceding projects on manufacturing system development, numerous challenges appeared and were addressed.

Most of these challenges were outlined in Paper C and summarised in Section 3.3, presented as en evolving case study conducted with the primary collaborator over the course of three years. Several of these challenges, particularly the ones that persisted through several of the projects, set the direction for much of the research in this Ph.D. project. The challenges, and recommendations on how to address them, can be useful to any manufacturer looking to develop manufacturing system platforms, providing an idea of how to prepare participants for platform projects, and highlighting the need for consistency and transparency in communication.

With Paper E, summarised in Section 3.5, a brownfield stage-gate approach to manufacturing system platform development was presented. Most previous approaches to platform development are greenfield approaches outside the constraints of prior work. The presented brownfield approach provides a set of generic, operational guidelines for how to conduct manufacturing system platform development while considering a company's existing manufacturing systems. A brownfield approach could potentially lower the barrier of entry for implementing manufacturing system platforms and changeable manufacturing, by providing manufacturers with an alternative to developing all-new solutions and systems, instead promoting redesign and reuse of existing equipment and systems.

Previous research has suggested the development of platforms based on commonality, and the application of concepts from other fields to the domain of manufacturing systems. The novelty of the research presented in this thesis lies in the introduction of tools to classify the processes and characteristics of manufacturing systems, using these to highlight commonality across manufacturing systems. Thereby, platform candidates can be identified based on existing systems, and platforms can be developed in a brownfield approach, providing an alternative to the prevalent greenfield development approaches.

While the findings presented in this thesis have primarily been applied at a large Danish manufacturer with numerous departments and manufacturing systems, they can be applied to individual departments or smaller manufacturers in a variety of circumstances as well. Both the process classification scheme and the classification code deal with fundamental aspects of manufacturing systems. Although they have been customised slightly to fit the case company for the purposes of implementation, this can be done to fit any manufacturer, assuming the recommendations for customisation and application are followed. The outlined challenges and recommendations from platform projects are generic enough, that they should be considered prior to any platform development project. Although the suggested approaches to platform development are likely not immediately applicable in all cases, the contents, tools, concepts, and steps can be useful to manufacturers looking to take up manufacturing system platform development.

Outside the direct benefits for manufacturers using platforms, the process of working with the tools and approaches presented in this thesis can greatly increase the understanding stakeholders and experts have of the manufacturing systems within the company. This could be especially advantageous for manufacturers with a system complexity level exceeding what system stakeholders and experts can, with relative ease, communicate and comprehend.

4.2 Future Research

While the overall research objective for this Ph.D. project has been achieved, there are still many areas and subjects related to manufacturing system platforms left to be explored. A few directions for future research are outlined below, with a focus on subjects directly related to the presented contributions.

Implementing a classification coding scheme such as the production system classification code is no easy task. Certain aspects of the coding scheme must be tailored to the specific manufacturer, requiring significant involvement from stakeholders. Besides customisation of digits, this also includes a selection of systems to be encoded using the scheme and the initial gathering of data. Gathering the data itself can prove a significant challenge if no infrastructure is set in place for this. While data can potentially be pulled from various databases (e.g. SAP), data will almost inevitably have to be gathered manually from system experts or observations of the systems themselves. To ease this process, a dedicated tool or application for implementing and using the production system classification code should be developed. The simple spreadsheet tool developed during application of the production system classification code will not be sufficient in the long run. A more versatile, user-friendly, and easily relatable tool is necessary to facilitate and motivate the encoding of manufacturing systems by system stakeholders and experts.

Coupled with the production system classification code, a decision algorithm or optimisation approach for platform candidate identification could be a significant benefit to manufacturers. Objective and trustworthy recommendations can back up system experts and their decisions in regards to continued development of and changes to manufacturing systems and platforms. Various customisable parameters or decision criteria in such an algorithm would let manufacturers define what they consider a platform candidate. Adding cost and performance data as supplementary data to the production system classification code and algorithm would only strengthen the recommendations.

Consistency and coherency has been a theme throughout the research presented in this thesis. It is a key aspect to working with platforms, and crucial for taking development of manufacturing system platforms to the next level. The needed consistency and coherency could be provided by a comprehensive manufacturing system platform framework. Such a framework should include a conceptual model for manufacturing system platforms, connecting all the necessary models, methods, concepts, and terms, e.g. the ones presented in this thesis. Thereby, it would effectively form a vocabulary for manufacturers and a collection of tools to use for manufacturing system platform development and utilisation. The framework and its contents should be generic but tailorable to individual manufacturers in order to account for differences in ambitions and circumstances, and should thus also include guidance on how to carry out this tailoring.

Index

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A

Production Platform Development through the Four Loops of Concern

Authors: D. G. H. Sorensen, J. Bossen, M. Bejlegaard, T. D. Brunoe and K. Nielsen

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Abstract: Managing product variety is still an issue in the industry and one that gets a lot of attention. Among several ways to address this issue is the development of platforms. Platforms, for instance, coupled with the use of reconfigurable manufacturing systems, can potentially enable manufacturers to deal with a more dynamic market, an increase in variation and decrease in product lifecycle. The development of these platforms and systems is often difficult to begin and even more so to finish. This paper presents a method for developing and codeveloping product and production system platforms, using concepts from the field of software architecture development. Development and implementation of the method were carried out through case studies in two Danish companies. The method is an iterative approach consisting of four loops with four steps each. It facilitates the utilisation of concepts and tools from software architecture development during the platform development process.

B

A Classification Scheme for Production System Processes

Authors: D. G. H. Sorensen, T. D. Brunoe and K. Nielsen

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Citation: D. G. H. Sorensen, T. D. Brunoe and K. Nielsen (2018b). 'A classification scheme for production system processes'. In: *Procedia CIRP* 72. 51st CIRP Conference on Manufacturing Systems, pp. 609–614. ISSN: 2212-8271. DOI: `10.1016/j.procir.2018.03.021`

Abstract: Manufacturing companies often have difficulties developing production platforms, partly due to the complexity of many production systems and difficulty determining which processes constitute a platform. Understanding production processes is an important step to identifying candidate processes for a production platform based on existing production systems. Reviewing a number of existing classifications and taxonomies, a consolidated classification scheme for processes in production of discrete products has been outlined. The classification scheme helps ensure consistency during mapping of existing production systems, and assists in providing an overview of when, where and how fundamental functions of a production system are realised.

C

Challenges in Production and Manufacturing Systems Platform Development for Changeable Manufacturing

Authors: D. G. H. Sorensen, T. D. Brunoe and K. Nielsen

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Abstract: Development of platforms for products has proven a successful way to manage and address several challenges related to increasing variety and accelerating product development cycles. Thus, it is natural to assume that platforms may facilitate similar benefits for manufacturing systems, as they are both technical systems. Production and manufacturing systems platform development is, however, still an area of research lacking maturity. Development of platforms in this field comes with a set of challenges not necessarily found in product platform development. Looking towards other fields of research or science may be necessary to address these challenges. This paper aims to study challenges related to production and manufacturing systems platform development and describe how these have been addressed. It does so through an evolving case study based on four projects with an industrial collaborator. This leads to setting the stage for future research on production platforms.

D

Classification Coding of Production Systems for Identification of Platform Candidates

Authors: D. G. H. Sorensen, H. A. ElMaraghy, T. D. Brunoe and K. Nielsen

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Abstract: Production platforms present an attractive solution to managing increasing product variety in production systems. Forming production systems platforms can potentially facilitate changeable manufacturing and co-development of products and production systems. One of the first steps in developing a production platform is the identification of the potential candidates. A scheme for classification coding of production systems is presented. Coded production systems can be compared across a manufacturer's departments in order to identify commonalities between systems, and thus identify candidates for platform development. The production system classification code consists of four sub-codes with four to ten digits each describing physical or logical characteristics on production system or cell levels. The four sub-codes are structured into blocks of classification code, which digitally represent and describe complete production systems. They facilitate the comparison and identification of similarity and commonality patterns using the code digits and values. A production system case study is used for illustration and is represented as a block of code following the developed coding scheme. The production systems classification code can be used as a decision support tool in the early phases of production systems platform development, and for capturing information on the rationale, structure, processes and enablers of flexible and changeable production systems.

E

Brownfield Development of Platforms for Changeable Manufacturing

Authors: D. G. H. Sorensen, T. D. Brunoe and K. Nielsen

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Citation: D. G. H. Sorensen, T. D. Brunoe and K. Nielsen (2019a). 'Brownfield Development of Platforms for Changeable Manufacturing'. In: *Procedia CIRP* 81. 52nd CIRP Conference on Manufacturing Systems (CMS), Ljubljana, Slovenia, June 12-14, 2019, pp. 986–991. ISSN: 2212-8271. DOI: `10.1016/j.procir.2019.03.239`

Abstract: Typically, development of changeability and reconfigurability in manufacturing are greenfield approaches. New platforms, products and manufacturing systems are developed with new features, capability or technology. While companies can achieve the desired level and type of changeability with greenfield approaches, development of new platforms and systems is a costly affair if existing systems and platforms in the company is not considered. This study outlines an approach for systematic brownfield platform development. Seven stages are listed, describing how candidates for inclusion in a platform are identified and subsequently developed based on existing manufacturing systems and production landscape.

F

Identification of Platform Candidates through Production System Classification Coding

Authors: D. G. H. Sorensen, H. A. ElMaraghy, T. D. Brunoe and K. Nielsen

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Abstract: Changeable and reconfigurable manufacturing appears as a natural response to a need for improved variety management. Such manufacturing systems are complicated to develop, and it can be advantageous to base or build these systems on product and production platforms. Development of platforms is, however, not a trivial task. Currently, identification and selection of candidates for inclusion in a platform is typically subjective relying on experts and tacit knowledge. The objectivity of this process can be strengthened by collecting data on existing production systems in a company and comparing these systems to each other. To do so, a coherent, consistent and preferably digital representation of multiple production systems is needed. In this research, a production system classification coding (PSCC) scheme is employed to classify and structure data for a number of existing production systems, spanning multiple departments and product families. Candidates for a production platform covering the included production systems are identified based on ranking certain platform drivers, processes and enablers.