Developing Modular Manufacturing System Architectures
The Foundation to Volume Benefits and Manufacturing System
Changeability and Responsiveness

Ph.D. Thesis

By

Steffen Nordahl Joergensen

Department of Mechanical and Manufacturing Engineering, Aalborg University
Fibigerstraede 16, DK-9220 Aalborg East, Denmark
e-mail: snj@m-tech.aau.dk

Special Report No.: 94
ISBN: 87-91464-52-8

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**Title:** Developing Modular Manufacturing System Architectures - The Foundation to Volume Benefits and Manufacturing System Changeability and Responsiveness

**Name of PhD student:**
- Steffen Nordahl Jørgensen

**Name and title of supervisor:**
- Associated Professor Kaj A. Jørgensen
- Professor Ole Madsen

**List of papers:**
- **Paper 2:** Joergensen, S., Nielsen, K., Jørgensen, K., A.; 2011 “DESIGN REQUIREMENTS FOR DESIGNING RESPONSIVE MODULAR MANUFACTURING SYSTEMS ”21st International Conference on Production Research; July 31 - August 4, 2011 in Stuttgart, Germany

This thesis has been submitted for assessment in partial fulfillment of the PhD 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. The thesis is not in its present form acceptable for open publication but only in limited and closed circulation as copyright may not be ensured.
Preface

This thesis has been submitted to the Faculty of Engineering, Science and Medicine at Aalborg University in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Mechanical Engineering. This thesis represents a culmination of work and learning that has taken place at the department of Mechanical and Manufacturing Engineering, Aalborg University during the period from January 2010 to April 2013. The thesis is conducted on the basis of scientific papers and under supervision of Associated Professor Kaj A. Jørgensen and Professor Ole Madsen.

This thesis contains studies within Modular Manufacturing Systems, Manufacturing Development, and Mass Customization. The purpose has been exploration of Modular Manufacturing Systems development and development of industrial applicable methods to design such systems.

The Ph.D. project is conducted in cooperation between the Department of Mechanical and Manufacturing Engineering at Aalborg University and Adept Technology Denmark (former InMoTx APS) initially and Grundfos A/S Technology Centre consecutively. The project was initially (the first 2 years) sponsored by Adept Technology Denmark with support from the Danish Agency for Science, Technology, and Innovation and consecutively fully sponsored by the Danish Agency for Science, Technology, and Innovation. The change was caused due to the closure of Adept Technology Denmark ultimo January 2012.

Acknowledgements

During this Ph.D. study, I have been cooperating and in contact with researchers and practitioners which have made the completion of this work possible. Therefore, I would like to take the opportunity to thanks the following people for their various contributions.

First of all, I would like to express thanks to my supervisors, Associated Professor Kaj A. Jørgensen and Professor Ole Madsen, for their valuable and competent source of inspiration and for their kind and skillful supervision during the entire Ph.D. project. Furthermore, I would like to thanks the staff and colleagues at the department of Mechanical and Manufacturing Engineering, Aalborg University, especially the people from the Robotic and Automation Group and the Mass Customization Research Group. I will like to address special and sincere thanks to Ph.D. student Kjeld Nielsen for his on-going support, competent inputs, and enjoyable being.

This project is conducted in cooperation with Adept Technology Denmark and Grundfos Technology Centre. I would like to thanks for this cooperation which has been both valuable to the project and educative to me. Furthermore, I send thanks to Grundfos Technology Centre for their willingness to step in and save the project after the closure of Adept Technology Denmark and for the openness and welcome which I have met. I would like to thanks the staff and colleagues I have met during these industrial collaborations. The
interest, openness, and cooperativeness I have met mean a lot to me. I will address a special thanks to my Grundfos contact person, Platform Engineer Bjørn Langeland, for enjoyable cooperation, valuable discussions, and for the openness and willingness to spend time including me in the on-going work and ideas.

Finally, I would like to express my grateful thanks to my family and friends for supporting me at all times during the project. Special and heartfelt thanks go to my girlfriend and life partner Ane Lundgaard Jensen – I could never have made this project without your patience, unconditionally interest, and endless support.

Steffen Nordahl Jørgensen

Aalborg, April 2013
Abstract

In this thesis, a framework has been developed which structures and guides development of Modular Manufacturing Systems architectures. The framework, and the underlying architecture based approach to Modular Manufacturing Systems, is developed on the basis of proven theories and methods known from product development and Mass Customization. The thesis both contains an exposition of the obtained understanding of modular manufacturing systems and their architectures, a presentation of the framework, and a comprehensive example on industrial use of the framework.

All over the world, researchers have studied the modular manufacturing concept, its advantages and disadvantages, basic technologies, etc. though without providing an answer on how such manufacturing systems should be developed. This project examines modular manufacturing systems from a development perspective with the goal of achieving industrial applicable methods and tools for development of such manufacturing systems and, hereby, for realization of the asserted modular benefits. The project is conducted in close cooperation with the industry and the generated results are based on both existing theory and on practical experiences and implementations.

Modular manufacturing systems have emerged in response to the manufacturing challenges, which our companies increasingly are facing regarding growing dynamic market requirements. These market requirements require rapid adjustment of the product assortment, high product variance, and customization and this in combination with low price and high quality. In regard to manufacturing, this creates a challenge of combining manufacturing profitability with the flexibility to produce a broad product assortment and the changeability to respond rapidly on changing requirements. Previously, Flexible Manufacturing Systems has been appointed as a solution to these challenges, but such systems have proven ineffective, complex, and cost-intensive.

Today the trend points towards modular manufacturing systems, where components, controlling, machine tools, etc. are decomposed in modules (building blocks) and manufacturing systems are developed as one particular combination of modules selected based on a specific set of manufacturing requirements. The ability to add, remove, exchange, and/or updating the manufacturing module(s) allows ongoing change of capability and capacity and, hereby, adjustment of the manufacturing system to new products, production volume, technologies, etc. For companies operating in dynamic markets this changeability entails both increased competitiveness and a risk reduction of manufacturing investments. Additionally, modular manufacturing systems imply increased reuse of manufacturing solutions (on module level) and, hereby, volume in the production of manufacturing systems which, among other things, enables: Reduction of cost price, faster delivery and running-in of manufacturing equipment, and a reduction of uncertainties on cost price, delivery time, and capacity.
Resume’


Verden over har forskere beskæftiget sig med det modulære produktionskoncept, dets fordele og ulemper, grundlæggende teknologier mm. dog uden at give svar på, hvordan sådanne produktionssystemer udvikles. Dette projekt undersøger modulære produktionssystemer fra et udviklingsperspektiv med det formål at bibringe industrielt anvendelige metoder og værktøjer til udvikling af modulære produktionssystemer og herved realisering af deres påståede modulære fordele. Projektet er udført i tæt samarbejde med industrien og de frembragte resultater bygger både på eksisterende teori og på praktiske erfaringer og afprøvninger.

Modulære produktionssystemer er opstået som en reaktion på de produktionsmæssige udfordringer, som vores virksomheder i stigende omfang møder i relation til stadigt stigende dynamik i markedsøkonomi. Disse markedskrav kræver hurtig tilpasning af produktmostortment, høj produktvarians og kundetilpasning og dette kombineret med lav pris og høj kvalitet. For produktion skaber dette udfordringer i at kombinere produktionsrentabilitet med fleksibilitet til at producere et bredt produktmostortment og omstillingsparathed til at respondere hurtigt og effektivt på ændringer i behov. Der er tidligere peget på fleksible produktionssystemer (Flexible Manufacturing Systems) som løsning på disse udfordringer, men sådanne systemer har vist sig ineffektive, komplekse og omkostningsstunge.

Udviklingen i dag peger således mod modulære produktionssystemer, hvor komponenter, styring, værktøjer mm. er nedbrudt i moduler (byggeklodser), og produktionssystemer udviklet som en specifik modulkombination udvalgt ud fra de givne produktionsbehand. Muligheden for at tilføje, fjerne, udskifte, og/eller opdatere et produktionssystemsmodul(er) giver mulighed for løbende ændring af kapabilitet og kapacitet og herved tilpasning af produktionen til nye produkter, produktionsvolumen, teknologier, mm. For virksomheder, som opererer i dynamiske marker, medfører denne omstillingsparathed både øget konkurrenceevne samt reduceret risiko ved investering i produktion. Herudover medfører modulære produktionssystemer øget genbrug af produktionsløsninger (på modulniveau) og herved volumen i fremstilling af produktionssystemer hvilket bl.a. muliggør: Reduktion af kostpris, hurtigere levering og indkøbning af produktionsudstyr samt reduktion af usikkerheder hvad angår kostpris, leveringstid og kapacitet.
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List of Papers:

Four scientific papers are enclosed to this thesis. The papers are referred to as Paper 1 to Paper 4 in accordance to the list below. Full versions of the papers are attached to this thesis.


- **Paper 2**: Joergensen, S., N., Madsen, O., Nielsen, K., Jørgensen, K., A.; 2011 “DESIGN REQUIREMENTS FOR DESIGNING RESPONSIVE MODULAR MANUFACTURING SYSTEMS” 21st International Conference on Production Research; July 31 - August 4, 2011 in Stuttgart, Germany


1 Introduction

This chapter sets the stage of the present project in terms of introducing the project motivation, including how this project is related to the challenges regarding western world companies’ competitiveness. Furthermore, the chapter introduces the related research question of the project, the basic idea of how to address the problem (research hypothesis), and the specific research objectives and delimitations. The introduction is structured in the following manner:

1. Project motivation – Introduction to the problem area and the motivation behind this project
2. Research question – Presentation of the research question derived from the project motivation
3. Research hypothesis – Presentation of the research objective of the thesis based on a short introduction to the related areas of theory
4. Research objectives and delimitations – Presentation of the research objectives and the delimitations made

1.1 Project Motivation

Customers today demand the newest technology, newest design, high quality, and all this at a low price. In addition, customers anticipate a high degree of fulfillment of their specific demands. For most manufacturing companies, these anticipations have led to an expansion of their product assortment from one, or a few, successful products to a broad product assortment of products tailored to specific market segments or individual customers – a product assortment which constantly is to be maintained and updated in accordance to market changes, new technology, etc. These trends challenge the traditional manner of operating in manufacturing companies, especially regarding product development and manufacturing. How to operate under, and taking advantages of, these conditions has gained considerable attention resulting in initiatives both in industry and academia. Initiatives which span broadly and involve aspects such as minimize cost, focus on flow and waste limitation, automation, quality programs, information handling, flexibility, and product structure. Regardless of these initiatives, our companies are still facing these challenges.

Furthermore, globalization entails that western manufacturing companies are challenged by the high difference on labor costs across the world – a difference which disfavor them in the global competition. In response, many companies have outsourced labor intensive processes. Outsourcing experiences have increased the understanding of the downsides related to lack in manufacturing expertise – or as expressed by (Bellgran, et al., 2010):

“If we do not have the ability to produce products, how long will it be before we also lose our ability to develop competitive products? The connection between product development, industrialization, and production are strong, but if one link is weakened there is a risk that all links are negatively affected (Bellgran, et al., 2010 p. 3)”.

As stated above, (Bellgran, et al., 2010) emphasizes the importance of manufacturing expertise and development for companies’ long term ability to develop, industrialize, and market new and innovative products. Such expertise could include product maturing and fast ramp-up, design for manufacturing, and
identifying and implementing new product features based on a new process technology. Maintenance and development of such manufacturing expertise does not necessarily imply full in-house production. However, is should include key manufacturing competences such as crucial processes, technologies, and expertise.

An alternative approach to overcome the disfavor of labor cost is to reduce the amount of labor cost by use of automation and, hereby, limiting the dependency between product cost price and place of production. But today industrial automation requires large initial investments and economical feasible automation, therefore, generally requires a high production volume to distribute the initial investment cost. Achievement of such production volume is challenged by the broad product assortment, constant changes, and the generally limited flexibility of automation equipment. Hence, automation equipment has the risks of depreciating over one or a small number of products of short lifetime. In addition to this economic implication, the limited ability to change and reuse manufacturing systems implies a challenge regarding the pace of new product introduction. Flexible Manufacturing Systems (FMS) evolved in the mid-eighties with the aim of holding the flexibility needed. Yet, FMS has never been widely adopted due to low system output (Koren, 2006), high complexity (Setchi, et al., 2004), and a high cost of general flexibility, which in most implementations are only partly used (Mehrabi, et al., 2000) and (Koren, 2006).

Mass Customization (MC) focuses on how to provide customized products (or high variety) to the mass market with the advantages of mass production. Hence, MC seeks to create a setup where internal operations, including manufacturing, are not significantly affected by market variability. A fundamental element of MC is to limit the internal complexity related to product variety and to postpone the point of variety creation. Modularization, modular product families, and modular product architectures have proven useful in doing so (Harlou, 2006), (Ericsson, et al., 1999) and have become widely used tools to meet market requirements of high variety. A modular approach means decomposing the product assortment into standard building blocks – building blocks to be reused across products and combined differently into product variants. By placing the variety into the module combination it becomes possible to produce each standard module on a higher scale. Modular products are often associated with a manufacturing setup of dedicated (or batch producing) manufacturing lines for module production and a flexible assembly system for module combination/assembly.

Robust process design is a key capability for successful MC implementation (Salvador, et al., 2009). In terms of manufacturing, robust process design can be interpreted as a manufacturing system which is capable of absorbing the fluctuations, varieties, and changes in manufacturing requirements. Hence, manufacturing systems need, regardless of MC, to possess flexibility to produce the different products of the product assortment and to switch between production batches and to possess changeability to adjust to future products and manufacturing requirements.

This is the asserted benefits of Modular Manufacturing Systems (MMS) where components, controllers, and machine tools are decomposed in modules, and manufacturing systems are developed as one particular combination of modules selected based on a specific set of manufacturing requirements. The ability to (re)configure (i.e. to change, add, and/or remove modules) entails the capacity and functionality to be adjustable, which imply responsiveness according to changes (Koren, et al., 1999). Therefore, MMS are aimed to possess the capacity and flexibility needed when needed (Mehrabi, et al., 2000), and to be the manufacturing paradigm of MC (ElMaraghy, 2005). In addition, modular structures imply a potential of
increased reuse across manufacturing lines, fast introduction of new manufacturing technologies, and a speed increase in developing and implementing new manufacturing systems. The main principles of MMS are illustrated in Figure 1.

In literature MMS has been described as Reconfigurable Manufacturing Systems (RMS) (Koren, et al., 1999), Holonic Manufacturing Systems (HMS) (Christensen, 1994), and Evolvable Production Systems (EPS) (Frei, et al., 2007) to which MMS appear as a super category. MMS is listed as a focus area in the European Commission Strategic Research Program for future competitive manufacturing in Europe (Commission, 2006), listed in the national findings of the Danish ManuFuture initiative (Johansen, et al., 2010), and appointed, in terms of RMS, as first priority among six grand challenges for the future manufacturing in the “visionary Manufacturing Challenges for 2020” by the US National Research Council (US National Research Council, 2000). The research effort in MMS is mainly focused on potential benefits, basic principles, and enabling technologies, while actual industrial achievement of modular manufacturing systems have received less attention.

1.2 Research Question
This project takes a design perspective to MMS and serves to develop industrial applicable development methods and guidelines of how to view and work with MMS in the industry. This is an attempt to assist industry in how to view and develop Modular Manufacturing Systems and, hereby, obtain the asserted benefits stated in the literature of MMS. This leads to the following research problem:

“How can industry be assisted with tools to achieve the stated benefits of Modular Manufacturing Systems?”

1.3 Research Hypothesis
As mentioned in section 1.1, modularization and modular thinking is well known from product development theory and MC. The modular approach is mainly related to products of high variety (or customization) to which modularization is applied to increase reuse and postpone the variant creation. An illustrative example is the so-called “white LEGO figure” (see Figure 2). The “white LEGO figure” possesses interfaces to product specific hats and handhold devices, interfaces which entail a common, and hereby mass producible, white basic figure (module). The transformation into specific variants is hereby postponed to the subsequent decoration process and to assembly of custom accessories at the stage of usage (hats and handhold devices).
Modular product architectures are used as a tool to develop, maintain, and manage a modular product assortment and, hereby, to obtain the variety in a cost effective manner. The term architecture is often used in relation to modular products and denotes the scheme of how functional elements are implemented into units (modules) and how these units are interacting with each other. Based on the mapping between functional elements and units, product architectures can be more or less modular. At one end of the scale, modular architecture consists of direct “one-to-one” mappings, whereas, integral architectures, at the other end of the scale, consist of complex mappings (“one-to-many” or “many-to-one”). However, in practice most architectures fall in between.

The Volkswagen “A” platform is a well-known example of a product architecture and forms the base for vehicles as different as VW Golf, VW New Beetle, Audi A3, Audi TT, and Skoda Octavia. The “A” platform is illustrated in Figure 3. The platform compresses all the common parts and individual models are obtained by adding so-called “bodies” – parts which the customers can see and feel (e.g. suspension). According to (Kruschwitz, et al., 2000) about 60% of a car consists of platform components. Further details are to be found in the primary case reports presented by: (Kruschwitz, et al., 2000), (Piech, 2000), (Piech, 2001), (Pischetsrieder, 2002), and (Eichhorn, 2001).

In the MC literature, it is generally accepted that achieving the modular benefits depends on the applied modular architecture; an architecture which must meet the customer requirements whilst still limiting the internal complexity (Ericsson, et al., 1999), (Harlou, 2006). These considerations are supported by the observations of (Östgen, 1994) who performed an empirical investigation of the effects of modularity. The study was based on before-and-after modularization measurements from eight companies in accordance to seven parameters: Lead-time, inventories, direct assembly time, direct material, logistic cost, quality, and
product development time. With the exception of one case (Volvo Cars), positive results were reported. The observed negative influence was related to direct material and logistic cost – observations which later studies by (Erixon, 1998) explained as a wrong product modularization. These findings illustrate the potential in modularity. However, they also stress the importance of the applied modular structure and, hence, the modular architecture.

Product modularity, modular characteristics, and modular product architectures are well known within product development, and numerous methods to develop and presume modular products exist. Similarities between the approach of modular products and MMS exist. This not only in the term “module”, but likewise in the basic idea of dividing into units which should be combined into numerous products/systems and in the asserted benefits of doing so. These similarities indicate a potential of operationalizing MMS though the use of related theories of product modularity and architecture. This leads to the following research hypothesis:

“Manufacturing can be viewed as a product to which existing modular design theory and methods, known from Mass Customization (MC), can be applied to understand and support the development of Modular Manufacturing Systems (MMS) and to develop a structured framework for MMS development”

1.4 Research Objectives and Delimitations

A number of research objectives are formulated in order to assist the exploration of the research question and related hypothesis. The objectives are formulated based on domain knowledge of both MMS and MC:

1. Identify and explore the potential to use modular product theory and methods to understand, guide, and support MMS development:
   a. Identify state-of-the art in MMS and MMS development, including MMS enablers, characteristics, and asserted benefits.
   b. Identify state-of-the art in MC regarding modular product theory and modular product development methods.
   c. Identify modular product theory and modular product development methods with potential use in MMS development.
   d. Identify potential domain gaps to be considered when transferring modular product theory and modularization methods to the domain of manufacturing.
   e. Explore, by practical application, to what extent the identified theories and methods can be applied on manufacturing, and if these enables or guides towards industrial achievement of the asserted benefits of MMS.

2. Modify the modular product theory to the domain of manufacturing:
   a. Modify, if needed, the modular product theory of MC to the domain of manufacturing and define the suggested interpretation of manufacturing architectures, manufacturing modularity, and the overall development approach.

3. Propose a structured framework for MMS architecture development:
   a. Design, based on the remaining findings, a structured framework for MMS architecture development.
   b. Test the suggested MMS architecture development framework on an industrial case.
1.4.1 Research Delimitations

The research question spans over a broad study field, which, in terms of time and needed resources expand the frame of the present project. This implies that not all aspects of the objectives are covered or treated at the deserved level of detail. Therefore, focus of this thesis is put on methods for developing MMS; a focus which entails delimitation from the following aspects:

- The surrounding business setup and change management aspects related to implementing (both at shop floor and introducing the new paradigm to the manufacturing developers) are out of scope and only addressed when they have a directly influence on the MMS development.
- The project focuses on the development of the manufacturing system setup (the physical manufacturing setup, related control systems, etc.). The focus of this thesis has been further limited to development of modular manufacturing systems at cell level (including tools, machines, stations, and cells).
- In the practical case work, use of modules and lower level platforms are only addressed according to the overall architecture/platform of the respective case. This implies a delimitation regarding alternative use as discussed in section 4.1.3.
- The project focuses on MMS architecture development and includes only manufacturing system configuration issues directly related to the architecture development and documentation.
2 Scientific Approach and Empirical Settings

The following chapter outlines the scientific approach utilized in the conducted research by presenting and discussing the type and characteristics of the project, the fundamental thinking of the project work, how the results are obtained, and the ability to draw conclusions based on these results. Furthermore, this chapter introduces the empirical setting of the conducted research. The chapter is structured as follows:

1. **The project type** – Presents the idea behind an industrial Ph.D. as well as the expected types of outcome
2. **Research methodology** – Presents and discusses the applied scientific paradigm and the methodological approach of this project
3. **Research design** – Presents how research is conducted and structured in order to ensure evidence of the obtained results
4. **Empirical setting** – Introduces the empirical setting in terms of an introduction of the industrial cases which serve as a great part of this project

2.1 The Project Type

This thesis is the documentation of an industrial Ph.D. project (in Danish: *Erhvervs Ph.D.*) – an industrially focused Ph.D. education where the project is carried out in cooperation between a private company, an Industrial PhD student, and a University. The general intent of the industrial Ph.D. initiative is to create growth in Danish business by establishing cooperation, network, and knowledge transfer between Universities and Danish industry – this by education of researchers at a Ph.D. level with knowledge about industrially focused research and innovation (DASTI, 2013). In this work, these general objectives have been translated into the following three main project characteristics:

1. The project must have a potential to contribute to the growth and commercial development of the case company/companies.
2. The project should contribute to the associated scientific society, particularly regarding application issues.
3. The project should support knowledge transfer between the involved parties from university and industry and serve as a platform to create and enhance network, understanding, and collaboration.

2.2 Research Methodology

People all have certain presumptions about the world, the surrounding environment, and their role in this environment. These presumptions are shaped by the area of study, past experiences, etc., which affect the manner of which problems are addressed, conclusions are drawn, etc. In research, consciousness and explicitness regarding presumptions are needed to reflect upon the research, e.g. in regard to the applied method(s), the validity of the outcome, and the ability to draw conclusions on these aforementioned outcomes. Paradigms, first introduced by (Kuhn, 1962), is a commonly used term for a set of presumptions, values, and ideals. (Kuhn, 1962) describes paradigms as a number of norms that serve as a strong selection mechanism to separate good and acceptable research from the unsound and unacceptable types of research within the scientific community. Different paradigms have been defined in philosophy of science
and several researchers have tried to classify and/or link them to different scientific areas. This present project has its offset in the Critical Rationalism paradigm of which related presumptions, research influence, etc. are discussed in the subsequent section.

2.2.1 Critical Rationalism

Critical Rationalism, introduced by (Popper, 1959), is based on the theory of falsification. In other words, it is based on the idea that a general acknowledged theory can be proved wrong (falsified) by a single contradicting observation. This implies that theories can and must be criticized and become a constant subject to tests. These tests have to be selected as radically as possible to challenge the theory the most and perhaps provoke a background for falsification. A widely used example on falsification is the discovery of black swans during an exploration in Australia. The discovery proved wrong the, at that time, generally acknowledged theory of all swans being white.

In critical rationalism falsification constitutes a source for theoretical improvements by making existing theories subject to criticism/test, and subsequently revise falsified theories to encompass the observations which originally falsified them (Schroeder-Heister, 2004). Hence, in critical rationalism theories are neither considered final nor to describe the whole truth – this due to the belief that the next observation may prove the theory wrong. However, a theory which has been falsified and subsequently revised is considered closer to truth than the original one (Schroeder-Heister, 2004). In critical rationalistic thinking, researchers seek to explain reality and the objective truth, but it is acknowledged that objective truth in its entirety is not possible to achieve. Therefore, a theory is perceived as being as close to the truth as possible given that it has not yet been falsified.

This present project serves to apply theory and methods developed for one area of application (mass produced products) onto a new and different area (manufacturing). This can be perceived as an extension of the existing theory to encompass a new application area, which, in this project, is tested by applying the theory and methods onto a number of industrial cases. These cases, and their included sub activities, constitute the falsification attempts of which the result can be one of the following scenarios:

1. The theory cannot be falsified. This indicates usability of the theory in the new area of application under the given set of observation settings. In this case, the findings contribute to the existing theory by extending the theory to cover the new area of application.
2. The theory is falsified and revised based on the observations. This implies either a specialization regarding the given observations/application area (e.g. development of a supplemental theory) or a general extension of the theory. In both cases, a contribution is made to the original theory making it a more encompassing theory that spans into a broader area of application.
3. The theory is falsified and cannot be revised to encompass the observations. In this case, the findings contribute to the current understanding and conclude on the limitations of the existing theory.

This approach has been utilized widely throughout the project to explore the usability of MC in the domain of manufacturing. The falsification attempts are conducted both implicitly, as part of the daily empirical work and observations (e.g. to view a given task in a MC perspective and utilize a related method), and explicitly in regards to testing the research objectives. As such, the project has constantly developed in
small incremental steps toward a greater understanding of MMS development and the project outcome in itself represents a contribution to theory bringing the original theory one step closer the truth.

2.2.2 Methodological Approach

(Arbnor, et al., 1997) introduced the term “methodological approaches” in an attempt to reduce the essential research methodological differences of business science into three overall approaches for conducting research: Analytical, systems, and actors approach. The main characteristics of these are summarized below:

- **The Analytical Approach** – The analytical approach assumes that reality is objective and knowledge developed from research is objective (not depending on individuals). The general belief in the analytical approach is that “the whole is the sum of its parts” (Arbnor, et al., 1997). Thus reality can be constructed from understanding its individual parts. The analytical approach explains parts through verified judgments and researchers that follow the analytical approach tend to encourage quantitative research strategies.

- **The Systems Approach** – The systems approach belief in reality which is not totally objective, it is objectively accessible. The general view is holistic and the whole is believed to consist of more than its individual parts (synergies). As such, researches must consider a research area as a number of problems, which need to be addressed as a whole to include implications of the relations between the problems. This contradicts the isolated view of addressing problems of a research area applied in the analytical approach. In the system approach a full understanding of the parts are gained through the characteristics of the whole.

- **The Actors Approach** – The actors approach assumes reality to be a social construction, and is mostly related to hermeneutics thinking. This approach differentiates from the remaining two in the fact that knowledge is assumed and gained subjectively and, hereby, dependent on the actors. Hence, results differ from case to case based on the actors and cannot be generalized. In the actors approach, a qualitative research strategy is encouraged and preferred.

The three approaches should not be mixed during the process of knowledge generation for a given aspect. However, application of another perspective can serve as a valuable approach to provide a complementary view of the study (Arbnor, et al., 1997).

This project makes use of all three approaches to add different views and to utilize and/or generate different types of knowledge and experiences. The need to apply a holistic perspective is generally accepted within the literature of production engineering and modular product design. In this project the systems approach is applied to obtain the requested holistic perspective. The systems approach constitutes the overall approach and is used to: Understand the task of MMS development, understand the requirements and surroundings of a manufacturing system, decompose the development task into subareas, understand the relations among these subareas, interpret related literature and observations to the contest of MMS development, etc. The analytical approach is, among other things, applied when studying literature on the different related aspects and to conduct detailed studies/analyzes. In this project, the role of the analytical approach is primarily to create an understanding of specific aspects and, hereby, a background for studying/developing the system and its relations. Use of the actors approach is mainly related to: Interpreting the literature, understanding the social aspects (e.g. of manufacturing requirements.
and organizational issues), and in understanding the social relationships among colleagues and team members of the empirical cases (e.g. in terms of interpreting and understanding the experiences of others based on the surrounding conditions, the personal background, etc.). Furthermore an actors approach is of relevance for implementation issues such as change management. Despite the importance of successful implementation, these issues have, due to the delimitations of this project (see section 1.4.1), only received limited attention.

According to (Creswell, 2009) research can be conducted based on three strategies of inquiry: Qualitative, quantitative, and mixed methods. The strategy of a research project is to be selected based on the specific project characteristics.

- **Qualitative Methods** - Qualitative methods are based on open ended questions and focus on exploring and understanding the meaning of something. Qualitative studies mostly consist of small (sometimes merely one) but in-depth data samples collected in natural setting. Research strategies such as case studies are closely linked to qualitative research.

- **Quantitative Methods** - Quantitative research methods are, on the other hand, based on closed ended questions and seek to apply numbers and statistics to examine the relationship between variables of a given theory. Quantitative data collection seeks for numerical data such as technical measurements, surveys, etc.

- **Mixed Methods** - The mixed research method combines or associates both qualitative and quantitative forms.

The research question and the related research hypothesis and objectives for this project encompass both qualitative and quantitative elements. In the selected strategy of inquiry, quantitative methods are encouraged where possible to increase validity (e.g. to base the study on scientific literature). Though in practice, the current state of MMS, MMS development, and modular product theory implies a need of exploration and, hereby, a study, which mainly relies on qualitative methods (due to the explorative nature of qualitative methods).

Qualitative methods can be conducted based on different empirical strategies. A strategy that encourages in-depth collection of data from natural settings is found to suit this present project – this in order to establish a basis for detailed exploration of MMS development and its related industrial implications. Within qualitative research, case studies are a general acknowledged strategy to collect such data (Creswell, 2009). The maturity stages of MMS do, though, entail limited opportunities to observe cases of MMS and MMS development (and in particular industrial cases). The use of case study is, therefore, mainly related to observing present use of design methods, surrounding settings, industrial conditions, etc. Action research (which will be described later in section 2.2.2.2) is a related strategy and is related to explorative studies as well. Researchers following an action research strategy are an active part and influence the subject themselves. These characteristics are advantageous for the present project and will allow working directly with the industry in developing and implementing MMS and, hereby, to create empirical data to test the research objectives. As such, the research strategy of action research forms the primary strategy for empirical data collection, but where possible case study is applied. Both case study, action research, and their related limitations are elaborated further in the following subsections.
2.2.2.1 Case Studies

(Yin et al., 2003) identify case study research as an appropriate research strategy for describing and analyzing contemporary phenomena in a single case. It is essential in case study research that the researcher has no control or influence over behavioral events i.e. the role of the researcher is to observe and subsequently to analyze the observations. Case studies rely on empirical data of a high number of variables (in-depth) and few or a single case (Yin et al., 2003). Case study research is, according to (Voss et al., 2002) (based on (Handfield et al., 1998)), appropriate to carry out exploration, theory building, theory testing, and theory extension/refinement research processes.

The criticism of the case study research strategy is questioning whether or not findings of a single case study can be generalized. (Abercrombie et al., 1984) argue that the case study approach has its main relevance in the initial explorative parts of a study, but must be followed by larger quantitative investigations. In relation to studies based on critical rationalistic thinking, (Flyvbjerg, 2006) argues that the case study approach is a powerful tool for falsification, especially if they are extreme or do not fit into general theory.

In this project, case studies are mainly utilized to obtain a basic understanding, and hereby serve as an input to plan and conduct action research. The case studies conducted generally rely on informal collected data from workshops, meetings, interviews, and studies of existing documents/proceedings; data, which are modeled to create an overview or used directly as input (background knowledge) to conduct action research.

2.2.2.2 Action Research

Action research possesses large commonalities to case study in the manner that it addresses contemporary phenomena, focuses on a single subject, relays on extensive empirical data samples (but few repetitions), and possess strength toward studies of exploratory nature (e.g. exploration, building, and testing of theories). The main difference between action research and case study is the role of the researcher. In action research, the researcher goes beyond being an observer and becomes interacting with the subjects (such as being involved in guiding the process, conducting project tasks, studying literature and previous experiences and translating them into the content of the present project, presenting literature, etc.). Hence, the researcher becomes an actor. According to (Gummesson, 2000), action research involves two goals: Solving a specific problem and contributing to science. Furthermore, (Gummesson, 2000) stresses the importance of familiarity to the research area, and defines it as a prerequisite for commencing action research.

Several researchers have studied the process of action research. Based on a comparison of (Susman, 1983), (Checkland, 1991), (McNiff et al., 2006), and (Coughlan et al., 2002), (Petersen, 2008) emphasizes the common presumption that action research is conducted in cycles of iteration. These cycles share the common structure of identifying a problem, acting to solve the problem, and finally evaluating and identifying new potential problem(s). These problems serve as input(s) to the subsequent cycle.

As described in regards to case studies, the main concern of action research is the issue of generalizing and drawing conclusions based on one or a low number of cases. In addition, action research is criticized for its lack of objectivity and the validity of the observations made under influence of the researcher/observer. Therefore, action research requires explicit regarding type of involvement, the researcher’s influence on
results etc. This limits the use of action research to mainly explorative studies and entails that generalization often requires subsequent research.

During the action research conducted in this project, the role of the researcher has primarily been to bring modular product theory and methods into the empirical case and to operationalize the theory and methods in the manufacturing systems development of the given empirical setting. The primary methods of doing so have been to create examples for using the methods, conducting test applications, studying related theory and being in charge of lecturing it at internal training programs (or meetings), facilitating workshops and meetings, generating workflows and procedures, and identifying gaps of success. The collected data is processed and documented as an integrated part of the data collection, this by on-going reflection, use of MC modeling methods, etc.

2.3 Research Design
Research design can be viewed as the plan or the procedure of how the topic is to be studied. Research design of this present project is based on the general model defined by (Jørgensen, 1992). The model is derived from general system theory, which makes it relevant and useful for research following a systems approach. The model is based on the concept of analysis and synthesis, which can be conducted in various sequences.

- **Analysis** - Analysis (of an existing system) is 1) to investigate properties of the system and 2) to divide the system into system components and a system structure
- **Synthesis** - Synthesis (of a new system) is 1) to create the system by relating existing systems to each other by a structure and 2) to add properties to the system

(Jørgensen, 2000) presents two general combinations of analysis and synthesis; a problem solving sequence, and a design sequence. The problem solving sequence initially utilizes an analysis activity to diagnose the problem which subsequently constitutes the offset for a synthesis performed to contribute towards a solution of the problem. The design sequence has a theoretical base as offset and begins with a synthesis activity. The synthesis activity creates the innovation, which is studied for validity etc. in the subsequent analysis activity. This project is based on a research question formulated on the basis of a problem on how to develop MMS; hence, the research design has its offset in the project sequence. Figure 4 illustrates the general problem sequence of (Jørgensen, 2000) and how it has been interpreted in this project. The usability of MC is, as illustrated, initially analyzed through literature, initial experiments, empirical observations, etc. This results in a diagnose on the usability of MC. Based on the subsequent synthesizes activity, the interpretation of MMS architectures and the MMS architecture development framework is generated and tested.
The empirical work conducted in this project were related to analysis activities and were, as discussed in section 2.2.2, based on a combination of the research strategies of case study and action research. The conducted activities of the analysis consisted of a multitude of sub-activities which were generally carried out as illustrated in Figure 5. As illustrated, the need/problem, which initiated the sub-activity, was subject for a pre-study prior to the intended test/exploration. This pre-study served to establish the familiarity needed to utilize action research in the test/exploration phase. The pre-study activity was based on activities such as literature studies (e.g. study of related MC theory and potential methods) and empirical observations in terms of case studies (e.g. observations of market conditions, existing procedures, existing design, etc.).

2.4 Empirical Settings
The research in this project has its outset in two industrial cases – cases performed with Adept Technology Denmark and Grundfos Technology Center. Both cases focus on developing modular manufacturing systems at cell level. The cases vary in cell type, the empirical surroundings, main motivations, position in production value chain, etc. The two cases are introduced individually in the following subsections. The
introductions are accompanied with an elaboration of how the industrial cases are included in the present research in terms of a list of conducted case studies and action research. The two cases were conducted in sequential time order as illustrated in Figure 6.

![Figure 6: The order and time of conduction of the two industrial cases.](image)

In addition to these two cases, manufacturing modularization experiences gathered by research colleagues from the Robotics and Automation Group, Mechanical and Manufacturing Engineering Department, Aalborg University have been utilized, but in a limited amount. These experiences were gathered in the “BinPicker” and “Little Helper” project, which together with the Adept Technology case form the empirical settings of a joint paper, see Paper 4.

2.4.1 Case 1: Adept Technology Denmark

Adept Technology Denmark focused on development, sales, marketing, production, and service of the industrial automation platform called OctoMation robotic workforce. OctoMation is a flexible robot based automation platform developed for food handling and packaging. The core of the platform is a number of proprietary technologies for handling the non-rigid, non-uniform nature of natural products. The company was founded in 2006 as InnoMation Aps and acquired in January 2011 by Adept Technology. Adept Technology is an American based global supplier of industrial automation technology such as robots, controllers, development software, etc. As a consequence of the acquisition, OctoMation related activities were relocated to the US facilities and the Danish department was closed in January 2012.

The market of OctoMation is business-to-business and the main market segment is food producing companies. The main sales argument of OctoMation is its ability to handle the non-rigid, non-uniform nature of food products in an automatic, gentle, and flexible manner. But winning orders demand more than a technical feasible solution; it requires a solution, which complies with the customer specific requirements regarding production speed, packing/loading media and pattern, blueprint, flexibility, etc. In addition, automatic loading and packaging is traditionally only one part of fulfilling the customer demands. Full customer satisfaction requires integration of the specific production line(s) (with other types of manufacturing cells). In the case of OctoMation, the job of integration is handled by local system integrators. The basic idea of the OctoMation platform is to meet these needs for customization by a modular product approach and, hereby, combine the advantages of scaled production with a product customized to the needs of the individual customer.

2.4.1.1 The Role of This Project

At the time of project initiation, the company was at a late start up state and mainly focused on activities such as getting the technologies and products in place, establishing formal sales channels, building the organization, etc. The present project was initiated to study modular manufacturing by assisting the company in its work with modular architecture, in configuring customer specific solutions, and in standardizing (and automation) of related business processes. During the initial project phase focus was
mainly put on establishing the modular platform. The acquisition changed the focus toward business process standardization, including formalization of related undocumented knowledge and implementation of supporting IT-systems such as Product Data Management (PDM) and Enterprises Resource Planning (ERP). In summation, this empirical case has contributed to the findings of this project in terms of case study observations and action research on the areas listed below:

Table 1: List of main case study and action research activities of the Adept Technology Denmark case.

<table>
<thead>
<tr>
<th>Case Study</th>
<th>Action Research</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Understanding current products, their structures, related market requirements, etc.</td>
<td>• Developing and implementing a modular architecture</td>
</tr>
<tr>
<td>• Understanding business structures and processes of project based industries</td>
<td>• Translating the studied literature on MMS, Production Engineering, MC, and modular product development into development of MMS under the given conditions of the case</td>
</tr>
<tr>
<td>• Understanding the market of manufacturing equipment and related manufacturing system supply value chain regarding both new and retrofitted systems</td>
<td>• Developing a proof-of-concept configurator for configuration of a subsystem</td>
</tr>
<tr>
<td>• Observing different business structures, market dynamics, strategy networks, etc. within the industry of manufacturing system development</td>
<td>• Standardization of business processes related to customization and realization of manufacturing systems (sales, component sourcing, production, documentation, etc.)</td>
</tr>
<tr>
<td></td>
<td>• IT-support of business processes and general enterprise architecture, including implementation of ERP and PDM systems</td>
</tr>
<tr>
<td></td>
<td>• Increasing company knowledge and understanding on modular architectures, including how to develop and manage MMS</td>
</tr>
</tbody>
</table>

2.4.2 Case 2: Grundfos Technology Centre

Grundfos A/S is a world leading pump manufacture which is globally represented on sales, manufacturing, development, etc. This case is conducted in cooperation with Grundfos Technology Centre in Bjerringbro, Denmark – an internal R&D department for manufacturing technology. Besides technology development, the Technology Centre is enrolled in providing new and retrofitting manufacturing machines, cells, and lines worldwide on the Grundfos factory sites and can, in addition to the development centre, be assumed as an internal machine builder and system integrator.

This case is conducted in close cooperation with Concepts and Sales Department, which, among other things addresses issues on how to introduce manufacturing architectures and platforms. It is a relatively new work area, which is driven by the ambition of increasing reuse, cost reduction, and faster time to profit in New Product Introduction projects. Prior to this case, Grundfos has addressed and gained experiences on what manufacturing architectures and modularity means to them, how to establish technology overviews and identify potential areas for manufacturing platforms, and in developing manufacturing line level architectures and modularity.

The conducted case addresses development of modular cell level platforms with an outset in a new technology which is potentially to be utilized broadly across the product assortment and, hereby,
implemented on multiple manufacturing lines and production sites. The research included both case study and action research as listed in Table 2 below.

Table 2: List of main case study and action research activities of the Grundfos case.

<table>
<thead>
<tr>
<th>Case Study</th>
<th>Action Research</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Technology management in terms of identifying and managing strategic manufacturing processes and technologies</td>
<td>• Developing an architecture for a manufacturing processing cell</td>
</tr>
<tr>
<td>• The manufacturing development process (both from the manufacturer’s and internal machine builder’s/systems integrator’s point of view)</td>
<td>• Translating the studied literature on MMS, Production Engineering, MC, and modular product development into development of MMS under the given conditions of the case</td>
</tr>
<tr>
<td>• Use of modularization and architectures on manufacturing at a line level</td>
<td>• Testing the manufacturing architecture and modularity interpretation in a new context</td>
</tr>
<tr>
<td>• The importance and examples of how to implement new initiatives in a large organization (change management)</td>
<td>• Testing methods of developing and working with modular manufacturing and manufacturing architectures</td>
</tr>
<tr>
<td>• Observing corresponding work on product architectures and ideas on bridging product and manufacturing architectures</td>
<td>• Integration of MMS and MMS development into the existing process of manufacturing development</td>
</tr>
<tr>
<td>• Increasing company knowledge on how to develop MMS at a manufacturing cell level</td>
<td>• Increasing company knowledge on how to develop MMS at a manufacturing cell level</td>
</tr>
</tbody>
</table>

2.5 Overview

The discussed methodological and research design considerations have resulted in a model for the methodological procedure which relates to the structure of this thesis, to the scientific papers, and to the empirical cases. Figure 7 illustrates these relations and, hereby, provides an offset for understanding and relating the contributions made in the present project.

Figure 7: Overview of how the methodological procedure, thesis structure (chapters), scientific papers, and the two empirical cases are used and related to each other.
3 Exploring the Potential Use of the Modular Approach of MC

This chapter explores the potential of utilizing the modular product theory and methods known from Mass Customization (MC) in the development of Modular Manufacturing Systems (MMS). The chapter is based on the four scientific papers of this thesis and focuses on exploring research objective 1. The four papers are summarized and discussed in accordance to the different topics addressed in this chapter. The chapter is structured as follows:

1. **Theoretical Exploration** – Identification of the theoretical potential to conduct development of MMS based on theory and methods known from modular product theory, this based on analysis and literature review.
2. **Practical Exploration** – Description of the practical experiences in developing MMS though modular product theory and methods. Furthermore, this section discusses these experiences and their coherence to the theoretical findings.

3.1 Theoretical Exploration

As discussed in Chapter 1, similarities exist between MMS and the modular product approach known from MC both regarding the basic idea of creating variety from the combination of modules and regarding the asserted benefits of doing so. These similarities indicate a potential to develop and mature MMS by presuming manufacturing systems as a product to which existing modular product theory can be applied to develop and manage modularity. This section presents the conducted theoretical exploration and serves to answer research objective 1a-1d.

3.1.1 The Potential to Develop MMS Though MC Theories

Paper 1 analyzes the theoretical potential to utilize existing modular product development theory and methods to develop and bring MMS forward. This analysis takes its outset in an included literature review of MC and Reconfigurable Manufacturing Systems (RMS).

### Paper 1: Exploration of Potentials Based on Literature Review

Through the included literature review, Paper 1 found that RMS literature focuses mainly on RMS characteristics and enabling technologies, while, how to develop and realize the asserted benefits has gained less awareness. In an attempt to bring RMS forward, Paper 1 analyzes the theoretical potential to use existing product modularity theory and methods from MC to develop RMS. This analysis takes its outset in the included literature review of RMS and MC (the MC literature review focused mainly on related modular product development theory). Shortcomings for RMS to succeed as a MC product are derived from a gap analysis between current state of RMS and the success criteria of MC. The analysis exposed three gaps: 1) RMS technology needs further development, 2) RMS architectures and platforms are needed, and 3) modeling and knowledge formalization is needed. The potential of using MC theory and methods in overcoming these gaps are subsequently identified by pinpointing MC theory and methods of, for the gaps, comparable or partly comparable issues. On the basis of this analysis, the paper concludes that MC theory and methods possess potentials to contribute to RMS in terms of theory and methods within modularization, modular architectures, and modeling of product families.
The included literature review revealed that MC literature defines modularity as direct one-to-one relations among functional elements and the units which implement the product. Modular product architectures are widely used to define the structures and interfaces of modular products. Thus they are used as a tool to develop, maintain, and manage modular products, product families, and/or product assortments. As such, developing MMS based on modular product theory implies development of a modular manufacturing architecture from which customized manufacturing solutions can be designed as a specific combination of the specified modules. In the MC literature it is generally accepted that achievement of modular benefits depends on the applied modular structure. This structure should meet the required market variety in a manner which limits the internal complexity. Hence, achievement of the desired MMS benefits depends on the applied MMS architecture.

Subsequently the publication of Paper 1, awareness of additional modular manufacturing concepts has emerged – this in terms of Holonic Manufacturing Systems (HMS) and Evolvable Production Systems (EPS). Like RMS, these manufacturing concepts utilize a modular approach to enable responsiveness and changeability. The focus of HMS and EPS deviates from RMS in a number of ways. For example, HMS is based on holons (autonomous and cooperative building blocks, which consist of information processing parts and physical processing parts) and focuses on Multi Agent Systems and Artificial Intelligence as suitable technologies for implementation. EPS, on the other hand, focuses on manufacturing evolution through process oriented modules with embedded intelligence. The main characteristics and differences of the three modular manufacturing theories are listed in Paper 4 table 1. The term Modular Manufacturing Systems (MMS) is introduced as a super category for RMS, HMS, and EPS, and is considered as a general term of modular manufacturing concepts – this is further discussed in Paper 4 section 2.2. Like RMS, HMS and EPS mainly focus on characteristics and enabling technologies. Thus, the awareness of HMS and EPS do not change the need to study modularization of manufacturing systems, modular manufacturing systems, or modeling of modular manufacturing families.

(Hvilshøj, 2012) has studied the technology maturity of dividing industrial robot systems into modules. From a review of software and hardware modularization maturity, (Hvilshøj, 2012) concludes that today’s robotics software platforms are at a level supporting modularization and (re)configuration while the hardware generally are developed without much modularization considerations. Nonetheless, the underlying hardware review shows clear function deviation and well defined interfaces at part level (robot arms, robot grippers etc.). Industrial automation represents one of the most complex and interrelated types of manufacturing systems. The findings of (Hvilshøj, 2012) are, therefore, considered to be applicable to manufacturing systems in general.

### 3.1.2 A Robust Offset for MMS Architecture Development

As it will be discussed in section 3.2, initial experiences on developing MMS though MC theory and methods has shown that achievement of the desired modular benefits requires a robust architecture. Furthermore, these experiences show that obtaining a robust architecture requires a robust development offset in terms of a thorough understanding of the related manufacturing requirements. Obtaining such robust offset is found to be a complex task which needs further exploration.
Paper 2: Understanding and Defining Manufacturing Requirements

This paper recognizes the role and importance of manufacturing requirements in MMS architecture development and simultaneously emphasizes the complexity in defining these requirements due to the close interrelations between a manufacturing system and its surroundings. The paper takes a holistic approach to understand manufacturing requirements in term of an offset in the transformation system model of (Hubka, et al., 1988). The paper suggests an analysis framework to support and structure the definition of manufacturing requirements (especially the indirect given requirements of the manufacturing environment). Furthermore, this paper contains a theoretical analysis of the general production implications of today’s dynamic markets which illustrates the use of the analysis framework.

In terms of MMS development, the main contribution of Paper 2 is an increased understanding of manufacturing requirements including consciousness of the holistic nature of manufacturing systems and the related modeling of manufacturing as an open transformation system. This has contributed to the understanding that manufacturing requirements can be directly given (directly related to the elements of the transformation system model) or indirectly given (related to the relationships between the system elements and their surrounding environments and stakeholders). Both direct and indirect given requirements can be deciding factors. Especially the indirect given requirements can be complex to define and require broad involvement of the stakeholders and surrounding initiatives as part of the requirement specification process.

3.1.3 Identification of Domain Gaps

As it will be discussed in section 3.2, experiences of utilizing the appointed MC theory and methods generally show positive results. However, these experiences simultaneously show a need of adjustments and modifications. Direct applicability of theory and methods from one domain to another requires that the new domain complies with all assumptions and preconditions of the theories/methods. The experienced needs of adjustments and modifications are, therefore, interpreted as insufficient coherences between the traditional application area of MC and the domain of manufacturing. Paper 3 analyzes these differences to increase the understanding of them and, hereby, provides the offset needed to evaluate the applicability potential. Furthermore, this understanding is needed to introduce general adjustments and modifications to theory and methods.

Paper 3: Identification of Domain Gaps

Paper 3 identify domain gaps between existing theory and methods of the three, in paper 1, identified areas and MMS (the manufacturing domain). The conducted analysis takes its offset in a list of product and business criteria defined from the literature. Both MC and MMS are evaluated according to the listed categories and a gap analysis is subsequently conducted by comparing MC and MMS characteristic of each category. The analysis reveals a number of differences which subsequently are discussed regarding use of modularity theory and methods on MMS. Section 3.2 of Paper 4 summarizes the main differences of the conducted analysis and related discussion. The summery is reprinted below:

- **Design Tradition:** In general, the MC literature focuses on how to transform product assortments into modular products and/or product architectures, as a response to market demands for product variety, customization, and rapid product updates. This assumes well-known products and market conditions, a
precondition, which contradicts the knowledge state of ETO-based products such as manufacturing systems and equipment. This leak in product and customer knowledge could potentially limit the direct application of MC theories and methods onto the MMS domain.

- **Product Type:** Overall, manufacturing systems consist of a combination of hardware, electronics, and software. This mechatronic structure contradicts the traditional hardware focus in the literature of modularization and modular product architectures. However, (Nielsen, et al., 2011) found these areas extendable in terms of mechatronic products – an extension, which requires adjustments in the module drivers and related areas. This indicates applicability of the basic MC theories, but a potential need for adjustments and/or elaborations of the methods.

- **Product Complexity:** Due to the complex nature of manufacturing systems, the mechatronic structure, and the high number of actors involved in manufacturing, the complexity of manufacturing extents the complexity level of products traditionally treated in the MC literature. According to the applicability of MC theories and methods, it is essential that the complexity of manufacturing systems does not eliminate the potential to achieve direct functional relations, i.e., modular structures. The design of a modular structure demands overview, which traditionally is provided by product family modeling tools. For products of low-to-medium size and complexity, such models tend to become extensive. However, the size and complexity of manufacturing might challenge the ability of these modeling methods to provide overview. Also, the complexity is a challenge in collecting the information needed to build such models. For instance, the customer demands of manufacturing systems consist of both direct and indirect demands, expressed as the needs of multiple stakeholders. Collecting and formalizing such knowledge can be a challenge for applying the MC methods.

Product volume is defined as one of the product characteristics evaluated in Paper 3, but this in terms of number of similar products only. Subsequent the conduction of Paper 3, awareness has emerged that product volume, in terms of the total production volume, is of relevance as well and constitutes a gap. Generally MC literature assumes a high total sales volume of products, and modularity is introduced to create stability and production volume of widely used units (modules). Contrary to this, MMS operates with a radically lower sales volume (often below 10 units) and a risk that not all modules will be used. The potential to benefit from the initial investment in architecture development and module design are directly related to this volume. In other words, sales volume and profitability of this modular approach are closely related. In regard to MMS development, this implies a challenge of limiting the time spending to a level which is in accordance with the pay-off potentials. This represents a challenge for the use of MC theory and methods as well. This challenge is further increased by an expected need of additional time spending to compensate the above discussed domain gaps (design tradition, product type, and complexity level).

### 3.2 Practical Exploration

Related to research objective 1e, a practical exploration of MMS development has been conducted simultaneously with the above described theoretical exploration. This exploration is related to the Adept Technology case work introduced in Section 2.4.1. The experiences of the Adept Technology case work are presented in Paper 4 together with two related cases on transforming industrial automation from ETO toward CTO by use of modular architectures as known from MC. The two additional cases are conducted by research colleagues from the Robotics and Automation Group, Department of Mechanical and Manufacturing Engineering, Aalborg University.
Paper 4: Exploration of Potentials Based on Practical Application

Paper 4 takes its offset in the previously described papers and explores the appointed potentials by practical application in three real world cases on transforming industrial automation from ETO toward CTO. The three cases are conducted individually. They utilize different methods but overall they follow a common development process of defining architecture scope, identifying module candidates, and formalizing the modular manufacturing architecture.

Section 4.4 in the paper presents experiences of the conducted Adept Technology case. Initial experiences regarding developing MMS based on MC theory and methods have, as discussed, resulted in an unstable architecture with a constant need of change and modification as new projects come along. This initial architecture complied with the one-to-one module definition and was a result of a bottom-up development approach (with offset mainly in knowledge from previous projects). Nonetheless, new leads and projects were experienced to require architecture modifications on the expense of the desired modular benefits. These modifications were related to new or overlooked customer requirements, new market openings, and to new and requested possibilities emerged from new or better understood technical possibilities. These modifications resulted in new or changed technical elements to be encompassed by the architecture. In order to increase the understanding of the market requirements, a holistic analysis including both direct and indirect manufacturing requirements was conducted. The resulting modifications of the architecture were experienced to have a stabilizing effect. In spite of the air-system (a subsystem) previous was considered too complex and project dependent to be standardized, detailed studies on using generic organ diagrams on the air-system resulted in successful modularization and standardization.

The paper discusses the applicability of MC theory and methods based on the experiences of the three cases. From this, the MC based architecture approach to MMS development are generally found useful and to provide an offset to achieve the asserted modular benefits of MMS. MC is experienced to provide a useful understanding of issues related to manufacturing modularity and, hereby, an offset to work with and communicate about MMS. The three cases utilize theory and methods differently. This has shown different needs of adjustments and modifications which generally can be related to the defined gaps. In the use of methods, it is found possible to get around these gap-obstacles by mixing, adjusting, and supporting the MC method. One example of such adjustments is the introduction of levels in modeling and modularization methods to reduce complexity and hereby ensuring the needed overview, see section 4.4 of Paper 4. The use of methods indicates that the required knowledge generally is present in the surroundings of the project but needs formalization. The paper discusses architecture presumption modification which indicates a need of increased understanding of manufacturing architectures and modularity. Furthermore, the paper appoints a need of a structured framework for MMS development.

As mentioned in the summery above, MC theory and methods are generally found useful in developing MMS, though, with a number of additions and adjustments. To the discussed experiences of the Adept Technology case, it should to be added that the case, in spite of non-complete implementation, has shown: A decrease in lead time on customer projects, increased ability to plan purchase and production, and an increased coherence between sales and final project (regarding performance, cost estimate, etc.). In spite of the positive results, the experiences indicates a need of structured design methods adjusted to the manufacturing domain and a need of increased understanding of manufacturing architectures and
modularity. These needs are related to a number of experienced differences. These differences are not only related to use of specific methods but likewise to the underlying interpretation of architectures and modularity. One of these differences is the architecture interpretation related to the low volume of manufacturing systems which tend to include project specific parts. This is found to entail that manufacturing architectures are used mainly as a design skeleton to ensure reusability and modularity of future projects. Likewise, the architecture interpretation is affected by the introduction of levels and related management of architectures at different levels which are included into and reused across one another. Furthermore, the transformation process of a manufacturing system is found to fall in between customer requirements and function elements of existing modularization theory and hereby to challenge the use of existing modularization methods.
4 Modular Manufacturing System Architectures

This chapter addresses the concept of modular manufacturing system architectures and presents the suggested interpretation of manufacturing architectures, manufacturing modularity, and the related high level process of MMS architecture development, modular design, and manufacturing system configuration. The chapter is related to research objective 2 and takes its outset in the product architecture and modularity shortcomings for use on MMS defined in Chapter 3. The suggested interpretations are a result of the conducted work on understanding these concepts. The interpretations have emerged based on the reviewed literature on MC, MMS, and manufacturing systems, the conducted theoretical exploration, and from experiences of the empirical settings. The chapter is structured as follows:

1. Manufacturing Modularity and Architectures – A presentation of the suggested interpretation of manufacturing architectures and modularity as understood and used in the presented thesis
2. MMS Development Process – A presentation of the suggested high level approaches to development and maintenance of MMS architectures and their modules

4.1 Manufacturing Architectures and Modularity

As discussed in chapter 3, developing MMS based on modular product theory implies development of a modular manufacturing system architecture (MMS architecture) from which customized manufacturing solutions can be designed as a specific combination of existing, planned, and customized modules. As discussed in chapter 3 this will bring manufacturing system development from ETO towards CTO.

The responsiveness and reconfigurability of this approach are, as illustrated in Figure 8, related to adding, exchanging, removing, and updating modules. It appears from the literature of modular product development that achievement of such modular benefits requires coordination of the modularity, a coordination conducted by the product architecture, see Paper 1 and Section 3.1.1. MMS architectures are introduced as a similar tool to manage and uniform the modular manufacturing structure and its modules across the specific manufacturing system installations. As discussed in section 3.2, experiences show that introduction of levels are useful to handle the complexity of manufacturing. For MMS architectures, this implies a need of supporting manufacturing levels and related use of manufacturing architectures of different levels as modules of one another. Such MMS architectures are likely to include a number of yet not developed modules and modules which need project specific design or customization. In other words, manufacturing systems have an open solution space. In most projects, this implies that MMS architecture should be seen more as a design skeleton, which ensure reuse and module benefits, than a final library of predefined modules. Finally, the experiences have indicated that the transformation processes of a manufacturing system affect the function elements and, hereby, the offset for modularization. These aspects imply a need of adjusting the theory and methods of product architecture and modularity to the domain of manufacturing. On the basis of a discussion of manufacturing composition and categorization structures, the following subsections present the suggested interpretations of manufacturing architectures and modularity.
4.1.1 The Compositional Structure of Manufacturing Systems

As discussed in section 1.3 and Paper 4, manufacturing systems can be divided into levels in several ways based on the applied view. For MMS, the following deviation in manufacturing levels is suggested: Line, cell, station, machine/tool level, see Figure 9. This level structure covers the focus area specified in Paper 4 and is derived based on the leveling suggested by (Wiendahl, et al., 2007) and the RMS literature’s division between system and machine/tool level, see Paper 1.

The hierarchy among the suggested levels induces aspects of the line level to be referred to as the highest of the four levels and aspects of machine/tool level as the lowest level. This notation is related to the internal inclusion of manufacturing systems into one another and hereby to the way functional requirements of one manufacturing level is translated into functional requirements of its subsystems (and hence requirements of the superior level manufacturing systems). In terms of object oriented thinking, manufacturing level structures and the included components are denoted as the compositional structure of the manufacturing systems. Such structure defines the “part-off” structure of the manufacturing system and can be modeled in a compositional tree structure as illustrated in Figure 10.
### 4.1.2 Categorization of Manufacturing Systems

Manufacturing systems with similar compositional structures can vary (or be changed) by differences in the specific type of one or more of the compositional structure components. In terms of object oriented modeling, different types and/or versions of a compositional component correspond to classification of the component. Hence, categorization can be used to describe components variety (e.g. specific manufacturing systems). Such categorization represents the “kind off” structure for the given manufacturing system and can, as illustrated in Figure 11, be drawn in a classification tree.

![Classification Structure](image)

**Figure 11:** Illustration of a classification tree of a given manufacturing system and its relation to the compositional structure.

In classification structures, properties of a given level are inherited downwards. In other words, properties of a higher level class are available for its lower level classes (its children). Classification of different types and variants of a manufacturing system should be conducted in a manner so subsystems and solutions are located as high as possible in the classification structure. Such classification structures increase reuse by inheriting subsystems and solutions across as many types and variants as possible. In relation to product architectures, (Harlou, 2006) discusses design units as the different elements which together constitute the product. Furthermore, (Harlou, 2006) introduces standard designs as the subcategory of design units which are used across the different products and which complies with a set of rules regarding re-use, documentation, and organizational ownership. In terms of manufacturing, design units are all the units used within the specific manufacturing system setups and standard designs are the set of design units located at a superior classification level (reused across several manufacturing system setups) and which contemporary comply to the listed rules.
4.1.3 Manufacturing Architectures

Generally, manufacturing requirements differentiate across manufacturing systems due to the specific manufacturing task, installation conditions, operator skill level, etc. This implies manufacturing systems of a given type (e.g., a robot station) to differentiate across individual system installations of the particular type. Manufacturing architectures are one way to manage and create commonality among such individual system installations of a given type (with a given basic similarity, e.g., type of manufacturing task).

Manufacturing architectures follow the composition levels of manufacturing systems and can be developed at line, cell, station, and machine/tool level. These levels possess high interrelations and dependencies since configuration(s) of a manufacturing architecture are likely to form component(s) and component variants of a superior level architecture. The composition structure of manufacturing system architectures is a generic structure from which the individual structure of all enclosed specific manufacturing systems can be derived. Such a generic composition structure both consists of general components (used in all specific systems) and of selectable components (system specific structural parts), see left part of Figure 12.

Manufacturing system variety can, beside variety in the compositional structure, be a consequence of different compositional components. Thus, a manufacturing architecture should encompass valid selection options and rules of combination of the different compositional components. As illustrated in the right part of Figure 12, a compositional component generally can have one of three types of variety: 1) No need of component variety exists or a single unit possess flexibility to cover the entire need of variety, 2) the need of variety can be covered by a well-defined number of classified units (e.g., commercial-off-the-shelf available systems such as a robot arm), 3) a set of valid configurations of a lower level architecture. These configurations can be subject for classification as well. As illustrated in Figure 13, different configurations of a lower level architecture can be used as subsystems in one or more superior level architectures; e.g., configuration of a station level architecture used in one or more types of manufacturing cell(s). Such use across more than one superior level architecture is denoted “alternative use” and should be considered before a lower level architecture is developed.

![Figure 12: Illustration of the three different types of composition components.](image-url)
In the product domain (Harlou, 2006) distinguishes architectures in three levels: Product, product family, and product assortment. To increase reuse, a given design unit should be located at the highest possible level. These levels correspond to categorization of manufacturing architectures, but a similar general categorization is not found useful in the domain of manufacturing. Nonetheless, manufacturing system architectures are found to include at least two categories: Specific manufacturing system and manufacturing system family – see Figure 14.

In summary, manufacturing architectures contain a generic compositional structure from which all valid structures of the covered specific manufacturing systems can be derived. Furthermore, a manufacturing
architecture defines the selectable types and the categorization of the different compositional components and imposes how these components and the compositional structure are related and should be combined into manufacturing systems of the given type. A modular manufacturing architecture is one such architecture which is characterized by modularity, see section 4.1.4 below.

Literature regarding product architecture distinguishes between architectures and platforms. According to (Harlou, 2006), a platform is a structural description of a subset of an architecture including only existing standard designs and their interfaces. For manufacturing, a similar distinction between manufacturing architectures and platforms is relevant. Manufacturing platforms are interpreted as a structural description of a subset of a manufacturing architecture including only the reusable/widely-used standard designs. This interpretation includes both existing and future standard designs, this due to the low volume of specific manufacturing systems and hereby the related use as a design platform for future manufacturing systems, see section 4.2.

4.1.4 Manufacturing Modularity
A general accepted definition of product modularity takes its offset in the relation among functional elements and how the physical elements, which implement the product functions, are grouped into building blocks. Based on this mapping, product architectures can be more or less modular. At the one extreme, modular architectures consist of “one-to-one” mappings and at the other extreme integral architectures consist of complex (many-to-one or one-to-many) mappings (Ulrich, et al., 2003), for illustration see Figure 15. Furthermore, according to (Ulrich, et al., 2003) modular architectures are characterized by well-defined interactions among these building blocks. These interactions generally are fundamental to the primary functions of the product. For further details see Paper 1. Adjusted to encompass the mechatronic nature of manufacturing systems, this definition is found to cover manufacturing as well. Hence, manufacturing modularity depends on the relation among functional elements and how the physical, electrical, and software elements are grouped into building blocks, building blocks which possess clearly defined interfaces (physical, electronic, and software/control interfaces).

![Figure 15: Illustration of modular characteristics known from product design theory.](image)

From the modularization methods reviewed in Paper 1 it appears that modularization methods generally take offset in the customer requirements and defines, based on this, the need of functional elements, including the relation among customer requirements and functional elements. This corresponds to the initial customer-function relation in the holistic design framework of (Jiao, et al., 2007) and Axiomatic design (Suh, 2001), see Paper 1 section 2.1.2. The relation among customer requirements and functional elements ensures that the modules reflect customer requirements and their diversity. This entails that
products can be derived from the architecture as a specific configuration in compliance with a set of the individual customer requirements. To ensure such configurability, functional elements of a MMS architecture should likewise be defined on the basis of the individual requirements of the different enclosed manufacturing systems. In other words, functional elements of MMS architectures should be defined in a manner ensuring low complexity in developing, producing, and maintaining the architecture. In regard to manufacturing, the transformation process is found to fall in-between some of the manufacturing requirements and their related functional elements. Hence, the functional elements depend both on manufacturing requirements and the transformation process design. This is illustrated in Figure 16.

![Diagram showing the relations among manufacturing requirements, transformation processes, function elements, unit/organs, and the practical implementation.](image)

**Figure 16:** The relations among manufacturing requirements, transformation processes, function elements, unit/organs, and the practical implementation.

As it appears from the discussion above, the modular manufacturing architecture approach to MMS is highly inspired by modular product theory. This approach is in accordance with the five characteristics of MMS (reviled in the literature study in Paper 1) in the following way:

1. **Modularity** – Manufacturing systems are constituted as a combination of modules.
2. **Integrability** – The modules are developed with clear interfaces to each other. The interfaces are defined and controlled by the architecture which ensures integrability across manufacturing systems.
3. **Customizability** – To provide the needed customizability, the architecture and its modularity are designed based on manufacturing requirements and requirement diversity.
4. **Convertibility** – The complexity of changing, adding, and/or removing functions of manufacturing systems is reduced due to the implementation of functions as separate units with well-defined interfaces.
5. **Diagnosability** – The well-defined functions and interfaces imply a possibility of isolated function tests which reduce time and complexity in tuning and troubleshooting manufacturing systems.

The modular drivers presented by (Ericsson, et al., 1999) are a general accepted list of reasons to form modules. These are formulated from an operational perspective and used actively to identify modules (or module candidates) in Modular Functional Deployment (MFD), see (Ericsson, et al., 1999). Likewise, these drivers are found useful within the domain of manufacturing, but their descriptions are, for some of the drivers, found to address modularity in a manner related mainly to the product domain. A translation into the domain of manufacturing is, therefore, conducted and the result is listed in Table 3. In this process “parallel development” and “uncertainty and individuality” are added to the list.
| Carry over | Reuse across the specific manufacturing systems of an architecture or reuse across different manufacturing architectures are important arguments to isolate parts or subsystems into a module. |
| Technology evolution | Technical solutions which are expected/likely to undergo changes within the lifetime of the architecture should be isolated in a module to enable update of the technical solution without updating the entire architecture. Such changes can be related to new and fast evolving technologies. |
| Planned product or production changes | Isolating manufacturing system parts or subsystems related to properties known, or expected, to change will limit the time, complexity, and impact of such changes/updates. This can e.g. be aspects related to planned future manufacturing concepts or technologies, QA systems, products, etc. |
| Technical specification | Technical solutions which are often influenced by variations in the technical specification can be favorable to isolate into a module. E.g. layout determining issues, product specific grippers, GUI language, etc. |
| Style | Some parts and subsystems of the manufacturing systems can be strongly related to customer specific requirements/standards or to user specific preferences. E.g. brand of the robot, type of manual, and GUI language. |
| Common units | Parts and subsystems related to functions used in all, or most, of the manufacturing systems can be grouped into a common unit module. E.g. safety systems, and control software. |
| Process and/or organization re-use | Similarities in professions involved in development, production, and maintenance indicates a potential module. This is due to possible development advantages and according to increased possibilities for use of sub-suppliers/contractors. |
| Separate testing | Grouping parts and subsystems in a manner which support individual function tests can be beneficial according to implementation, run-in, and subsequent debugging. |
| Supplier offers black-box | Parts or subsystems which are available as commercial-off-the-shelf products are potential module candidates. Such modules can be treated as a black-box with known properties and a sub-supplier who has the responsibility for manufacturing, quality, etc. A robot arm is one example of a unit often integrated as such a module. |
| Service and maintenance | Service and maintain issues can form a reason to integrate parts or subsystems into a module, e.g. quick replacement, disassembly, etc. |
| Upgrading | In MMS the ability to upgrade and change functionalities forms an essential argument to group parts and subsystems into a module. This can e.g. be in regard to upgrade the automation level, scale the production volume, introduce new features related to future products and processes, adjust the degree of flexibility, etc. |
| Recycle | Environmental issues such as recycle is a reason to form a module, e.g. regarding disassembly of materials and separation of polluting materials so these only are used when needed and should be removable at time of disposal. |
| Parallel development | Parallel development of modules represents a potential to speed up the development and, hereby, reducing lead time, e.g. on designing modules to a given manufacturing system. Such a potential of lead time reduction by parallel development represents a driver for isolating parts and subsystems into modules. |
| Uncertainty and individuality | Forming a module in order to isolate parts and subsystems of high project individuality or uncertainties regarding requirements and technology can be beneficial to obtain reuse and volume of the remaining modules. This correspond to project specific units such as gripper jaws, shape determine parts of a deep drawing tool, etc. |
4.2 MMS Development Process

Unlike traditional MC products and as appointed by one of the gaps in section 3.1.3, the number of systems which should be designed based on a manufacturing architecture is limited. In addition, the “batch” size of manufacturing systems is typically one. Developing MMS architectures are initially associated with a time investment which is to pay-off in terms of the MMS benefits. Ahead of MMS architecture development projects it is, therefore, advisable to conduct a technology management process to appoint appropriate architecture candidates (e.g. based on module drivers) and to evaluate and prioritize the potential architecture projects based on estimated investment/benefit trade-off and strategic importance (availability from supplier as commercial-of-the-shelf, importance for key product/production competence, time to market, etc.). This is relevant for architectures at all level of manufacturing.

Two different strategies, or a combination of these, can be applied to development and implement a MMS architecture: Front-loaded development and project-based development. Following the strategy of front-loading means to conduct the architecture development and the module design ahead of the specific manufacturing projects, see upper part of Figure 17. Front-loading corresponds to the strategy traditionally assumed in MC literature and possesses the advantages of full MMS benefits, including low lead time, in all subsequent projects of derived specific manufacturing systems. The downside is the high initial investment which has to pay-off over these subsequent projects, see illustration in lower part of Figure 17. This investment involves risk regarding lifetime of the architecture, and hereby a risk of the investment not to pay-off, and a risk of designing modules which will never be sold/used. Furthermore, front-loading requires upfront presence of the knowledge needed to develop the architecture and design its modules. As discussed regarding the design tradition domain gaps, see section 3.2, presence of such knowledge is likely to be a challenge and, hereby, a limiting factor of a front-loading strategy.

![Figure 17: Front-loading strategies of MMS architecture development (upper) and related investment and project cost principles (lower).](image-url)
On the other hand, following a project-based strategy means to develop the architecture as the initial activity of the first coming project and to design its modules as they are required by the projects (specific manufacturing system), this is illustrated in upper of Figure 18. As illustrated in the lower part of Figure 18, the investment in module design is in a project-based strategy distributed over the projects. This strategy limits the investment risk and ensures presence of the needed knowledge to design the modules; this in the shape of information from the specific projects (or projects if iterations are needed). The expense of the project-based strategy is a reduction of the MMS benefits of the first projects (e.g. longer project lead time, not full project certainty, etc.).

![Figure 18: Project-based strategies of MMS architecture development (upper), and related investment and project cost principles (lower).](image)

4.2.1 Development and Maintenance of Architecture and Modules
The process of maintaining and updating an architecture and its modules can be illustrated by an “eight number model”, see Figure 19. The left circle of the model illustrates development and updating of the architecture and the right circle illustrates designing and updating of the related modules. Version control of both the architecture and the modules is needed to relate the modules to the architecture version(s) to which they are valid (occur as a module and comply with the interface). This means that modules can be updated independent of the architecture as long as compliance to the function description and interfaces is maintained. In relation to a project-based strategy, this implies that a module initially can be developed as a design unit of a specific system and subsequently be “promoted” to a standard design by iterating and generalizing the unit as knowledge becomes present through the projects.

![Figure 19: Eight number model of the relation among develop and update/maintaining an architecture and its modules.](image)
5 Developing Modular Manufacturing System Architectures

This chapter addresses structured development of MMS architectures and presents a framework for MMS architecture development. Furthermore, this chapter includes a comprehensive industrial case work which illustrates use of the framework. The chapter is related to exploration of research objective 3 and is based on the findings of both chapter 3 and 4. The chapter is structured as follows:

1. **The Selected Approach to MMS Architecture Development** – Presentation of the selected approach to development of MMS architecture. This approach constitutes the basis of the development framework and its use
2. **Grundfos Case Presentation and the Developed Platform** – Introduction of the conducted case work at Grundfos including the developed modular manufacturing cell platform
3. **Development Framework for MMS Architectures** – Presentation of the suggested framework for structured MMS architecture development including comprehensive exemplification of how the framework was used in the Grundfos case
4. **Grundfos Case Conclusions** – Discussion of final results and conclusions of the conducted case work

5.1 The Approach to MMS Architecture Development

It is chosen to take a top-down approach to MMS architecture development. This is based on the practical experiences of the Adept Technology case discussed in section 3.2 and Paper 4. A top-down approach to MMS architecture development implies that architecture projects take offset in development of the highest involved manufacturing level architecture and subsequently address development of the lower level architectures in gradual order. This approach supports structured transformation of requirements among the included manufacturing levels and hereby reuse as discussed in section 4.1. Nonetheless, this top-down approach should be supplemented by initial considerations of aspects from all included levels of manufacturing. Establishing such an initial holistic overview limits the number of large iterations, and hence, increases efficiency of the development process. This is the main focus of the MMS development process model discussed as part of the development framework, see section 5.3.3. The alternative to the selected top-down approach is a bottom-up approach. A bottom-up approach to MMS development means to define modules directly as reusable function units of specific manufacturing systems. This approach was initially applied in the Adept Technology case work but was experienced to result in an architecture (and modules) of constant need of modification and adjustments, see section 3.2 and Paper 4.

A MMS architecture generally encompasses a number of subsystems and variants of these. Likewise, such subsystems can be subject for varying requirements and hereby candidates to form a lower level MMS architecture. Before initiating the development of a lower level architecture, alternative options should be considered, e.g. to source the subsystem as a commercial-off-the-shelf system. If a lower level architecture should be developed, alternative use of this lower level subsystem should be considered (use as a subsystem in other higher level architectures, see section 4.1.1). A subsystem architecture, which is intended for alternative use, should form a MMS development project by itself to ensure correct definition of the requirements, etc. On the other hand, if the lower level architecture should be used as a subsystem
of this specific higher level architecture only, then its requirements, function descriptions, etc. can be defined from the superior architecture directly.

5.2 Grundfos Case Presentation and the Developed Platform
The Grundfos case work is a comprehensive industrial case work on MMS architecture development which has been conducted to test the suggested development framework and its underlying interpretation of manufacturing architectures and manufacturing modularity. The background, focus of this case work, and the developed platform are presented in Grey Box 1. Additional information and an elaboration of the platform development are provided in section 5.3, while, the final results and conclusions are discussed in section 5.4.

**Grey Box 1: Grundfos Case Work Introduction**
This case work tests the suggested development framework and its underlying interpretation of manufacturing architectures and modularity by applying the framework on a case at Grundfos A/S – a world leading pump manufacture. In the case work a modular manufacturing platform was developed for a special insert injection moulding technology which currently is under development at the Grundfos Technology Centre - an internal manufacturing development center as well as technology supplier. The technology will be implemented in the production of numerous products and across the production lines and sites. At the time of case conduction, the technology was in an exploration and validation state. Grundfos has, previous this case, worked with and conducted initiatives on modular manufacturing, manufacturing architectures, and identification of strategic important production areas, technologies, and processes.

The driving industrial motivation of this work was to reduce the lead time on bringing new products to the market (increased speed in design, implementing, and run-in manufacturing lines of the new products). This entails driving MMS advantages to be the ability to perform parallel development activities, to reuse existing modules, and to front-load production development activities. Additional motivations included scalability in terms of volume and automation level, cost reduction, and increased changeability to adapt rapidly to changes/updates of existing products.

The conducted case focused on development of a cell level platform of the specific technology including the enclosed stations and machine/tool level platforms, see left part of Figure 20. The case focused on developing and documenting the platform. The case followed a front-loading development strategy but included the platform development only. The overall development process is illustrated in the right part of Figure 20. The developed platform includes configurations of lower level platforms of both station and machine/tool level. These platforms were developed one at a time in a top-down process as discussed later in Grey Box 9. Similarities in the use of methods and in the detailed development process were experienced in the development of these platforms. Therefore, it is chosen to use the cell level platform as examples in section 5.3 and only include station and machine/tool level examples to illustrate differences from the cell level platform development. If possible, such differences will be illustrated by examples from the handling system (a station level cell subsystem).
The conducted case work has resulted in a platform for the insert injection moulding technology from which future manufacturing cells of this type should be designed. The platform defines valid designs of such manufacturing cells and how they are integrated into manufacturing lines. On a cell level, the platform defines a common compositional structure consisting of 5 subsystems: Feeding-, handling-, moulding-, cooling-, and control and safety system, see left side of Figure 21. On the top level, cells are categorized in horizontal and vertical cells, this based on the included type of injection moulding machine - see right part of Figure 21. These two cell categories have several units and functions in common. In order to increase reuse, these common elements are located at the top level of the cell classification. Examples of such elements include valid types of feeding, handling, cooling, and control and safety systems.

All five cell level subsystems are exposed to project individualities and hence implemented as configurations of a station level platform. On a cell level, these configurations are classified according to cell level properties. Examples are classification of handling system according to handling principle (manual, 6 axes robot, etc., see right part of Figure 21) and classification of the feeding system according to component input type and internal interface to handling system (e.g. Single Input Single Output (SISO)).
This classification is selected due to cell level configuration issues which requires linkage between the mentioned classes and the lower level platform properties/parameters. On the top level, a coordinate system of both vertical and horizontal cells have been drawn to create overview of scalability and to relate valid cell level configurations to automation and production level, see Figure 22.

![Figure 22: Production volume and automation level scalability of cell level platform concepts (valid combination of cell level component categories).](image)

As mentioned, each of the five subsystems relates to a station level platform. These platforms can potentially be used in other types of cell level platforms. However, such alternative use was not addressed due to the time limitations of this project. The five station level platforms are all composed with a generic composition structure from which the composition structure of a specific manufacturing station should be defined. The handling system contains, as an example, tree generic compositional components of cardinality 1 (handling unit, gripper system, handling algorithms) and one selectable component of cardinality 0 or 1 (the buffer), see Figure 23. The subsystems of the five station level platforms are implemented either as commercial-of-the-shelf systems or as configurations of machine/tool level platforms. As an example, the handling unit is implemented as selections of commercial-of-the-shelf systems (e.g. specific 6-axes robot arms) and the handling algorithms as configurations of a lower level platform. These examples are illustrated in Figure 23 and further discussed below.

![Figure 23: Composition structure of the handling system and related classification of handling units and handling algorithm.](image)

As mentioned above, some of the station level subsystems are implemented as commercial-off-the-shelf machine/tool level systems. Such commercial-off-the-shelf systems are included directly as modules of the
respective station level platform. As an example, 6 axes robots (including associated robot controllers) are introduced as a class of handling units to which the specific 6 axes robot variants should be added as a specialization, see Figure 23. Related to such commercial-off-the-shelf systems, reuse and commonality across different platforms should be considered in terms of compliance to, and/or the possibility to form, corporate standards and preferences.

The handling algorithm is an example of a station level subsystem implemented through a machine/tool level platform, see Figure 24. The handling algorithm platform contains six generic handling algorithms. Each of these generic handling algorithms is related directly to a handling concept, i.e. a combination of one out of three machine type setups (1K, 2 x 1K, or 2k machines) and a gripper type (simple gripper or rotation gripper). The handling algorithms should be implemented in the cell controller as generic algorithms of how to conduct the handling tasks, this in a manner which provides flexibility to adapt the algorithm to the specific system though selecting/deselecting optional handling elements (the process steps of the handling algorithm). The six handling algorithms are constituted from six different types of handling elements which constitute the lower level compositional components of the handling platform, see right part of Figure 24. These handling elements are highly dependent on gripper system, feeding system, tool design, etc. and are, therefore, classified based on their links to the surrounding systems. In the control software, these handling elements should be implemented as individual classes and the different variants of a handling element as the methods of the respective class. Each of the six handling algorithms should instantiate the related handling element classes and should call the specific methods needed with parameters defined by the specific manufacturing system configuration.

The conducted machine/tool level platforms likewise consist of a generic composition structure and related classification of the composition elements. For machine/tool platforms, the lowest category of each composition components relates to design units in terms of commercial-off-the-shelf systems/parts,
predefined internal systems/parts, or systems/parts which have to be designed or customized based on the project requirements. One example is the gripper system, see Figure 25. As illustrated in the figure, the gripper platform contains three generic compositional components and three selectable compositional components. The top level categorization takes offset in station level gripper properties. In the gripper system, the tool changer and gripper unit are implemented by commercial-off-the-shelf systems and the gripper jaws are project specific parts which should be designed. In the conducted case work, only the main categories of grippers are defined; hence the specific valid gripper units should be defined and added subsequently.

![Diagram of gripper system platform](image)

**Figure 25:** Illustration of the gripper system platform.

A cross level excerpt of the composition and classification tree and an illustrative representation of the associated platform elements can be seen in Figure 26 and Figure 27 respectively. It should be noted that, due to the stage of technology maturity, the conducted platform have incompleteness at station and machine/tool level regarding selection of specific machines, etc. This incompleteness is experienced to imply a lack of specification and parameter quantification. In order to determine and quantify higher level platform parameters, and to link them to the scope parameters, these low level details are found to be important and to result in a lack of platform finalization. This is further discussed in the case work conclusion, see section 5.4.
Figure 26: Illustrative excerpt of the platform composition and classification on cell, station and machine/tool level.
Figure 27: Illustrative excerpt of the developed platforms at cell, station, and machine/tool level.
5.3 Development Framework for MMS Architectures

A development framework for MMS architecture has been developed to support and structure the development of MMS architectures. The suggested framework consists of a reference framework of how to view MMS architecture development and a high level model of the MMS architecture development process. The high abstraction level of the MMS development process model provides flexibility to meet the project individualities regarding the sequence of the detailed design process and use of specific methods within the different framework activities. The framework is constructed with offset in:

- The understanding obtained from the theoretical exploration discussed in chapter 3.1
- The practical experiences gathered from the conducted Adept Technology case work (see section 3.2 and Paper 4), the Grundfos case work (see section 5.2 and the later grey boxes) and from experiences extracted from the remaining two cases presented in Paper 4 (the Little Helper mobile robot and the bin-picker cell)
- The understanding and interpretation of manufacturing architectures and manufacturing modularity defined in chapter 4

The subsequent description of the framework is, due to readability, divided into three parts: 1) An overall presentation of the reference framework, 2) a description of the individual elements of the reference framework, and 3) a description of the overall development process model and the included steps.

5.3.1 A Reference Framework for MMS Architecture Development

The suggested reference framework forms an offset of how to view the task of developing manufacturing modularity and architectures at a cell, station, and machine/tool level. Hereby the reference framework is intended to create the basic understanding of how to conduct and communicate issues regarding MMS architecture development.

![Figure 28: The reference framework of MMS Architecture Development.](image)

As illustrated in Figure 28, the framework consists of 3 phases: Analysis and Concept Generation, Modular Architecture Design, and Documentation. Each phase contains one or more activities which support the accomplishment of the goals of the phase. In practice, these phases and their related activities are highly
iterative and can, therefore, not be separated clearly. Nonetheless, the description of the phases and their related activities makes a clear separation to increase readability. The sections below describe the framework elements and the offset for using the framework. The description briefly covers the focus of the phases and their related activities. This brief description serves to provide an overview of how the phases and their individual activities are related and how they lead to a MMS architecture. Detailed descriptions of the purposes, preconditions, related methodological instruments, etc. of the individual activities can be found in section 5.3.2.

5.3.1.1 The Offset of MMS Architecture Development
In general, two types of offsets of MMS architecture development exists: 1) A new emerging technology, process, or type of manufacturing system which should be used across several manufacturing setups or 2) an already existing/well known type of manufacturing system, manufacturing process, or technology used in a multitude of manufacturing setups. These two offset types constitute the inputs of the framework and one of them must be present in order to start a MMS architecture development project. In regard to new technologies it should be noted that such technologies must be at a relative high maturity state (in end of the technology development phase) before a MMS architecture development project can be initiated. This is relevant to ensure presence and robustness of the needed information. A description of the offset of the conducted Grundfos case work can be found in Grey Box 2.

Grey Box 2: Offset of the Grundfos Case
As it appears from Grey Box 1, the conducted case work has its offset in a newly emerged technology which is to be used in manufacturing of a multitude of products and is to be implemented at several manufacturing setups across the manufacturing sites. As mentioned, at the point of the case conduction the technology maturity was still at a technology development stage. This is experienced to result in a number of challenges which are presented in the later Grey-boxes and discussed as part of the case work conclusion in section 5.4.

5.3.1.2 Phase 1: Analysis and Concept Generation
The purpose of this phase is to establish the offset needed to conduct the subsequent MMS architecture development. The phase includes the introductory activities of creating the overview and familiarity needed in regard to the requirements and focus of the architecture, the function elements, the possible technical solutions, and the related concepts of implementation. The activities related to the phase are:

- **Define Focus Area** – Define the overall intended production task and functionalities of the architecture, the related level of manufacturing, and the main relationships to higher level manufacturing systems (how does the architecture fit into the higher level manufacturing systems?).
- **Scope Definition** – Define and specify the architecture focus area and the related manufacturing requirements and requirement diversity which should be covered by the architecture.
- **Function Elements** – Identify the generic process flow(s), the related process and handling elements, and the remaining function elements of the architecture.
- **Technical Solutions** – Define and study potential technical solutions and their implications, advantages, and delimitations.
• **Concept Generation** – Generate concepts, both overall and specific parts/details, of manufacturing systems related to the requirements of the scope, the function elements, and the technical solutions.

These activities are in practice highly interrelated and modifications and new inputs in one of them tend to manifests itself in resulting modifications in the other.

5.3.1.3 **Phase 2: Modular Architecture Development**
In the modular architecture development phase the concepts are transformed into a MMS architecture. The phase is highly iterative and is experienced to entail a high number of iteration loops, both within the phase and back to phase 1. The concepts and related focus area, scope, function elements, and technical solutions of phase 1 constitute the offset for the modular architecture design activity of this phase.

5.3.1.4 **Phase 3: Architecture Documentation**
Documentation of the architecture should be present according to maintenance and future development of the architecture and according to the three use cases of an architecture: Module design, manufacturing system configuration, and product design for manufacturing (DFM). The use cases, and how to document architectures according to them, are described in section 5.3.2.7.

5.3.2 **The Elements of the Framework**
The individual activities of the reference framework are described in further details in the following subsections. These activities are, in spite of their interrelations and iterative nature, described separately.

5.3.2.1 **Define Focus Area**
Clarity should be established initially regarding intended task and functionality of the architecture, its level of manufacturing, and how the architecture is related and integrated into higher level manufacturing systems. Drawing a system black-box is one method to create such clarity. A system black-box is drawn by:

1) Analyzing the manufacturing process of the higher level manufacturing systems and, if possible, identify one or more Generic Process flow(s)
2) Identifying the, to the architecture, related processes step(s) of the higher level manufacturing processes (within the generic process flow)
3) Extracting and modeling the system black-box based on the process step(s) which should be conducted by the manufacturing systems of the architecture
4) Defining the general functionality and the external interfaces of the black-box (incoming and outgoing materials, components, semi-manufactures, information flows, etc.).

For lower level architectures, this system black-box can eventually be defined directly from the superior level architecture. When doing so, alternative usages should be considered. If alternative use is intended, the focus area should be defined by the four step procedure listed above. Illustrative examples of focus area definitions, both regarding use of the four step procedure and definition based on a higher level platform, can be seen in Grey Box 3.
Grey Box 3: Define Focus Area of the Platforms

In the conducted Grundfos case work, two methods were used to define the black-boxes and hereby the focus areas of the included platforms. The above discussed four step model was applied to define the system black-box of the cell level including how this cell level platform was related to, and should be integrated into, manufacturing lines. In this case, such line level information was partly present and used as an offset to define a generic process flow of the line level processes. For the lower level platforms the system black-box model was defined based on the superior level platform. The following description is divided into three parts: 1) How to define the generic process flow (step 1 of the system black-box model), 2) define the cell level system black-box (step 2, 3, and 4 of the system black-box model), and 3) define the lower level system black-boxes based on the cell level platform.

Define the generic cell level process flow:
Identification of the generic process flow took its offset in the product archetypes to be produced (group of products with certain similarities). These were analyzed regarding their production processes. On the basis of this, one or more process diagrams were drawn for each product archetype. These process diagrams were subsequently drawn above each other as shown in Figure 29. In this process, the individual diagrams were remodeled to a common structure to emphasize commonalities between the production processes. It should be noticed that a process does not have to utilize all steps of the common processes structure. The generic process was drawn at the bottom of the diagram by summing up the vertical commonalities. In this case a single generic structure was found. If the process diversities have been too extensive to encompass in a single generic processes flow, an alternative would be to group the archetype process flows and create two or more generic process flows. In regard to this, it should be noted that multiple generic processes can indicate a need of development of separated platforms.

![Diagram](Image)

Figure 29: Principle of how to identify the generic process flow based on analysis of the superior level manufacturing process.

Define the system black-box based on a generic process flow:
The process-step which should be covered by the platform was identified in the generic process flow and
subsequently extracted and modeled as a black box. Furthermore, the generic process flow served to define a generic function description and the external interfaces of the system black-box. This was done by studying the specific process steps of the individual product archetype process flows (the ones used to define the generic process flow). In this case, the interfaces involved: Materials, components, information flows, and electrical supply. The system black-box and how it was extracted and modeled from the generic process flow is illustrated in Figure 30.

**Figure 30: Extraction of the system black-box from the generic process flow.**

**Define system black-box from a superior level platform**

The station and machine/tool level system black-boxes are all directly defined from the superior level platform. The higher level platform (e.g. the cell level platform) contains, among other things, information regarding its internal processes, process steps, and on how these are related to the subsystems including the subsystem functionality, interfaces, variety, etc. These are the information needed to define the system black-box for the platform one level lower. Hence, the system black-boxes of the lower level platforms were defined directly from their respective superior level platform. In the case work, five station level system black-boxes and related functional descriptions were defined directly from the cell level platform, one for each of its subsystems. Machine/tool level black-boxes and function descriptions are likewise directly defined, but from the information of the related station level platforms. Figure 31 illustrates definition of the Handling System black-box and function description.

**Figure 31: Illustration of how handling station system black-boxes and function descriptions are defined from the handling subsystem of the cell level platforms.**
5.3.2.2 Scope Definition

The architecture scope is a requirement specification of the architecture including both the total span of requirements of all included manufacturing systems and the diversity among these (need of variance). In a more illustrative manner, the scope can be perceived as a specification of the requirements (including the requirement diversity) of the manufacturing systems portfolio which should be derived from the architecture, see Figure 32.

According to the transformation system model of (Hubka, et al., 1988), a manufacturing system transforms an operand through a transformation process guided by a human system, a technical system, an information system, and a management system, for further details see Paper 2. To define what should be included in a manufacturing architecture, the architecture scope should compress the span of requirements and requirement diversity of all these system elements (including indirect requirements of the environment). In an attempt to simplify the scope definition process, the system elements are transformed into a number of information categories with a higher similarity to traditional manufacturing system requirement specifications. Table 4 lists and describes the information categories and links them to their corresponding transformation system elements.

Table 4: The architecture scope information categories and their relation to the elements of the transformation system model of (Hubka, et al., 1988).

<table>
<thead>
<tr>
<th>Information Category and Description</th>
<th>Related System Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Products to be produced</strong>: What are the production/transformation task(s) which should be performed? Incoming materials and components, resulting products or semi-manufacture, tolerance on incoming components and resulting products, etc.</td>
<td>The operand at its initial and final stage</td>
</tr>
<tr>
<td><strong>Operational conditions</strong>: What are the operation conditions of the productions where the systems should be installed? Need of flexibility, changeover, and reconfiguration? User interfaces and language requirements? Safety issues? Production volume and automation level? Quality and uptime? Strategies and management requirements (Lean, sustainability, OEE reporting, etc.), production planning and control, etc.</td>
<td>Technical system, Human system, Information system, Management system</td>
</tr>
<tr>
<td><strong>Installation and service conditions</strong>: What are the supply, service, and installation condition where the manufacturing systems should be installed? What are the supply connections (electricity standard, high</td>
<td>Technical system, Information system, Management system</td>
</tr>
</tbody>
</table>
Standards, systems restrictions, etc. solutions

**Roadmaps and forecasts:** What are the expected technology roadmaps (expected future technologies and changes which should be encompassed), product and production trends (production volume, automation level, type of production, etc.), expected architecture versions, etc.

**Technical requirements:** Special requirements regarding technical solutions and ways of implementing: Supplier brand restrictions, use of specific protocols, infeed/outfeed restrictions, corporate standards, best practice, higher level architectures to comply with, etc.

Specification of the transformation process of transforming incoming materials, components, etc. into the defined output is treaded separately in section 5.3.2.3.

As discussed in Paper 2, production requirements are influenced by a multitude of stakeholders. To obtain a robust offset for the subsequent development process, and hereby lowering the number of iterations, a holistic view is needed when defining the scope – see section 3.1.2 and section 3.2.

When specifying the above listed information categories the relevant properties should be defined, e.g. production volume and product size. These properties should be selected with regard to the related technical issues which correspond to the initial step of Modular Function Deployment (linking customer requirements to product properties). These properties can be quantified in several ways depending on the assessed importance and available information. Examples of parameter quantification include fixed parameters, a parameter span, and distributions (e.g. the sales volume distribution of current product assortment), see illustration at Figure 33.

![Figure 33: Different ways of quantifying the properties of an architecture scope.](image)

The scope definition process generally takes its offset in the information provided in the architecture focus area (system black-box). The process is a gradually process of developing and perfecting the scope simultaneous with more in-depth analysis of given aspects, reviews, comments, and increased knowledge of the remaining activities of architecture development. Broad stakeholder involvement is needed to achieve a robust scope and hereby the fundament for the architecture development. The scope definition can be compared to the customer view of PFMP, initial states of MFD, etc. Hence, such methods can be utilized to support the scope definitions, for scope documentation, and to establish overview of the scope and its relations to the remaining activities of architecture development.

Before large time spending is made on concept generation, modularization, and architecture development the scope should be reviewed to ensure a stable offset and hereby limit the number of large iteration
cycles. The review team should consist of stakeholders of the subsequent architecture usage, e.g. PT engineers, product designers, module developers, potential customers, etc.

Grey Box 4: Define the Platform Scope
The conducted case work on scope definition utilized the cell level system black-box model as an offset to define the platform scope, e.g. regarding functionalities of the platform, types of incoming components, and regarding types of resulting semi-manufactures. Additional information was gathered from analysis and study of existing documents, product review, company standards, interviews with experienced engineers, etc. To obtain an overview, this information was initially modeled in a PFMP. The PFMP was found to constitute a good modeling tool to create overview, but only among people directly involved in the modeling process. To increase the ability to communicate with a broader audience, the PFMP was transformed into a graphical representation of the same information. An illustrative example can be seen in Figure 34.

The conducted scope contains, in accordance with the discussed scope information categories of Table 4, five main categories. For each of these categories, Table 5 lists the specific type of information included in the scope of the conducted case.

Table 5: The specific types of information for each scope information category which was included in the scope of the conducted case work.

<table>
<thead>
<tr>
<th>Products to be produced</th>
<th>Operational conditions</th>
<th>Installation and service conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Product archetypes</td>
<td>- Flexibility</td>
<td>- Supply connections</td>
</tr>
<tr>
<td>- Incoming components</td>
<td>- User interfaces</td>
<td>(Electricity, air, environment, noise regulations, etc.)</td>
</tr>
<tr>
<td>- Incoming materials</td>
<td>- Safety</td>
<td>- Interfacing equipment</td>
</tr>
<tr>
<td>- Products/outputs</td>
<td>- Management and strategy</td>
<td>- Line control and information systems</td>
</tr>
<tr>
<td></td>
<td>- Sustainability</td>
<td>- Floor space/blueprint regulation</td>
</tr>
<tr>
<td></td>
<td>- Operation measures</td>
<td>- Service restrictions</td>
</tr>
<tr>
<td></td>
<td>- Operator skill level</td>
<td></td>
</tr>
</tbody>
</table>
A set of scope documents was developed to document the scope. These documents followed the graphical format illustrated in Figure 34 and the information structure of Table 5. The scope documents formed the offset for the scope review which were conducted by delegates from PT engineering, potential customers, module designers, etc.

The scope parameters were experienced to be difficult to quantify due to the lack of technology maturity and the parameter quantification was therefore only partly completed. In relation to the conducted scope definition, a potential was seen to increase reuse of scope elements by defining corporate or line level standards. Examples includes aspects of “operation condition”, “installation and service conditions”, “roadmaps and forecasts”, and “technical requirements”.

**Scope of involved station and machine/tool level platforms:**
The station and machine/tool level platforms are all developed without concerning alternative use. This limitation entails that only requirements related to the cell level platform are included in the scope of the station and machine/tool level platforms. The scope definition of these lower level platforms are, therefore, translated from the cell level platform in a top-down procedure following the cell, station, and machine/tool level structure. Addressing alternative use would, most likely, have implied a need of conducting a scope definition process for all the platforms similar to the process performed at cell level.

### 5.3.2.3 Identify Function Elements

An essential activity in MMS architecture development is to define the different processes of transforming the incoming components, materials, etc. to the specified products/semi-manufactured products. The individual manufacturing systems which should be designed from the architecture are likely to perform specific variant(s) of one or more transformation process(es). This implies a need of defining generic internal process flow(s) and using them as offset to develop an architecture which encompasses all of these individual process flows. The internal generic process flow(s) are identified based on process commonalities. This in a process similar to the one described for the generic process related to the system black-box definition, see section 5.3.2.1 and Grey Box 3. The definition of the internal generic process flow(s) can e.g. at cell level take its offset in a transformation process analysis of the product archetypes which should be produced and the different ways of doing so. The defined processes should subsequently be generalized and grouped. Different types of process diagrams constitute important tools to define and structure these processes. It should be noticed that products generally can be produced in several ways and a decision regarding the desired process generally should be made.

Process elements can be identified from the process steps of the generic process flow(s). The process elements represent the general transformations which should be conducted and hereby a critical functionality which should be supported by the manufacturing architecture. A process element can be mandatory or optional based on its presence in the generic process flows. The corresponding elements of a handling process are denoted handling elements. The elements which perform a function not directly

<table>
<thead>
<tr>
<th>Roadmaps and forecasts</th>
<th>Technical requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Technological roadmaps</td>
<td>- Supplier brand restrictions and preferences</td>
</tr>
<tr>
<td>- Trends (regarding flexibility, production volumes, batch size, change over time, etc.)</td>
<td>- Safety systems</td>
</tr>
<tr>
<td>- Expected platform generations</td>
<td>- Protocols</td>
</tr>
<tr>
<td>- Automation levels</td>
<td>- Infeed conditions</td>
</tr>
<tr>
<td></td>
<td>- Globalization and transfer</td>
</tr>
</tbody>
</table>
related to the transformation process are denoted support elements, e.g. control and safety. Support elements are important for the functionalities of the architecture but cannot be defined directly from the process analysis. The process, handling, and support elements together constitute the function elements of an architecture. Defining the function elements on the basis of the internal generic process flow(s) ensures the relation among the scope, transformation process, and function element discussed in section 4.1.4.

A need of variants of a function element, or their implementation, can occur based on the scope, transformation processes, technical solutions, and/or conceptual issues. Such variety indicates a need of flexibility or module variants in the implementation of the elements. Application examples can be found in Grey Box 5.

**Grey Box 5: Identification of Internal Generic Process Flow and Function Elements**

The internal process of transforming the identified components, materials, etc. from their initial state into the specified semi-manufactured products should be defined. In this case, identification of the transformation process was performed in a process similar to the one of “defining generic process flow” – see Grey Box 3. In the work of doing so, all possible transformation process flows of generating the identified semi-manufacture products archetypes from the different component types were identified. Furthermore, a selection between process flows was made and a single generic process flow was defined based on commonalities among the remaining ones.

Six process elements were identified; one for each type of process steps in the generic process flow. In addition, control, production data handling, and safety were added as support elements. Together these process and support elements constitute the function elements of the cell. The identification of the transformation processes, the internal generic process flow, and the function elements are illustrated in Figure 35.

![Figure 35: Identification of function elements to be implemented by the platform. Left part: Identification of the internal generic process flow based on analysis of the different transformation processes of producing the specified semi-manufactures. Right part: Identification of the process and support elements which together constitute the function elements of the cell level platform.](image)

**Station and machine/tool level process identification**

The conducted identification of station and machine/tool level generic process(es) and function elements follows the above described development process of the cell level. Though, deviations occur regarding the
resulting number of generic processes and the type of elements included as function elements. As an example, the handling system results in six generic processes, where three of them are related to one gripper concept and the remaining three processes are related to another, see Figure 36. These six handling processes should be implemented in the cell controller as generic algorithms for conduction of the handling task, see Grey Box 1.

![Figure 36: Identification of the generic handling flows and their related generic handling elements.](image)

The steps of these handling processes are constituted by handling elements identified across the six generic handling processes. These processes were defined in a process similar to the above described cell level function elements identification process.

### 5.3.2.4 Search Technical Solutions

A precondition for defining the most suitable transformation process(es), function elements, generating concepts, etc. is to know the possible technical solutions of how to conduct the specified manufacturing task. If not already present, such technical familiarity should be established both in regard to technical possibilities, advantages, alternatives, limitations, requirements, etc. Knowledge regarding technical solutions is not only useful as inspiration for the concept generation, process development etc., but also as a proof-of-concept (e.g. something similar is already made or tried).

How to obtain such familiarity differs as the technical solution differs. Typically the requested information is, to a high extent, present as unformulated knowledge of experienced engineers, and should be formalized to create the needed overview. For the remaining issues and for new emerging technology, studies and experiments can be needed to create the offset for a MMS project. The search for technical solutions can be conducted within, or across, the subsystems, and can e.g. be a search for types and sizes of robots for automatic handling. Experiences from the study of technical solutions in the Grundfos case work are presented, together with the concept generation experiences, in Grey Box 6.

### 5.3.2.5 Concept Generation

This is the activity of generating concepts of how to conduct one or more of the identified functional elements. These concepts should both comply with the requirements of the functional elements, the remaining requirements of the scope, and be technical feasible. A manufacturing concept is perceived as an outline of the manufacturing setup and/or the operation principles of how to transform components, materials etc. into the resulting specified product or semi-manufacture. As indicated, manufacturing
concepts are a broad term covering principles of layout, component handling, logistic, processing, etc. Hence, the search and ideation of concepts should cover wide and include aspects such as mechanical, electrical, control, logistic, etc.

An offset for the concept generation can be found in concepts and ideas of the preceding technology development (for projects related to a new emerging technology) or in the earlier implemented systems (for projects related to already known manufacturing setup). Subsequently it is suggested to step backwards and broaden out the concept generation to involve aspects of all the manufacturing systems which should be covered by the architecture. In this process, it is advisable to take offset in the value creating functions (value creating process and handling elements), and define the different possibilities of how to conduct these. To constitute a functional manufacturing system, these concepts of value adding functions should be accompanied by support, control and safety concepts. These concepts should be related to, and generated based on, the remaining function elements (the non-value adding process and handling elements and the support elements).

This activity generally results in a multitude of different concepts of how to conduct the manufacturing task and its sub tasks. Modeling methods can be used to create an overview of the concepts and their relations to the function elements and the scope. In regard to this, it is found advisable to introduce a preliminary level structure. In other words, to define the main concepts, related subsystems concepts (station concepts), etc. Furthermore, preliminary function descriptions should be defined in accordance with the function element(s) implemented by the system/subsystem. Before continuing to the modularization and architecture development activity, it is furthermore advisable to evaluate the concepts and select the most promising ones. This to ensure only valid concepts are passed on and to limit the task and complexity in the subsequent process of transforming concept(s) into a modular architecture.

### Grey Box 6: Concept Generation and Study of Technical Solutions

The investigation of the technical solutions and the concept generation of the conducted case work took its offset in the ideas and concepts generated during the preceding technology development. Based on these, and some additional initial generated concepts, an initial high level cell structure was defined and a function description of its subsystems was made (initial versions). This is illustrated in Figure 37.

![Cell Structure Diagram](image)

**Figure 37:** The overall cell structure including main subsystems (stations) including related function description.

The initial cell structure formed an offset for searching technical solutions and generating additional concepts. Furthermore, concepts were generated based on the function elements. This was experienced to add new perspectives to technical solutions and concepts, and hereby to result in new/changed concepts especially regarding the non-value adding support systems such as feeding and handling. Knowledge of the
technical solution was actively used throughout the concept generation, both as inspiration for new concepts and as a quick proof-of-concept.

As the work was conducted, the concept information was modeled in a PFMP model in an on-going process. The modeling was experienced to create a structured overview, to relate concepts to the scope and function elements, and to create a preliminary idea of the leveling structure. Furthermore, the overview was experienced to form a source of inspiration for new ideas both regarding concepts, function elements, and the scope. The generated concepts spanned wide and covered both layout sketches, handling strategies, feeding ideas, etc. Illustrative examples of concepts at cell, station, and machine/tool level can be seen in Figure 38.

<table>
<thead>
<tr>
<th>Basic Setup Concepts</th>
<th>Logistic Concepts</th>
<th>Handling Concepts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manual setup</td>
<td>6 AXI ROBOT</td>
<td>Manual 6 axle robots</td>
</tr>
<tr>
<td>IM machine</td>
<td>Single IM Machine</td>
<td>Single Gripping platform</td>
</tr>
<tr>
<td>Feeding</td>
<td>IM machine</td>
<td>Multi Gripping platform</td>
</tr>
<tr>
<td>Portal Robot</td>
<td>Feeding</td>
<td>Tool changer</td>
</tr>
<tr>
<td>Multi IM Machines</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Figure 38: Examples of concepts at cell, station, and machine/tool level.](image)

An attempt to select among, and to validate, the concepts before proceeding to the modularization and platform development was made. This was done to reduce complexity of this activity and to ensure that only valid concepts, with a likelihood of being realized, were carried on. The conducted concept evaluation, and the related estimates, was mainly related to station and machine/tool level concepts and the results were subsequently used in the cell level concept. In regard to this, the maturity state of the technology was found to limit the ability to estimate on certain crucial aspects, e.g. cycle time of the value adding operation. This induced a limited ability to estimate on related and higher level systems and hereby a limited fundament for rejecting concepts. This was experienced to imply that the conducted attempt to select only had a limited elimination effect.

A modified Gantt-chart of the handling system is one example of concept estimation and validation at station level. Such Gantt-charts were conducted for all main handling concepts to establish an overview of the handling flow, implications to the related stations, and to estimate bottlenecks. Furthermore, the Gantt-charts were used to estimate critical parameters such as the maximum number of mould machines to be served by the handling system. The Gantt-charts were conducted based on the related concepts (handling, feeding, etc.), the related handling process, and time estimates of the involved operations (e.g. pickup operation with a robot). An illustrative example can be seen in Figure 39.
5.3.2.6  Modular Architecture Design

The task of transforming the concepts into a modular architecture is a process of relating, grouping, selecting, and redesigning the concepts into a divided structure characterized by: Clear relations among the specified scope and the process and function elements, a one-to-one relationship between function elements and the division in groups/subsystems, and by well-defined interfaces among the groups/subsystems. As discussed in relation to the Adept Technology case work, see Paper 4 and section 3.2, modular theory and methods can be used to support this modularization and architecture development regarding ways to model the information, evaluate and iterate concepts, evaluate interfaces, etc.

As discussed in section 4.1.4 manufacturing modularity, and achievement of modular benefits, depends on the mappings between manufacturing requirements, transformation processes, function elements, organs/units, and their relation to the hardware, electrical, and software implementations. Transforming the concepts into a modular architecture requires overview of the listed issues and their internal relations. It is found that a multitude of methods can be used, and/or combined, to support this transformation, e.g. Design Structure Matrix, PFMP, Generic Organ Diagrams, and Combination Tables. Such analyses and modeling should be conducted in an iterative process where they form input to one another. The methods should, if needed, be modified according to the requirements and preconditions of the specific project.

In the modularization and architecture development, the scope and related functional elements are used actively to define and evaluate the modular structure. Obtaining a robust scope and clearly defined function elements is therefore advisable before large time investments in modularization and architecture development to ensure an effective work process and a stable architecture. Besides the role in MMS architecture development, the scope is crucial to define configuration rules of how to combine modules into a manufacturing system based on a set of customer requirements.

Grey Box 7: Modularization and Architecture Development

A number of analyses and modeling methods have been utilized to transform the concepts into a modular architecture. Figure 40 illustrates the relation among the applied methods (both of the previous and of this activity) and how the methods have been used to create overview of, or relating, the scope, process, function elements, unit/organisms, and implementation. The methods of the modularization and architecture
development activity are described below, this separately due to readability. It should be noted that the transformation of concepts into modular platforms are conducted in a top-down approach (cell level first, then station level, and finally machine/tool level platforms) and that the below described methods in practice are used concurrently as input for one another in an iterative process.

![Diagram](image)

**Figure 40:** Overview of the applied methods and how they are used to create modular relations among the manufacturing requirements, transformation process, function elements, units/organs, and the practical implementation.


To understand and create an overview of the process/function-elements relations, processes were mapped against function elements in a modified Design Structure Matrix (process DSM). In the process DSM, the sub-processes of the manufacturing platform were listed instead of product components in the order they occurred in the production process. Relations were identified and market in terms of strong relation (X), weak relations (/), timing/control relation (T), and gripper commonality (G), see Figure 41. The process DSM emphasized the interactions and interfaces. A search among these clearly reviled four out of five of the cell level subsystems. The fifth subsystem, the handling system, showed three individual sub-tasks with clear relations regarding timing, equipment (gripper), and the type of task to be conducted. Based on these commonalities, the three tasks were grouped and treated as one subsystem with three individual processes/jobs to be conducted.
Combination Table of Process/Subsystem (Process <-> Organ)
A combination table relating potential subsystems and the internal generic process flow was constructed to expose their relations. This was done by listing the generic process flow horizontally, the subsystems vertically, and then mark the relations among them, see Figure 42. An extra row was added at the bottom of the table and was used to list relations between subsystems of process steps which were related to more than one subsystem.

Solution Design Structure Matrix (Solution DSM) (Technical Solutions <-> Organs)
To group the technical solutions of the generated concepts into possible modules, a Design Structure Matrix analysis was conducted. The analysis followed the principle illustrated in Figure 41 but instead of process steps the technical solutions and their components were listed in the horizontal and vertical directions (in same order). Subsequently, relations were market in terms of physical (P), control/logic (C), and signal/electrical (S). This solution DSM emphasizes commonalities between components (and technical solutions) which provides a basis for identifying groups with a high degree of interrelations and, hereby, potential to form a module.

Combination Table of Potential Modules/Function Elements (Function Elements <-> Organs)
A combination table between the function elements (the result of the process DSM) and the potential modules (the result of the solution DSM) was constructed to relate the potential modules to the functions
elements and hereby the scope. The combination table emphasizes potential modules of the same or similar functions. The need of more variants (modules) to conduct a function was subsequently evaluated based on the scope, possible realizations, etc.

![Figure 43: Combination table emphasizing potential modules with similar functionality by relating findings of the process and component DSM.](image)

**Engineering View PFMP (Overview of Functions and Organs)**

As a part of the on-going development process, a PFMP model was initially developed and subsequently updated. This was done to create and maintain an overview. The PFMP model was conducted (not graphical as the scope/customer view PFMP) and linked to the scope by use of enclosed combination tables, rules, and comments. Based on the overview generated by this PFMP, potential modules were identified from the mapping relations and from the known reasons to form a module (the modular drivers, see section 4.1.4.).

**Overview Table (Organ)**

The identified module candidates and variants of these were drawn in an overview table as the one illustrated in Figure 44. Such tables were added to the documentation of all platforms concepts to illustrate the included modules and the valid module variants within the concept. For instance, if a table was related to a concept of a vertical injection moulding cell, only the vertical injection moulding subsystem option would be market.

![Figure 44: Overview table of the cell level subsystems and variants of these.](image)

**Generic Organ Diagram and Interface Tables (Organ)**

Interface diagrams were drawn to analyze and to create an overview of the interfaces. This was done by means of Generic Organ Diagrams which show the organs of the platform, its variants, and their interfaces
– see Figure 45. Toward the finalization of the platform, interface tables were added to the Generic Organ Diagram. The Generic Organ Diagrams of the station level platform and related machine/tool level platforms were generally drawn together in one diagram.

Module Library (Overview of Modules/Organs)
Toward the platform finalization, a module library was established. This library listed all variants related to the modules of the platform. These were listed in terms of a principle sketch, function description, module relations, and their advantages and disadvantages, see Figure 46.

Lookup Tables to Relate Conceptual Aspects (Organs and Station Level)
A lookup table has been utilized at station level to related conceptual aspects within or across the stations. An example can be seen in Figure 47 which, based on similarities in the system setup, relates concepts of how to conduct the different handling elements (pick & load components, unload, components, and reload
components). Furthermore, the table divides concepts based on overall job and system type (single multi component feeding and single/multi cavity mould systems). These relations are essential to the subsequent system configuration, e.g. selecting handling elements which can be conducted in immediate continuation of each other without changeovers (shift of grippers, etc.).

Figure 47: Example of a lookup table which relates handling elements to their associated system setup parameters.

5.3.2.7 Phase 3: Documenting the Architecture

An architecture has to be documented to insure the intended use and according to maintenance and future development of the architecture. It is found that documentation of a modular manufacturing architecture should include 1) overview of overall functionalities, main systems, and relations to higher level manufacturing systems, 2) the architecture scope, 3) the internal generic process flow(s) and function elements, 4) the selected concepts, 5) internal and external interfaces, 6) a module library, and 7) rules of configuration. A set of documents with descriptions, illustrations, diagrams etc. is one way to conduct the documentation. In Table 6 the seven categories of documentation are described and related to the purpose of the documentation. As it occurs from the table, the three use cases of an architecture (module design, system configuration, and design for manufacturing) require different information and hereby utilize different parts and aspects of the seven documentation categories. The documentation requirements and the relation to the documentation categories of the three use cases are elaborated separately in the following subsections. An example from the case work is presented in Grey Box 8.

Use Case 1: Module Design – It is likely that differences occur between the people involved in the MMS architecture development and the people who design its individual modules. To design modules, the following architecture information is needed regarding the modules: Functionality, overall principles, interfaces, etc. Thus, this information should be included in the interface and component library information. Furthermore, design work generally requires understanding of the intended use, concepts etc. This information should be found in the documentation categories: Overview, function elements, and concept information. In addition, design information should potentially be obtained from the specific projects of which the module should be a part of (project-based strategy, see section 4.2).
Table 6: Architecture documentation categories including their relation to use case/purpose.

<table>
<thead>
<tr>
<th>Description</th>
<th>Maintenance/ future devel.</th>
<th>Module design</th>
<th>DFM</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Overview</td>
<td>X</td>
<td>X</td>
<td>(x)</td>
<td>(x)</td>
</tr>
<tr>
<td>A documentation of the scope</td>
<td>X</td>
<td>X</td>
<td>(X)</td>
<td></td>
</tr>
<tr>
<td>The internal generic process(es), the associated process and handling elements, and the remaining function elements (support elements)</td>
<td>X</td>
<td>(x)</td>
<td>(x)</td>
<td></td>
</tr>
<tr>
<td>List/sketch/description of the selected concept(s)</td>
<td>X</td>
<td>(x)</td>
<td>(x)</td>
<td></td>
</tr>
<tr>
<td>Interface diagrams and interface tables – both internal and external</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>List of all cells/subsystems/modules/parts including advantages, concerns, and other relevant notes</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>How to put a production line, cell, station, or machine/tool together based on the architecture</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Use Case 2: Manufacturing System Configuration – Development of manufacturing systems based on architecture is a configuration task of defining the combination of modules which constitute the best match to the requirements of the specific case. To conduct such configurations, knowledge is required regarding the modules’ combinatorial abilities and their relation to the elements and parameters of the scope. This information should be included in the configuration documentation. It should be noted that it is likely that a subsequent task of designing one or more custom modules will follow the configuration process, e.g. designing the fingers of a robot gripper.

Use Case 3: Product Design for Manufacturing – Companies’ future products should, in order to take advantage of the MMS benefits, be developed to fall within the scope of the manufacturing architecture. The overview and scope documentation contains information of possibilities and limitations of the architecture and forms, hereby, guidelines to be used in Design For Manufacturing (DFM). To increase the possibilities of DFM product design, guidelines can be included in the scope or defined as a supplementary source of information.

Grey Box 8: Platform Documentation
In the conducted case work, the documentation follows the suggested structure and is conducted by a set of graphical platform documents. The included platforms use the scope documents discussed in Grey Box 4. For the remaining categories of documentation, a set of platform documents are worked out for the cell and station level platforms. Due to some incompleteness in the machine/tool level, the platforms of this level are documented as a section within the respective station level documentation. An illustrative example of the cell level platform documentation can be seen in Figure 48.
1) Overview
Relation upwards and sideways, functional description, and black-box model

2) Platform scope
3) Internal generic process flow(s) and function elements

4) Concepts
5) Interfaces

6) Module library
7) Configuration rules
For use when designing a specific production line (should follow the manufacturing level structure)

Figure 48: Illustration example of the cell level platform documentation
5.3.3 The MMS Architecture Development Process

The activities of the reference framework are in practice highly interrelated and should not be conducted in completely separation of each other. An example can be seen in the scope definition of the Adept Technology case, where the scope tends to develop constantly. This not only as a function of increased market understanding and evolving requirements but also due to new application ideas and competitive advantages identified from understanding the involved technologies, processes, concepts, etc. Such changes course modifications and rework across the conducted architecture work and manifest itself in an unstable architecture (constantly changing) at the expense of the asserted MMS benefits. For further details see section 3.2 and Paper 4.

![Figure 49: The MMS architecture development process and its relation to the reference framework.](Image)

In an attempt to limit the number of time-costly iteration loops, a step-based development model for MMS architecture development is suggested. The model consists of 3 high level steps, see Figure 49. The initial step (concept sketch development) focuses on establishing a preliminary holistic overview of the scope, technologies, function elements, and concepts. This overview should include the relations among these aspects. The second step (modular architecture development) concerns refinement of the scope, function elements, knowledge of technical solutions, concept generation, and the modularization and architecture development. The last step (documentation) is documentation of the developed architecture to make it available for subsequent use and implementation. In spite of their iterative nature, these three steps are elaborated separately below.

- **Step 1: Concept Sketch Development** – The purpose of this step is to establish a preliminary overview early in the development process. This overview should include the architecture focus area, scope, function elements, technical solutions, and concepts generation; this including the relations among these aspects. The intent is not to develop a complete and in-deep overview, but rather to establish a draft or initial version covering basic ideas, capabilities, etc. In other words, the purpose is not to form the final architecture but to establish the general and holistic understanding needed for subsequent separate study of the involved aspects. The type of information and methods used are similar to the ones used later on and hereby the activities of the reference framework. It should be noted that the need, or extent, of this step is reduced for
experienced engineers with preceding insight to both technical and market aspects of the given manufacturing system.

- **Step 2: Modular Architecture Development** – This step covers a process of gradually developing and perfecting the architecture by an on-going process of analyzing, searching, developing, modifying, etc. The step takes its offset in the draft versions and knowledge generated in step 1 and conducts the in-depth information gathering, analysis, and design work of the reference framework’s *Analysis and Concept Generation* phase and the subsequent *Module Architecture Design* phase. In this process, attention is towards both the individual activities of the two phases and towards their interrelations. It is experienced that most of the development activities and decisions to be made are somehow related to the scope of the architecture. Hence, it is important to get the scope in place relative early in step 2. This is complicated by the opaque requirements of manufacturing which cause the scope to evolve as knowledge comes along. Experiences show that scope definition is a non-trivial task and that obtaining a robust scope requires broad consideration of both direct and indirect manufacturing requirements, see Chapter 3, Paper 2, and Paper 4.

- **Step 3: Documentation** – The final step is to document the developed architecture in accordance with phase 3 of the reference framework.

MMS architecture development should take its offset in the highest involved manufacturing level and gradually address the involved lower levels, see section 4.1.1. Development of the highest level architecture is experienced to include issues, ideas, and constrains related to details of the involved lower levels. Therefore, it is found advisable to include aspects of all related levels of manufacturing in step 1 and then subsequently tread manufacturing levels in a gradually more formal and hierarchical manner in step 2 and 3. This approach reduces the restrictions in the early activities of architecture development and hereby supports obtaining the holistic overview intended in step 1. Manufacturing leveling will gradually be introduced in step 2 in a top-down approach where the top level architecture is developed first and requirements of included lower level architectures defined from it. The documentation in step 3 should be strictly hieratical to ensure the intended use and to achieve modular benefits related to reuse of lower level architectures across higher level architectures, see discussion in section 4.1. Application of the step based development process model in the Grundfos case, including gradually introduction of manufacturing levels, is described in Grey Box 9.

**Grey Box 9: Use of the Process Model**

The Grundfos case has been conducted in accordance with the suggested three step development process model and the enclosed manufacturing levels (cell, station, and machine/tool) were treated in all three steps but in a gradually more formal and hierarchical manner. In the initial part of the case work, information was gathered and an analysis was conducted to create an overview of the platform scope, its related transformation processes and function elements, the technical solutions, existing concepts, and the interrelations among these aspects. To create the intended holistic overview, modeling methods such as PFMP were used. Use of such modeling methods was experienced to give rise to initial considerations regarding manufacturing levels.
Subsequent the creation of the initial holistic overview, a detailed analysis was conducted to determine the platform focus and how it should be included in the superior line level systems. Furthermore, a detailed analysis was conducted to define the scope of the platform, its internal generic process flows, and the function elements. Before initiating the modular architecture development activity, further effort was invested in generating concepts, searching and studying technical solutions, and in modeling the findings of these activities (including introduction of levels). The leveling was hereby introduced in advance of the modular architecture design activity. The modular architecture design activity was conducted in a top-down approach where the different platforms were addressed one at a time. The conducted documentation took its offset in a developed platform document format and was conducted strictly hierarchical. The methods used in step 1 and step 2 were the same or similar, but differentiated in the applied level of details and treatment of manufacturing levels.

5.4 Grundfos Case Conclusions
The development framework presented in Section 5.3 and its underlying presumptions of modular manufacturing architectures discussed in Chapter 4 has been utilized actively throughout the case work to guide and understand the development task and process, to select analysis and modeling methods, and to communicate on MMS. It is the experiences that the reference framework, and its phases, activities and related methods, constitutes useful guidelines of how to address, view, and understand the MMS architecture development task. Likewise, it is experienced beneficial to conduct the MMS architecture development according to the three steps of the suggested overall development process model and to introduce manufacturing levels gradually over these steps. In spite of a number of issues and challenges, it is found that the suggested development framework is applicable and valid regarding the treated levels of manufacturing. The experienced usability of the design framework and the issues and challenges discovered are further discussed in the following subsections.

5.4.1 The Specific Development Process
The applied specific development process can be summarized by the six steps below:

1) Define the system black-box (the function/job to be conducted, the manufacturing level, how these manufacturing systems are related and integrated into higher level manufacturing systems
2) Define the platform scope
3) Define the generic process flow(s) and the function elements (process-, handling-, and support elements)
4) Generate concepts including search/study of technical solutions
5) Modularization and platform development
6) Document the platform

This detailed development process has been applied in accordance with the overall development model of the framework. In other words, initial concept sketches were generated from a fast execution of step 1-4 followed by a thorough execution of step 1-6. This specific development process has been applied, and is found useful for development of both the cell level platform and its underlying station and machine/tool level platforms. This indicates generality of the defined process model and hereby a potential that this model can be transformed into a general model of MMS development. One such specific development process model possesses potential to reduce complexity in MMS development and is a subject for further
research. Throughout the case work it has been observed that ideas and possibilities are interrelated across the manufacturing levels. Hence, it is crucial that such a MMS development process model encourages the ideas of the suggested three step development model, see section 5.3.3. Lack of holistic understanding and an early introduction of levels will most likely influence architecture development negatively and/or lead to a high number of large iteration cycles.

5.4.2 Use of Analysis and Modeling Methods
The development of the modular platform has been supported by use of numerous analyzes and modeling methods, most of them are well known within MC and modular product development. The methods have been selected, modified, and applied based on the needs of this case work. Between the methods used throughout the case, clear repetitions and similarities can be seen. This indicates a potential to form a more formal and generic toolbox of methods for MMS development. These methods should, if possible, be related to the individual steps of the above discussed specific development process model of MMS development. This is likewise a subject of further study.

5.4.3 Time Consumption
In the conducted case work, attempts have been made to speed up the platform development. One of these attempts is the early establishment of a broad and holistic understanding (step one of the overall three step development process). It is the conviction that this has contributed positively to limit the numbers of large iteration cycles. Another positive contributing factor was the effort made to get the scope right early in the development process. The scope development was conducted in step one of the overall development process and subsequently finalized in the early part of step two. Thereafter, only few minor adjustments were made to the scope and this only directly related to new and important discoveries and hence to the stage of technology maturity.

Regardless of the time saving attempts, it is still the general impression that time consumption is a challenge. Thus, time consumption versus platform potentials (including number of manufacturing systems) is an issue to consider for all manufacturing architecture projects. The major time consumers of the case work are found to be:

- **Scope Definition:** The scope definition process is experienced to benefit, in regard to time consumption, from the increased understanding of manufacturing requirements and from the defined scope information categories (this compared with the previous experiences of scope definition from the Adept Technology case). In spite of these initiatives, scope definition is still time consuming and expected to possess further time saving potentials. One such potential is, as mentioned in Grey Box 4, a potential to formulate cooperate standards regarding general elements to be included in the MMS architecture scope, e.g. regarding operation conditions such as user interfaces. In addition to the time savings potential, such standards are expected to contribute positively to standardization and reuse.
- **Lack of Decisions** – As discussed in the section below, the limited technology familiarity implies a lack of decisions which manifest itself in a broad, general, and accommodating platform. This introduces unnecessary complexity which course an increase of the time consumption.
- **Graphical Format:** The utilized graphical representation of the scope, platform documents, and models are experienced to form a good offset for communication but also to be time consuming both regarding development and maintenance. This time consumption can be lowered if the initial
level of graphical details is reduced and/or if the need of extensive use of graphic supported communication is postponed. One way of doing so is to ensure a fundamental familiarity to the platform project and to the traditional modeling methods of modular design (e.g. like the general familiarity to UML in software development).

5.4.4 The Role of Technology Maturity Stage
Complications have been experienced regarding specification of elements directly related to the process technology and regarding quantification of both technical parameters and scope parameters. These complications can be related to a lack of technology familiarity (and hereby state of maturity) and regarding scope development to the time limitations of the case work as well.

It is experienced that concurrent technology and platform development results in uncertainty regarding technical capabilities and process parameters. According to platform development, this implies a lack of knowledge which complicates the platform development, particularly regarding decisions on critical aspects which depend on the low level details. The lack of knowledge and parameters of these lower level details hereby implies a lack of information regarding higher level platform decisions, quantification, and linkage between scope and platform (configuration rules). An example of such is the mould tool. The mould tool was treated as a black-box with only external interfaces and function description to compensate for the lack of technology clarification. For the station and cell level platforms this lack of knowledge implies, among others, high uncertainty regarding process times. Since the process time of the value adding process is critical information in manufacturing system development, this lack of knowledge was found to limit the ability to estimate on overall performance and hereby to select among concepts and possible modules. This has resulted in a platform which is broader and more embracing than needed. In other words, time and complexity of both development and subsequent use of the platform are radically increased which contradict achievement of MMS benefits. Furthermore, the lack of knowledge has limited the ability to link concepts of the platform to the production volume groups of the scope, and hereby the ability to define configuration rules. As this example indicates, the lack of specification and quantification is experienced to entail a time consuming and complex platform development process. Thus, in future projects it is advisable to postpone initiation of the platform projects to the needed technical familiarity is present.

An iteration of the developed platform is recommended when the required technical familiarity becomes present. This is needed to take full advantages of the intended module benefits and to limit the workload of platform implementation (design of modules, etc.). One such iteration should include qualification of parameters, selection on solutions, definition of configuration rules, etc.
6 Conclusions

The following chapter draws up the project conclusions and remarks on future work. The chapter is structured as follows:

1. Conclusion – This section relates and draws up the results of chapter 3, 4, and 5.
2. Summary of Contributions – This section summarizes the project contributions and relates them to the initial presented research problem.
3. Future Work – This section remarks on future work related to MMS architecture development and the related industrial realization of MMS.

6.1 Conclusion

Today, manufacturing systems are typically developed as engineer-to-order (ETO) solutions tailored to a predefined set of manufacturing conditions. This implies a limited reuse across manufacturing systems which limits volume benefits in fabrication of manufacturing system. Furthermore, such tailored manufacturing systems possess generally a low flexibility to change and hereby evolve with the company’s manufacturing requirements. Requirements of which the pace of change seams to increase constantly. Modular Manufacturing Systems (MMS) change manufacturing systems from ETO in the direction of configure-to-order. This change provides a fundament for achieving volume benefits and for enabling manufacturing changeability and responsiveness. In other words adding, removing, exchanging, and updating modules become possible. MMS literature focuses on aspects such as potential benefits, enabling technologies, and key characteristics. However, this project explores specific methods of how to develop MMS in industry, this with outset in modular product theory of Mass Customization (MC). This research has been supported by the following three research objectives:

1. Identify and explore the potential to use modular product theory and methods to understand, guide, and support MMS development
2. Modify the modular product theory to the domain of manufacturing
3. Propose a structured framework for MMS architecture development

On the basis of Papers 1-4, Chapter 3 addresses research objective 1 by both theoretical and practical exploration. The exploration shows usability of the MC based architecture approach to MMS development. Furthermore, it demonstrates that this approach leads to the desired modular benefits. An MC based approach to MMS entails development of an MMS architecture which defines and manages the module structures, interfaces, and modules. Manufacturing systems are designed from the architecture as a specific module combination (configuration) of modules. This configuration is to be defined in compliance with the specific requirements of the given project. The exploration shows that the achievement of the modular benefits is highly dependent on the applied modular structure and on robustness of the architecture scope from which it is developed. Obtaining a robust MMS architecture scope is found to be a complex task which requires broad involvement from surrounding stakeholders. The results shows that MC theory and method related to modularization, modular architecture, and product family modeling are useful to understand, guide, and support MMS architecture development. However, a number of additions and adjustments should be made to fit theory and methods to the domain of manufacturing. These
additions and adjustments relates to the four identified domain gaps: Design tradition (offset in ETO instead of well-known products), product type (mechatronic structure instead of hardware), increased product complexity, and the production volume of products/systems. These experiences show a need of increased understanding of manufacturing system architectures and modularity and of a structured framework for MMS development.

Chapter 4 addresses research objective 2 by suggesting an interpretation of architectures, modularity, and the development process which encompasses the experienced peculiar aspects of MMS. The suggested interpretation takes offset in the MC literature but presents the following additions and adjustments:

- **Compositional Structure:** Levels have proven useful to MMS architecture development. In relation to this it is found that manufacturing systems generally have a four level composition structure: Lines, cells, stations, and machine/tool. Manufacturing architectures can exist at all four levels and configurations of lower-level architectures can be used in one or more higher-level architectures. This implies that manufacturing architecture have a generic composition structure from which the composition structure of all valid enclosed specific manufacturing systems can be derived.

- **Composition Element Variants:** Classification can be used to describe variety of architectures composition elements. Likewise, this variety and the related classification is defined by the manufacturing architecture which imposes how these components are related to the compositional structure and how the components should be combined into manufacturing systems. For manufacturing architectures, three types of compositional elements exist: 1) No need of component variety exists, 2) the need of component variety can be covered by pre-defined variants, and 3) the need of variety can be covered by configurations of a lower level architecture. Furthermore, categorization of manufacturing system architectures is found to include at least two categories: “specific manufacturing system” and “manufacturing system family”.

- **Architectures vs. Platforms:** MC literature distinguishes between architectures and platforms. Likewise, this is of relevance for manufacturing, but the platform definition of manufacturing platform should be extended to encompass both existing and future standard designs. MMS architectures and MMS platforms are architectures and platforms which are characterized by modularity.

- **Manufacturing Modularity:** The well-known definition of modularity of a one-to-one relation among functional elements and physical units apply to manufacturing as well. However, this requires that physical units are interpreted as mechatronic units, including both hardware and software elements. The transformation processes of manufacturing systems are found to fall in between manufacturing requirements and the function elements of a manufacturing system. Regarding modularization, this implies a need to address the transformation process as part of the modularization process to ensure correct function element definition and hereby achievement of the modular benefits.

- **The Development Strategy:** A project-based development strategy is introduced as an alternative to the traditional front-loading development strategy of MC. In the project-based strategy, the architecture development and the module design are postponed to the stage of use. This strategy is introduced to compensate for the low production volume and the knowledge level of ETO but at the expense of full module benefits achievement. The strategy of a given MMS project should be selected as one of, or a combination of, the two strategies.
Chapter 5 answers research objective 3 by presenting a MMS architecture development framework. The framework takes its offset in a top-down development approach and consists of a reference framework of how to view MMS architecture development and of a process model of how to conduct MMS architecture development. The reference framework encompasses and relates the individual MMS development activities. In overall, these activities are grouped into three phases: Analysis and Concept Generation, Modular Architecture Design, and Architecture Documentation. The suggested development process model consists of three steps and is introduced to limit the number of time-costly iteration loops. Step 1 focuses on initial obtainment of a general and holistic understanding, while step 2 and 3 focus on the detailed architecture development and architecture documentation respectively.

The development framework is applied to an industrial case of cell level manufacturing platform development. In addition to its validation purpose, this case work is used to exemplify application of the suggested framework and its related use of methods. From the case work, positive results are generally reported regarding use of the framework, the underlying manufacturing architecture and modularity interpretation, and regarding use of MC methods to assist accomplishment of the framework activities. Furthermore, the case work served as a fundament to formulate a six step detailed MMS architecture development process and a need to formalize the used methods into a formal toolbox. Despite time saving initiatives, time consumption is still an issue in MMS architecture development. In regard to this, it should be noted that additional time saving potentials have been appointed. Furthermore, the case work illustrates the framework’s sensitivity to low manufacturing technology maturity which constitutes one of the preconditions for using the framework.

6.2 Summary of Contributions
The following list summarizes the project contributions and how they answer the research objectives:

1. **Research Objective 1** – MC theory and methods in terms of modularization, modular architectures, and product family modeling are useful in MMS development and guide toward achievement of the asserted MMS benefits. Achievement of these benefits is challenged by a complex process of identifying manufacturing requirements and by four identified domain gaps which limits direct usability of MC theory and methods within the domain of manufacturing. The practical exploration illustrates different ways to get around these gap-obstacles by mixing, adjusting, and supporting the MC methods. Furthermore, these experiences indicate a need of minor additions and adjustments of the architecture and modularity interpretation and a need of a structured framework for MMS architecture development.

2. **Research Objective 2** – Additions and adjustments to the general MC theory of product architectures and modularity are suggested to encompass the experienced peculiar aspects of the manufacturing domains. This includes the introduction of compositional levels, specification of compositional elements classification, manufacturing platform interpretation, introduction of project-based development strategy, and the identification of the role of manufacturing systems transformation processes in modularization.

3. **Research Objective 3** – A structured framework for MMS architecture development is suggested and validated by application in development of an industrial cell level manufacturing platform. The framework is developed with offset in the remaining findings and MC methods have been actively deployed in conduction of the specified framework activities.
6.3 Future work

The Grundfos case work reports time consumption as an issue related to MMS architecture development and hereby a potential threat regarding general use and industrial implementation of MMS. This conclusion is made regardless of the experienced time reducing effect of a number of initiatives of the framework. Additional time saving potentials have been appointed on the basis of the reported time consuming aspects of the case works. These are discussed in section 5.4.3 and should be further explored, preferable in combination with potential learning curve effects. Furthermore, the case work appoints general use of a common six step detailed development process model across the developed platforms at the different levels. This indicates a potential to formulate a general applicable detailed development process model and hereby a potential to simplify and reduce time consumption in MMS architecture development. In addition, the case work points at a potential to define a toolbox of methods for MMS architecture development and a related potential in linking these methods directly to the framework activities and/or to the steps of the above mentioned detailed development process model. In spite of the case work, further explorations on these potentials are needed regarding final adjustments, generalizations, and validation. It is the suggestion that this exploration includes validation cases with both “new technologies” and “well known manufacturing type” offsets.

Industrial realization of MMS requires more than MMS architecture development. The conducted empirical work has shown a number of such issues which need further exploration. One of these issues is how to integrate MMS and MMS development in the business processes of both machine builders, system integrators, and the manufacturing company. This requires both definition and standardization of work processes and implementation of IT systems in support of MMS architecture management and in support of the conduction of these business processes. Related to this, it is worth noticing the mechatronic structure of manufacturing which implies that the challenge of MMS modules consist both of mechanical, electrical, and software elements. These types of elements relate to different engineering professions and hereby different traditions, work processes, terms, IT systems, etc. The case experiences show a link between modular product and manufacturing architectures and a need to explore this link to take full benefits of the modular approach. Furthermore, MMS direct a question on how to price and calculate cost on projects and introduces a need of manufacturing system configuration. But how are manufacturing system configuration conducted and how can this be supported by a configuration system supporting both configuration of new systems and reconfiguration of existing ones? How to handle project specific design units and include system layout in a configuration system? And how to ensure selection of the most appropriated configuration (according to layout, performance, cost, etc.)?

New research in automation and robotics focuses on “skill” based programming. The main idea is to program by combining and configuring preprogramed basic software elements (skills) and hereby create a basis for high level programming of automation (e.g. drag and drop) and self-tuning and programming systems (for further details see (Bøgh, 2012)). This approach to programming possesses potentials which are related to the overall needs of manufacturing changeability and responsiveness. But how is the coherence between skill based programming and MMS architectures? And do skill based programming and MMS supplement each other in achievement of manufacturing changeability and responsiveness? This and related aspects are found to be subjects of future research.
7 Bibliography


Hansen Poul Henrik Kyvsgaard. Slids.


Scientific Papers
Paper 1

Paper 1 was initially presented at the MCPCE 2010 conference and subsequently published in a conference edition of International Journal of Industrial Engineering and Management. The references of the two papers are given below and the journal edition is enclosed on the following pages.

Reconfigurable Manufacturing Systems as an Application of Mass Customisation

Steffen N. Joergensen
Industrial Ph.D Fellow, InMoTx Europe, Fiskerihavnsgade 23, 9900 Frederikshavn, Denmark,
- and Department of Mechanical and Manufacturing Engineering, Aalborg University, Fibigerstræde 16, 9220 Aalborg East, Denmark, snj@m-tech.aau.dk

Kjeld Nielsen
Ph.D Fellow, Department of Mechanical and Manufacturing Engineering, Aalborg University, Fibigerstræde 16, 9220 Aalborg East, Denmark, kni@m-tech.aau.dk

Kaj A. Joergensen
Associate Professor, Department of Mechanical and Manufacturing Engineering, Aalborg University, Fibigerstræde 16, 9220 Aalborg East, Denmark, kaj@m-tech.aau.dk

Received (15.07.2010); Revised (26.09.2010); Accepted (02.10.2010)

Abstract
Manufacturing systems are today developed as engineer to order solutions tailored to producing a specific product or a limited product mix. Such dedicated systems are not consistent with market demands for rapid product changes, product variety, and customisation, which require flexibility and responsiveness of manufacturing systems. A Reconfigurable Manufacturing System (RMS) is aimed at possess such flexibility and responsiveness and is said to be the manufacturing paradigm of tomorrow. RMS is, though, not yet fully developed. A similarity between RMS and modular product families, known from Mass Customisation (MC), is seen and based on this similarity a potential to maturing RMS further by applying MC methods and techniques is identified. Based on literature surveys this paper analyses this potential by diagnosing gaps for RMS to succeed as a MC product. For each gab MC theory holds related methods and techniques, which indicates a potential and, hereby, an area of interest for further study.

Key words: Reconfigurable Manufacturing System, Configuration, Mass Customisation, Modular Product Architecture

1. INTRODUCTION
The globalised and increased competition on today’s market generally implies a need for rapid product change, high product variety, and customised products. As argued by [52] product variety initially increases sales but as variety keeps increasing the law of diminishing returns suggests, that the benefits do not keep pace. To counteract such an effect it is imperative to optimise external variety with respect to the internal complexity [49] which is a keystone of Mass Customisation (MC). MC aims at satisfying individual customer needs while taking advantage of mass production efficiency [38]. A key method of MC is modular product architectures/families, which has been recognised as an effective means to achieve economy of scale contemporary with increasing product variety [32] [48] and to increase reuse, reduce development risk and system complexity, and improve upgradability [43].

Regardless of MC the new demand of the market has increased manufacturing complexity and, hereby, a need of flexible and responsive manufacturing systems is emerged. In response Flexible Manufacturing Systems (FMS) evolved in the mid-nineties but due to complexity, low system output, and the high cost of general flexibility FMS fail to gain industrial acceptance [26] [44]. The trend today is towards Reconfigurable Manufacturing Systems (RMS) [44]. RMS is a modular manufacturing paradigm where manufacturing system components, controllers, machine tools, etc. is modularized [27] and the modules form a manufacturing family corresponding to the product families known in MC theory. A manufacturing system is developed as one particular module configuration tailored to the production needs of a company’s product assortment. The modular approach enables reconfiguration (change, add, and remove modules) in response to market changes and RMS is, therefore, aimed at holding the capacity needed when needed [30]. RMS is identified as first priority among six grand challenges for the future manufacturing in the ‘Visionary Manufacturing Challenges for 2020’ by the US National Research Council [7] and listed as one of the focus areas in European Commission Strategic Research Program for future competitive manufacturing in Europe [6].
The research effort on RMS is mainly focused on the principals of RMS and the RMS enabling technologies. This implies that aspects such as manufacturing family architecture, system configuration, etc. have received less or little attention. Based on the similarities of RMS and highly customised MC product it is the objective of this paper that RMS can be treated as a MC product and, herby, that MC methods and techniques can be applied on RMS in order to cover these areas. As a foundation for examine the objective, section 2 and 3 review MC and RMS respectively. Section 4 examines the objective by presenting the analysis, its results, and a discussion of the potential of applying MC methods and techniques. Finally section 5 draws up the conclusions.

2. MASS CUSTOMISATION - REVIEW

In order to differentiate markets in a highly competitive and segmented market, the concept of MC emerged in the late eighties and provided high variety and customised products at a reasonable low cost[38]. Hereby, MC is a response to an increasing market demand for product variety, product customisation, and a lowering of product lifecycle which destroy many mass production industries [17], [28], [2], and [39] through [45]. Several definitions on MC exist where a practical one is:

“A system using information technology, flexible processes, and organisational structures to deliver a wide range of products and services that meet specific needs of individual customers at a cost near that of mass-produced items [45].”

Based on a literature review [45] present six success factors of MC: 1) Customers’ demands for variety and customisation must exist, 2) market conditions must be appropriated, 3) the value chain should be ready, 4) technology must be available, 5) products should be customisable, and 6) knowledge must be shared. [45] further identifies a number of MC implementation enablers as the methods and technologies used to achieve the success factors. The enablers can be divided into three groups [45]:

• MC process and methodologies: Agility of manufacturing, organisational coordination, customer driven design/manufacturing process, customer value definition, waste reduction, etc.
• MC enabling technologies: Advanced manufacturing technology (flexible manufacturing systems, CNC machines, CAD/Cam systems, etc) communication, and information technology
• Information translator: An efficient customer-manufacturer communication link for information transfer

The customer involvement can be incorporated at many stages in the value chain, which is treated by several authors such as [14] and [29]. Based on [39],[14], [29], and [46] Silveira et al. [45] introduce eight levels of customisation formulated from a manufacturing point of view (divided by the product decoupling point). The eight levels are [45]:

1. Standardisation: Standard products without any customisation/variation, pure standardisation [29]
2. Usage: Products can be adapted to different functions/situations in the use stages
3. Package and distribution: Fitting of products to a market segment by individual packaging
4. Additional services: Customisation of the service around a standard product
5. Additional custom work: Customised by adding additional work to a standard product in the sales situation
6. Assembly: Modules are assembled into custom products
7. Fabrication: Customer tailored products based on basic predefined designs
8. Design: Individual engineered to order products

The modular approach of RMS corresponds to a customisation level of 6 or level 7 if predefined parts need to be tailored. The remaining review is, therefore, preliminarily focused on methods related to these high customisation levels. From the list above it should be noted that a high level of customisation requires customer involvement in an early stage of the value chain. This is traditionally associated with high product cost. A means to achieve successful MC implementation is modular product design combined with postponement of product differentiation [4] and [38]. This is supported by[15] who argues that part standardisation and modularisation in form of modular product architectures is a means to achieve a high customisation level in a cost effective manner.

2.1 Modular Product Architectures

Ulrich and Eppinger [51] define product architectures as:

“The scheme by which the functional elements of the product are arranged into physical chunks and by which the chunks interact.”

Functional elements can be defined as “the individual operations and transformations contributing to the performance” and the chunks as “building blocks consisting of a collection of physical elements (parts, components and subassembly which implements the product functions) which together implement the function of the product” [51].

Based on the mapping relation between functional elements and chunks/physical elements product architectures can be more or less modular. At the one extreme modular architecture consist of “one-to-one” mappings and at the other extreme integral architectures consist of complex (many-to-one or one-to-many) mappings [51]. In the theory of domains [3] a generic description of a product design is gradual determinate by four domains: Process, function, organ, and parts. By introducing the organ domain in between the function and the part/physical domain the theory of domain varies the modularisation discussion process.

A direct mapping (modularity) makes it easy to customise a product by tailoring the module combination or by changing, adding, and removing modules of predefined products. The variety between
products developed by modular product architectures is created in the assembly structure of standard modules (modules which can be reused in and across product families). Hereby, it becomes possible to achieve volume in the module production and, thereby, delivering variety and at the same time obtaining economy of scale. Modular product architectures are, furthermore, aimed at increasing reuse, reducing development risk and system complexity, and improving upgradability [43].

2.1.1 Modularisation

Architecture modularity (or product modularity) is a relative property and is often stated in regard to a comparative architecture/product [51]. As stated above, modular structures are characterised by a “one-to-one” mapping between functional elements and physical elements/chunks. Another characteristic of modular structures is a well defined interaction between chunks/modules (interfaces), interactions which in general are fundamental to the primary functionality of the products [51]. This implies that modules are identified so interactions between modules are minimal but can be high within modules [50].

![Figure 1: Slot, bus, and sectional architectures [51]](image)

According to [51] modular architectures can be divided into three categories: Slot-, Bus-, and Sectional architecture, see Figure 1. [33] takes the classification further and relates each class to the life phase which benefits the most. It is, hereby, possible to relate the modularisation approach to the point of customer involvement. [12] and [11] express the various reasons for modularisation in a set of modular drivers: Carry over, technology evolution, planned product changes, technical specification, style, common unit, process and/or organisation re-use, separate testing, supplier offers black-box, service and maintenance, upgrading, and recycle.

2.1.2 Product architecture

Modular product architectures can be seen as a tool to develop, maintain, and manage the product assortment and, hereby, obtaining product variety in a cost effective manner. A comprehensive work on architectures is to be found in [15] who defines architectures as: “An architecture is a structural description of a product assortment, a product family, or a product. The architecture is constituted by standard designs and/or design units. The architecture includes interfaces among units and interfaces with the surroundings”.

Harlou [15] distinguishes between architectures and platforms, where a platform is a subset of an architecture including only existing standard designs and their interfaces. As stated in the definition, an architecture (or platform) can be on assortment, family, and product level as shown in Figure 2. Architectures include both design units and standard designs where design units are: “the function, organ, part, or an encapsulation of a group of these. A design unit together constitutes a product” [35] through [15], and standard designs are: “design units which complies with one or more product family and the rules of re-use, documentation, and responsibility” [15]. From the above stated definition and from the architecture approach it should be noticed, that in a modular architecture based development, the standardisation, reuse, etc. are performed at part level and not only at the higher module levels. According to [15] this approach is proven effective in industrial cases regarding R&D resources reduction, reuse of solutions, knowledge, lead time reduction, etc.

Sanchez [41] introduces process architectures which decompose the functionalities of a process into specific functions and functional activities. Related to process architectures [41] states the importance of aligning
product and process architectures in order to harvest the benefit of architectures. In [42] knowledge architectures are added as a third architecture. The importance of a holistic view of architecture is supported by [19] who presents a holistic decision framework of product family design and development inspired by the Concept of Design [47]. The framework consists of customer-, functional-, physical-, process-, and logistics-domains and a product portfolio, product-, process-, and supply-platform to assist the domain transformation between these domains respectively, see Figure 3.

**Figure 3:** Holistic design framework covering the value chain [19]

Related to manufacturing [19] outlines the need for firms to adapt, integrate, and reconfigure more sufficient, the need of information technologies, concurrent engineering, and methodologies to describing and sharing capabilities. [19] is further outlining an expectation for further research on “building up rigorous frameworks of reconfigurable process and process platforms, integrated management for product and process families, coordination of product and process variety, etc.” [19].

### 2.1.3 Developing modular product architectures

Modularisation and development of modular product architectures are widely described in the literature. A consensus concerning the importance of a “customer need focus” in the development phase seems to appear. Several methods with various focuses exist. One general accepted method for modularisation of a structure is the Design Structure Matrix (DSM). In order to identify structures with limited interaction, which can be encapsulated into modules, DSM examines interfaces and interactions among system components. Modular Function Deployment (MFD) [12] is a method to identifying modules in a given product and consists of five linked tools:

1. Clarify customer requirements
2. Select technical solutions
3. Generate concepts
4. Evaluate concepts
5. Improve each module

Design for Variety [10] is a domain oriented approach for modular design, where the relation between the functional, technological (organ), and physical domain must be understood and for each domain a product model must be developed and standard interfaces defined. Design for variety is closely related to Theory of Domains [15]. [53] and [1] suggest a method to identify reusable modules across product families by use of function structures (mapping of energy, material, and information connections of sub functions). A method to design product platforms regarding market segments is the Power Tower [31] and the four related methods of mapping a platform to segments (niche specific platforms, vertical platform scaling, horizontal platform scaling, and beachhead strategy). On a strategic level a number of authors [14], [29], etc. stress the importance of selecting the right point of customer involvement in order to meet the market demand. In relation to this the design rule of postponing the product decoupling point must be taken into account.

### 2.2 Developing products based on product families

From a modular product family a product can be derived as one specific module combination. Such a combination is called a product configuration and the design process of combining modules into one specific product is called a product configuration process. The customisation approach of MC entails customised configuration, which have to fulfill a set of customer needs. In order to achieve MC the configuration process of each individual customer product and the following generation of documents, production basis, etc. has to be simple and fast, and preferably automatic. This requires formalisation and representation of knowledge related to the entire value chain such as design, manufacturing, and supply chain knowledge. A cornerstone of MC is, therefore, to formalise knowledge and representing knowledge in a useful way [40]. One such representation is a model (such as product and process models) which applies the formalised knowledge in order to transform information inputs into useful outputs. Models are, therefore, crucial for achieving MC and the ability to formalise and modelling knowledge can be a limiting part of a platform and, hereby, the architecture. In order to handle, generate, and distribute information, MC solutions often include an information network as a part of the architecture. This is supported by [40] who argue that a successful implementation of MC must integrate all information flows in a so-called Information Cycle of Mass Customisation and by the MC success factor no. 6 - Knowledge Must be Shared [45].

#### 2.2.1 Product models and configuration

A product family usually includes a large number of possible products, which are not feasible to treat as individual product variants. Instead it is suitable to treat the product family as a whole and derive the particular product as an instance/configuration of the product family. In order to do so, a model of the product family, its components, modules, etc. is needed. Such a model is called a product family model, which describes the product family and all its possible products. The result of a configuration is according to [36] and [22] a model...
of the configured product (product model) from which the physical product can be produced. To secure that only legal configurations can be configured a product family model should include "restrictions about what is feasible and not feasible" [22]. [15] argues that the following four aspects are essential for modelling an architecture (and, hereby, modelling product families):

1. Organ structures: Structure and variety of a product families organs, where organs refer to the organ domain in theory of domains [3]
2. Organ interfaces: Overview or interfaces among organs
3. Visualise variety: Overview of variety from a commercial, functional, and physical point of view
4. Linking variety: Description of how commercial, functional, and physical variety are related

Furthermore, [15] emphasises the essential of gaining an overview of a company's product assortment, describing the structure of the product family, and the variety within the product family.

It is important to distinguish product family models from the product configurator. The product configurator is a software system supporting the product configuration process. A product configurator is based on the product family model and can be rule-based or constraint-based. A rule based configurator is sequential (predefined order of parameter specification) and use predefined rules (if-then logic) to determine the actual solution span whereas constraint-based systems directly derive consequences of a choice and is, hereby, random-sequential [24].

Product family modelling has been treated in the literature by several authors and a number of methods exist. [20] and [8] describe a product family by three views: Functional, technical, and structural. The functional and technical views describe the customer's functional requirements and the design parameters respectively. The structural view represents the mapping between the functional and technical view as well as describing the configuration rules. Product Family Master Plan (PFMP) [16] and [34] is a pragmatic method, which according to [15] has its origin in the object-oriented paradigm [5], system modelling (system theory, [25]), theory of technical systems [18], and theory of domains [3]. The PFMP describes a product family from the customer, engineering, and part view. The modelling formalism of PFMP consists of three types of elements (classes, attributes, and constrains) and two types of structures ("part-of" and "kind-of"). Another common modelling formalism is Object Oriented Modelling [13], often performed by use of Unified Modelling Language (UML). Object oriented modelling was originally developed for software modelling and the formalism consists of four key elements (objects, classes, attributes, and instances), which can be related to each other by generalisation connections, specialisation connections, and whole-part connections. By use of the object oriented UML modelling approach [36] and [23] presents a multiple abstraction level modelling approach supporting the business process of Engineer to Order (ETO) products. The Generic Organ Diagrams [15] is modelling architectures from a functional point of view by a block diagram of the organs and organ interfaces of a product assortment or family. A block in an organ diagram can represent an organ or a group of organs [15] and the interface among the organs is market with interface types, which according to [37] can be divided into four interface types (spatial, energy, information, and materials).

According to [21] most existing product family modelling methods focus on modelling the solution space (attributes of the product and product structure) of a configuration process and do not include important information related to the product value chain.

3. RECONFIGURABLE MANUFACTURING SYSTEMS

Since the time of industrialisation, manufacturing systems is traditionally developed as Dedicated Manufacturing Lines (DML). In order to produce the products at a high volume in a cost effective manner, DML is developed as a dedicated/ fixed system around one specific product. DMLs are cost effective as long as demand exceeds supply and they can operate at their full capacity [27].

As introduced FMS was evolved in the mid-eighties as a response to the new markets demand for flexible and responsive manufacturing systems. FMS consists of general purpose CNC machines and other programmable automations [26], often operating in parallel. FMS aims to hold such flexibility but has never been widely adopted due to low system output [26], high complexity [44], and a high cost of general flexibility, which in most implementations only partly are used [30] [26].

RMS was introduced in the mid nineties and aims to be flexible, responsive, and less complex and costly compared to FMS [44] [27]. This also appears from the definition: "A Reconfigurable Manufacturing System (RMS) is designed at the outset for rapid change in structure, as well as in hardware and software components, in order to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or in regulatory requirements" [27]. The module based approach is essential for RMS and is enabled by the two RMS enabling technologies: Open-architecture modular controllers (reconfigurable controllers/software) and module machines/tools (reconfigurable hardware) [27].

RMS is based on modules, interfaces, etc. as known from modular product architectures and a manufacturing system is designed as a configuration of the modules. RMS configurations are like DML customised around the target product or product family in order to provide only the features and flexibility needed [26]. RMS, hereby, provides customised flexibility through scalability and reconfiguration instead of a general flexibility through equipment with a build in high functionality like FMS [30]. The key feature of RMS is that, unlike DMS and FMS, its capacity and
functionality are not fixed [30] [9]. [27] presents a number of key characteristics of RMS:
1. Modularity: All major components have to be modular
2. Integrability: Modules are designed with interfaces for component integration
3. Customisation: The system flexibility and the control is customisable for production of a product family
4. Convertibility: Systems need to be designed to shorten conversion/setup time between batches
5. Diagnosability: Easy to tune a system to produce good quality, etc.

RMS is designed at two levels: System level (machine interfaces, link to ERP, etc) and machine level (internal machine/tool modularity, interfaces, etc.). To ensure a high level of reconfiguration, both of these system levels have to be characterised by the key characteristics of RMS [26]. In regard to the reconfigurability [30] argues that "for a system to be reconfigurable these subsystems and their components must be designed to be reconfigurable at the outset" [30]. This is supported by [27].

RMS is aimed at being the manufacturing paradigm of MC [9] and high expectations of the potential of RMS are illustrated by the high priority of RMS in [7] and [6]. Until now the main focus of RMS has been on the principals of RMS, basic structures, enabling technologies, etc. while minor attention is put onto the architectural aspects and system configuration process, which mainly is treated as an engineer design task. When comparing the modular structure of RMS with a modular product family a structure similarity should be noted. A further similarity is the configuration approach where a product or a manufacturing system is developed, based on needs, as one particular module combination. In RMS these needs are the production demands of the company’s product assortment. Also in the purpose of applying the modular approach similarities can be seen. In both theories this approach is applied in order to create volume in manufacturing and to speed up product/manufacturing development and adjustment (add/shift/remove modules, option of parallel activities, and shorten run-in time due to module testing and easy debugging). Based on these similarities it is found relevant to analyse the opportunity of treating RMS as a MC product in order to adapt MC methods and techniques.

4. ANALYSIS AND RESULTS

In order to evaluate the opportunity for treating RMS as a MC product and, thereby, applying MC methods and techniques to RMS, a GAB analysis is performed to identify area of improvements for RMS to succeed as a MC product. The potential of applying MC methods and techniques is then identified by pinpointing the MC theory covering, for the gabs, comparable or partly comparable issue. The GAB analysis is performed by compare RMS and the MC success factors introduced by [45], see Table 1. From the evaluation of success factor 1 and 2 it appears, that the market demands customisation, but at the same time the market needs confidence before adapting a new technology like RMS. From the evaluation of the remaining factors, it should to be noted, that the tendencies are pointing towards RMS, but there are still a way to go. Overall the gabs related to these factors can be divided in three categories:

1. RMS technology development: In order to realise RMS, further RMS technology development is needed, both on system and machine level.
2. Platform/architectures: Standardisation and standards are needed regarding development of equipment, control algorithms, software, models, etc. This implies a need of various platforms such as development, information, configuration, ramp up (adjusting/diagnosing), supply chain, etc. In order to relate these platforms, a holistic development framework covering the entire value chain is needed. In relation to a market with many players, there is a need for standards to be open and shared in order to ensure acceptance and rapid development.
3. Modelling and knowledge formalisation: Models and modelling methods within a broad area such as product, process, self adjusting, and self diagnosing are needed. Easy modelling and model implementation are keys to gain acceptance, which demand easy to use standard methods with standard interfaces to the information network in the architecture. RMS is further challenging excising models such as forecasting, pricing, and returns of investment. This put forth a demand for such new models.

By comparing MC theory with the three categories of gabs, it appears that MC theory covers methods and techniques for comparable or partly comparable issues. These are modularisation, platforms/architectures, and product modelling respectively. In order to make a successful transferring of methods and techniques related to these areas, the scope of the methods and techniques must cover the new area of application. Consequently, the potential of applying these methods and techniques onto RMS is evaluated by conceptually hold their scope against the RMS requirements.

4.1 Adapting modularisation methods and techniques

An important issue in regard to RMS technology development is modularisation and interface standardisation where the Design Structure Matrix and Modular Function Deployment are found applicable in regard to the hardware components while usage on the software components of RMS is an object for further study.

4.2 Adapting architecture and platform methods and techniques

In category 2 a need of architecture and platforms covering the many aspects related to manufacturing appears. In order to define such platforms in a way which are relevant for the value chain and to relate
these platforms, it is found reasonable that inspiration of a framework can be found in the product development framework presented by [19]. The need of standardisation and standards requires the architecture to include design rules and standards for modules and their interfaces, control issues, simulation models, product model data, in/out-put information demands, etc. These designs rules and standards must ensure achievement of the RMS characteristics at both machine and system level. In a market with many players, such standards have to be easy to use and ensure that modules can be shared. A RMS architecture have to be applicable at several levels such as the global market of manufacturing machines, tools, and technology, on a company level, and on firm level. It is found likely that a distinction similar to [15] architecture/platforms distinction is suitable for treating such levels and a deviation similar to assortment, platform, and product [15] can be useful to distinguish firm, manufacturing lines, and specific manufacturing setup respectively. The separation in standard designs and design units [15] is further found applicable in order to include special designed modules in a particular architecture (e.g. a firm).

Table 1: Comparison of MC success factors and RMS in order to identify gabs of applying MC methods and techniques on the configuration/reconfiguration process of RMS.

<table>
<thead>
<tr>
<th>MC success factor</th>
<th>Current status</th>
<th>Needs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Customers’ demands for variety and customisation must exist</td>
<td>• Manufacturing systems/equipment is today an ETO market with a high level of customisation</td>
<td>• Marked acceptance of the “new” way of customise and the related increase in standardisation level</td>
</tr>
<tr>
<td>2) Market conditions must be appropriated</td>
<td>• High market demands for flexibility and responsiveness of manufacturing systems</td>
<td>• The concept of RMS and its probability for a business outcome must be industrial validated by pilot projects and case-studies</td>
</tr>
<tr>
<td></td>
<td>• Market requires a high degree of confidence and proven reliability, performance, quality, etc. before adapting new manufacturing solutions</td>
<td></td>
</tr>
<tr>
<td>3) Value chain should be ready</td>
<td>• Focus on corporative supply chain</td>
<td>• Introduction of RMS across the supply chain</td>
</tr>
<tr>
<td></td>
<td>• Supply chain structures need flexibility and responsiveness</td>
<td>• Extended supply platforms regarding information exchange, etc.</td>
</tr>
<tr>
<td></td>
<td>• No general model/platform combining the value chain like the holistic decision framework presented in [32]</td>
<td>• New models for corporation, pricing, forecasting, etc.</td>
</tr>
<tr>
<td></td>
<td>• The theory of RMS is still under development both regarding machine and system level technology, but the enabling technologies exist</td>
<td>• Development of a general holistic framework covering the entire value chain</td>
</tr>
<tr>
<td></td>
<td>• Limited amount of formalised knowledge which is needed for systems to be flexible and responsive (self adjusting algorithms, etc.)</td>
<td>• Further research on RMS on both system and machine level</td>
</tr>
<tr>
<td></td>
<td>• No general design rules or common standards</td>
<td>• Formalise knowledge and develop models for use in self adjustment and diagnosing algorithms on both machine and system level</td>
</tr>
<tr>
<td>4) Technology must be available</td>
<td>• Per definition the structure of RMS is customisable, but the customisation process is today an engineering process</td>
<td>• Development of standards and standard interfaces for tools, machines, support systems, etc.</td>
</tr>
<tr>
<td></td>
<td>• Individual system integrators, machine builders, software developers, etc. share little or no knowledge</td>
<td>• Easy to use development platforms stating design rules, standards, etc.</td>
</tr>
<tr>
<td></td>
<td>• PDM and PLM tendency put data collection and sharing on the agenda</td>
<td></td>
</tr>
<tr>
<td>5) Products should be customisable</td>
<td>• Product models and configuration systems supporting the needs of RMS</td>
<td>• Shared standards for virtual models, product family modelling information, control systems, signal exchange, etc.</td>
</tr>
<tr>
<td></td>
<td>• Shared standards for virtual models, product family modelling information, control systems, signal exchange, etc.</td>
<td></td>
</tr>
<tr>
<td>6) Knowledge must be shared</td>
<td>• Information structures and infrastructures in and across systems and companies</td>
<td></td>
</tr>
</tbody>
</table>
4.3 Adapting product family modelling methods and techniques

Communality in the product structure is found, which indicates a potential of transferring product family modelling methods and techniques such as PFMP and Object Oriented Modelling. It is found that most of today’s MC methods focus on hardware products, which limit them in regard to the software parts of RMS. Due to an origin in software modelling it is the expectation that Object Oriented Modelling can be expanded to cover both hardware and software. The different views presented in Theory of Domain can be useful to describe the many aspects of RMS. It is found likely that a multiple abstraction level approach like[36] and [23] can be used regarding the system/machine level approach. To generate a virtual manufacturing system, it must support optimisation of the needs of black/grey-box modelling of the enclosed modules and to introduce a multiple number of design stages in the configuration process.

Most likely RMS will be constantly modified; modules will be updated, etc. This calls for version control of the product family model and the enclosed modules and also for compatibility modelling, which is found to be a limitation of today’s modelling approaches. Another limitation of the modelling approach is to balance the many related aspects of a manufacturing system in order to find the trade-off which provides the best performance. To do so in a configuration system, it is found likely that a product family model and the configuration system must support optimisation techniques. This typically requires feedback to the optimisation algorithm, which most likely can be generated as the output of a virtual manufacturing simulation.

5. CONCLUSION

Based on reviews of Mass Customisation (MC) and Reconfigurable Manufacturing Systems (RMS), it appears that RMS hold great similarity to modular product families known from highly customisable MC products. Such products are developed as one particular configuration of a product family, which is the approach in both MC and RMS. RMS still hold research potential. A potential to take RMS further by applying MC methods and techniques is indicated by the similarities with MC. This objective is supported by the analysis, which results in the following three focus areas for product maturing of RMS as a highly customisable MC product:

1. RMS technology need to be further development
2. RMS platforms/architectures are needed
3. Modelling and knowledge formalisation is needed

A potential of applying MC methods and techniques occur for each of the areas as a similarity between the scope of methods and techniques and the requirements of RMS.

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Paper 2

Joergensen, S., N., Madsen, O., Nielsen, K., Jørgensen, K., A.; 2011 “DESIGN REQUIREMENTS FOR DESIGNING RESPONSIVE MODULAR MANUFACTURING SYSTEMS” 21st International Conference on Production Research; July 31 - August 4, 2011 in Stuttgart, Germany
DESIGN REQUIREMENTS FOR DESIGNING RESPONSIVE MODULAR MANUFACTURING SYSTEMS

Steffen Nordahl Joergensen, Ole Madsen, Kjeld Nielsen, & Kaj. A Jørgensen
Department of Mechanical and Manufacturing Engineering, Aalborg University,
Fibigerstræde 16, 9220 Aalborg East, Denmark

Abstract

Customers demand the newest technologies, newest designs, the ability to customise, high quality, and all this at a low cost. These are trends which challenge the traditional way of operating manufacturing companies, especially in regard to product development and manufacturing. Research and industrial work are conducted in this area and has resulted in a wide span of theories, models, and methods. Manufacturing companies are, regardless hereon, still facing these challenges, especially regarding their manufacturing systems. Several theories state that modular manufacturing concepts possess the needed flexibility and responsiveness, but such systems are not yet fully achieved. From related theory it is known that achieving modular benefits depend on the modular architecture; a modular architecture which must be developed according to the customer needs. This makes production needs a design requirement in order to achieve responsiveness and other benefits of modular manufacturing systems (MMS). Due to the complex and interrelated nature of a production system and its surroundings these production needs are complex to identify. This paper presents an analysis framework for identification of production needs related to a given marked situation. Furthermore, based on this framework this paper performs an analysis of the general production implication of the new dynamics marked conditions.

Keywords:
Modular Manufacturing, Reconfigurable Manufacturing Systems, Holonic Manufacturing Systems, Mass Customisation, Modular Product Architectures, Production Engineering, Modularisation

1 INTRODUCTION

Increased competition and globalisation implies new marked conditions where cost and quality moves towards order qualifiers and increased customer value become order winners. This has implied a marked segmentation and a high marked dynamic. In response to this, companies launch product assortments of high variety and decreased lifecycle (1). Several theories and initiatives focus on operating firms and taking advantages of these new marked conditions. But these conditions still challenge several firms (2), especially regarding their production, which must possess both flexibility and responsiveness (3). In response to this Modular Manufacturing Systems (MMS) in terms of Reconfigurable Manufacturing Systems (RMS) and Holonic Manufacturing Systems (HMS) is evolving. These are manufacturing concepts, where components, controllers, machine tools, etc. are modularized and manufacturing systems developed as one particular module configuration tailored a set of production needs. The ability to reconfigure the module combination (change, add, and remove modules) ensures responsiveness and such systems are, therefore, aimed to possess the capacity needed when needed (4). The research effort is mainly focused on basic principles and enabling technologies while manufacturing systems design has received less attention.

Based on a comparison (5) emphasise the similarities between the modular approach of Mass Customisation (MC) and RMS and indicate a potential of bringing RMS forward by applying related MC theories and methods such as Modular Product Architectures (MPA), Modularisation, and Configuration. It is well known in MC literature that achieving the modular benefits depends on the applied modular architecture; an architecture which must meet the customer needs in a way limiting the internal complexity (6). (7) Designing methods of MPA takes offset in the customer needs, which in regard to RMS makes production need a design requirement of MMS architectures. Production needs consist of directly given needs, like the processing needs of particular products, and indirect needs associated the complex relation between a manufacturing systems and its environment. Relations which are affected by the new marked conditions in terms of manufacturing constraints associated the initiatives on operating under and taking advantages of, the new marked conditions. These constrains are indirect and hard to identify but influence the production needs and, hereby, the needed responsiveness of MMS.

This paper presents an analysis framework for identification of the direct and indirect production needs associated a given marked situation and performs, based on this framework, an analysis of the general production implication of the new marked conditions. The framework, and its development, is outlined in chapter 2. Chapter 3 presents the analysis and its results. Chapter 4 discuss the application and further work before chapter 5 sums up the results.

2 DEVELOPING A DESIGN FRAMEWORK

Production development is a broad field with relations to both internal and external aspects of the company. In regard to this (8), (9), and (10) empathise the need for a holistic perspective when designing and operating production systems. Today this is generally accepted (11). In regard to MMS this indicates a need for a holistic view when defining the production needs of the new marked conditions. According to (12) a holistic perspective on manufacturing requires taking technical and physical parts, the humans in the system, and the way to organise the work into consideration. Applying a system perspective on production is a way to do so (11).

In a system perspective, production systems can be described as a transformation system (11). The major elements of a transformation system are a process, an operant, and the operators (13), and the goal is usually to transform the operant from an existing state to a desired future state. The transformation process is driven and guided by the operators in terms of the executing system (the human and the technical system) and the active
A production system depends on, and gets affected by, its environment and must, therefore, be modelled as an open system (11). Open systems have dynamic relations to their environment, which are important for a production system’s ability to adapt and respond on changes in the environment. In general three properties characterise an Open System (14): 1) The system is goal seeking and hierarchical, 2) it is holistic, and 3) the goals can be achieved in a number of ways.

In regard to MMS this entails knowledge of how the new marked conditions affect the production systems regarding their environments (active and passive), operands, and transformation/process becomes a prerequisite for designing the MMS execution system in a way ensuring the modular benefits. It is the objective that the needed knowledge of these production demands can be developed on a general level by inherit the marked conditions through the related theories and initiatives to which they are exposed during the process of product realisation. Here product realisation refers to “all activities necessary to develop solutions satisfying an identified customer need, and all those activities required to realise these solutions in terms of physical products with associated services” (15). In order to do so an analysis framework is constructed, see Figure 2. The framework contains the key actors of product realisation and their internal relations.

3 ANALYSIS

The framework must be populated with the theories, methods, and initiatives related to product realisation before the analysis can be conducted. In order to gain a better overview, this framework population and the analysis is divided into three steps. In the following the steps are examined stepwise. The three steps are:

- Implication on product development and downstream supply chain
- Implications on internal aspects and upstream supply chain
- Related production demands

The analysis focuses on selected initiatives and theories directly related to the new marked conditions.

3.1 Product development and downstream supply chain

Increased competition and globalisation has, as stated earlier, entailed a high marked dynamic - a marked where customers are more demanding and wants the newest, the smartest, the unique, and all this at a low cost and high quality (16). In response to this companies became marked oriented and focused increasingly on creating value for the customers. Due to more narrowed marked segments this has in general resulted in broader product assortment, increased variety, customisation, etc. (1). Broad product assortments must constantly be updated and renewed in response to new technologies, regulations, marked trends, etc. This entails time to marked and, hereby, the lead time of marked response to be increasingly significantly in order to achieving the potential market benefit.

Managing firms under, and taking advantages of, these new conditions has been the focus of several theories and industrial initiatives like Mass Customisation, Product Development, Modular Product Architecture, Innovation Strategies, etc.; initiatives which have affected most firms regarding their product structures, business strategies, ways of acting, etc. Table 1 provides an overview of the marked changes, the associated changes of business focus, and selected related theory, technologies, and initiatives.

The increased customer focus has entailed a need of rapid product change, high product variety, and customised products. A response to this is Mass Customisation (MC), which focuses on creating external variety with respect to the internal complexity and is aimed to satisfying individual customer needs while taking advantage of mass production efficiency (1). (17) define MC as “A system using information technology, flexible processes, and organisational structures to deliver a wide range of products and services that meet specific needs of individual customers at a cost near that of mass-produced items (17).” It, hereby, occurs that MC put demands on a company’s use of information technology, process, and organisation.
MC emphasises a closer customer relationship and has changed the focus from company activities towards what creates value for the customer. One example is product development, which to a higher extent has become user-driven. This places customer knowledge and understanding as a key competence of a company. In order to support closer customer relationships upfront, information systems, product configuration systems, and other IT-based communications systems have emerged. Based on a literature review (17) identify eight levels of customer involvement spanning from standard products to Engineering To Order products. In regard to the higher levels, modularisation has, in terms of MPA, been recognised as an effective means to achieve economy of scale contemporary with increasing product variety (18) (19) and as a means to increase reuse, reduce development risk and system complexity, and improve upgradability (20). This requires a modular architecture which complies with the customer needs in a way limiting the internal complexity. To design such an architecture require cross functional understanding and cooperation (6). The internal and external interfaces restrict design and development but conversely contain advantages regarding fast / parallel development, reduced complexity, module testing, outsourcing, etc.

Product development research has resulted in structured ways to perform and manage product development effectively. One example can be found in (21). Product development research has implied increased focus on the impact of which product development choices have on later stages in the product realisation (21). This has increased the focus on integrating product development and the remaining product realisation.

Companies to a larger extend externalise their product development in terms of cross company cooperation, joint ventures, acquisitions, etc. This occurs in response to the new marked conditions and increased product complexity (22). Such business concepts and innovation strategies are addressed in Open Innovation. Generally this has entailed companies to focus on a number of strategic selected key competences (22). To a larger extend such a collaborative business form requires communication and clearly defined interfaces among products, technologies, etc. This entails a need of well defined interfaces, documentation, standards, etc. These are all demands, which increase the need for well defined product architectures.

### Table 1: Product development and downstream effects and responses

<table>
<thead>
<tr>
<th>Marked changes</th>
<th>Business Focus</th>
<th>Theory, technologies, and initiatives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Customers want the newest, the unique, the personalised, and all this at a low cost and high quality</td>
<td>Set customers in focus</td>
<td>Business strategies</td>
</tr>
<tr>
<td></td>
<td>• Create value for the customer</td>
<td>• Mass customisation</td>
</tr>
<tr>
<td></td>
<td>• Create customer variety</td>
<td>• Open Innovation</td>
</tr>
<tr>
<td></td>
<td>• Product personalisation</td>
<td>• Blue ocean</td>
</tr>
<tr>
<td></td>
<td>• Customer relation information link</td>
<td></td>
</tr>
<tr>
<td>Time to market</td>
<td>Fast product development to respond quickly on competitors, new technologies, and regulations</td>
<td>Product Development</td>
</tr>
<tr>
<td></td>
<td>• Product structures</td>
<td>• Development methods</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• IT based support tools like CAD, PDM, etc.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Modularisation (upfront perspectives.)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Modular Product Architectures</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Configuration</td>
</tr>
<tr>
<td>New business models</td>
<td>Marked differentiation</td>
<td>Customer contact</td>
</tr>
<tr>
<td></td>
<td>Cooperation, joint venture, etc</td>
<td>• Sales supporting IT</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Communication technologies</td>
</tr>
</tbody>
</table>

#### 3.2 Internal aspects and upstream supply chain

The use of IT to support company activities like design, production, sourcing, sales, etc. is increasing and includes IT support tools ranging from advanced Computer Added Design Systems, documentation and report generation tools to custom data processing tools. The increased use of IT entails a high amount of data and a high data dependency. There are, therefore, focus on implementing information systems and building information networks for storing, distributing, and handling data, for control workflows, automating business process, etc. Examples of such systems are Enterprise Resource Planning (ERP), Product Data Management (PDM), Manufacturing Information System (MIS), Manufacturing Execution System (MES), etc. In order to support business processes the most, these systems should most likely be integrated into an information infrastructure.

The modular product structure maintains production volume on module level and represents a potential to limit the flexibility need of business and production processes associated to the increased variety. Furthermore, the modular product structure possesses a potential to lower the impacts of product changes. Achieving these benefits is dependent on the relation of the modular architecture and the internal aspects of the company. This relation should be designed in such a way, that it limits the internal complexity of delivering the needed variety (6) (7). This restricts the design of both the modular structure and the internal setup and requires cross functional understanding, coordination, and corporation. This put further demands onto the information infrastructure.

Awareness of the impact, which product design and development decisions have on a product’s production cost, has entailed development of Design for Manufacturing (DFM). The objective of DFM is to design products for easier production (23). DFM consists of a set of design guidelines and checklists of how to increase products’ manufacturability and is one of the methods within Design for X. Another initiative on integration is the decision framework of product family design and development presented by (24). This framework links the customer, functional, physical, process, and logistic domain, and, hereby, creates visibility of the consequences related to design decisions. In order to assist the domain transformation, the framework utilises a product portfolio, product, process, and supply platform respectively. These platforms can be established in terms of models, like for instance a process model describing the capacity and capability of the production setup.
The increased externalisation entails focus on supplier relations and building strategic alliances. In regard to this process the modular structure and well defined interfaces are, due to the opportunities of parallel development, function test at module level, etc., seen as an advantage. The external cooperation, outsourcing, focus on key competence, etc. have increased the focus on standards and documentation. Furthermore, it has increased the need for external data / information exchange and entailed a lowering in own fabrication. Hereby assembly becomes an increasingly part of a firm’s production setup. Several companies focus on streamlining and cost reduction in terms of LEAN, etc.; a focus which likewise has affected intercompany cooperation in regards to lead time on delivery, batch sizes, etc.

Fejl! Henvisningskilde ikke fundet. presents an overview of the changes of business conditions, related business focus and responses, and the associated theories, technologies, and initiatives associated to the internal and upstream aspects of the new marked conditions.

The findings of the analysis indicate that there is a complex relation between a production and its surrounding business setup, activities, strategies, etc. These relations are interconnected and the associated production needs should be defined in the intersection of related theories, initiatives, work areas, etc. The identified relations indicate the importance of including production needs associated manufacturing/business relations in the design specification of manufacturing systems. The relations are found to be dynamic and will most likely change rapidly.

### 3.3 Related Production Demands

The MMS system/architecture corresponds to the execution systems in a transformation systems; a system with relations to the remaining components of the transformation system. The production demands related to the discussed initiatives is, therefore, outlined in terms of the system environment and the operant and transformation process - see Table 3.

### 4 APPLICATIONS AND FURTHER WORK

The findings of the analysis indicate that there is a complex relation between a production and its surrounding business setup, activities, strategies, etc. These relations are interconnected and the associated production needs should be defined in the intersection of related theories, initiatives, work areas, etc. The identified relations indicate the importance of including production needs associated manufacturing/business relations in the design specification of manufacturing systems. The relations are found to be dynamic and will most likely change rapidly.

### Table 3: Main categories and responding production needs/effects

<table>
<thead>
<tr>
<th>Changed business conditions</th>
<th>Business focuses and response</th>
<th>Theory, technologies, and initiatives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased product variety and change rate, decreasing batch sizes and introduction of customized products</td>
<td>Information handling:</td>
<td>Information handling:</td>
</tr>
<tr>
<td></td>
<td>• Increased focus on documentation and standards</td>
<td>• Information systems (ERP, PDM, PLM)</td>
</tr>
<tr>
<td>The product structure has to a higher extend been modularized and product volume maintained on module level</td>
<td>Integrating functions</td>
<td>• System integration</td>
</tr>
<tr>
<td></td>
<td>• Third part involvement</td>
<td>• Design for X</td>
</tr>
<tr>
<td>Need for cross functional coordination, cooperation, and understanding has increased</td>
<td>• Establish close supplier relations and strategic alliances</td>
<td>• Outsourcing</td>
</tr>
<tr>
<td></td>
<td>• Increased focus on documentation and standards</td>
<td>• Increased focus on documentation and standards</td>
</tr>
<tr>
<td></td>
<td>• Third part involvement</td>
<td>(Lean production, 6-sigma)</td>
</tr>
<tr>
<td>Need for transparency on impacts of design choices</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Increased focus on documentation and standards</td>
<td></td>
</tr>
</tbody>
</table>
Overview design consequences
- DFMA and Decision Framework
- Module architecture design require knowledge on manufacturing
- Need for process platforms providing information on a manufacturing capability (processes properties, span, volume, etc.). Models which MMS must interface and populate with information on the MMS families.
- Need for cross functional understanding and production engineering involvement in product and modular architecture design, sourcing , etc.

<table>
<thead>
<tr>
<th>Operant &amp; transformation process</th>
<th>Modular product structure</th>
<th>Uncertainty regarding</th>
<th>Focus on lean production (internally)</th>
<th>Increased quality expectation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maintain volume at module level</td>
<td>Product assortment and lifetime</td>
<td></td>
<td>Need to produce high quality and to comply with associated regulations and standards for documentation</td>
</tr>
<tr>
<td></td>
<td>Limit impact of product changes, need for process flexibility, etc.</td>
<td>Production mix</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Volume on module level, increased reuse, reduced risk and complexity, etc.</td>
<td>Production volume</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Process often intended fabrication/assembly of a span of products which requires flexibility; a flexibility requirement which can be limited by organising the production according to the modular product structures</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Process flexibility to handle unique process demands, production routes etc. of customised products and small batch sizes</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>High focus on creating flow, reduce waist, limit stock, etc</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Demand for fast process changeover times</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Support Kanban pull production control</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Flexibility to uniform process times</td>
</tr>
</tbody>
</table>

according to new initiatives, theory evolutions, future changes in surroundings, new marked strategies, etc. Therefore, in order to ensure the needed responsiveness of MMS these requirements must not only be included in designing a particular manufacturing setup, but also in the architecture design.

The analysis framework represents a structured way to identify the direct and indirect production needs of a marked change or similar issues of interest. The list of findings in the analysis represents general production demands of the new marked conditions and the related initiatives included in the analysis. For the further work this list represents guidelines or a check list of issues to consider when identifying production needs of particular industries, business, and even for particular manufacturing jobs. The framework can be of relevance for analysing special issues of the particular case. The production needs will then serve as input to the modular manufacturing design process and, hereby, ensure the architecture to possess the needed responsiveness. Hereby, the analysis framework and analysis findings are a step towards a structured design framework of MMS.

5 CONCLUSION
The relation between manufacturing systems and there environments are characterised by being complex and dynamic. This makes the identification of production needs a complex task. In order to design modular manufacturing architectures, with the aimed benefits of Modular Manufacturing Systems, knowledge on production need is required. An analysis framework for identification of production needs related to a given marked situation has been developed in this paper. This framework inherits the marked conditions through the responding initiatives to which they are exposed during the process of product realisation. Based on the framework, an analysis of the general production implication of the new dynamics marked conditions is performed. This analysis has resulted in a check list of areas to consider when identifying production needs of a particular case. Furthermore, the analysis and its findings support the need of including the indirect determined production needs as design requirements for modular manufacturing architectures.

6 ACKNOWLEDGEMENTS
Adept Technology Denmark are gratefully thanked for their support and involvement in this research project.

7 REFERENCES
Paper 3

Utilising Mass Customisation Methods for Modular Manufacturing System Design

Steffen Nordahl Joergensen\textsuperscript{a}, Alexia Jacobsen\textsuperscript{b}, Ole Madsen\textsuperscript{a}, Kjeld Nielsen\textsuperscript{a}, & Kaj. A Jørgensen\textsuperscript{a}

\textsuperscript{a} Department of Mechanical and Manufacturing Engineering, Aalborg University, Denmark
\textsuperscript{b} Center of industrial production, Aalborg University, Denmark

\textbf{Abstract}

Markets today have become dynamic and demand rapid product changes, product variety, and customised products. In order to operate under and taking advantages of such conditions requires, amongst other aspects, manufacturing processes robust to product changes – a contradiction to traditional manufacturing systems developed as dedicated engineer-to-order solutions, tailored to production of a specific product or a limited product assortment. In response, modular manufacturing concepts are evolving, which are aimed at possessing the needed responsiveness and aimed at being the manufacturing paradigm of Mass Customisation (MC). Research focus has been on the basic principles and enabling technologies, while modular architectures and system design have received less attention. A potential to fill these gaps by applying selected design theories and methods of MC have been seen. Based on a communality analysis between these theories/methods and the modular manufacturing approach, this paper discusses and evaluates the potentials and appoint possible obstacles of application.

1. Introduction

Most markets have become dynamic and demand product which satisfies individual customer’s needs. These conditions require rapid product changes, high variety, and customer involvement in the product realisation. Mass Customisation (MC) focuses on how to operate and take advantage of these new market conditions and is aimed to satisfy individual customer needs, while taking advantage of mass production efficiency (Pine, 1993). This requires companies to create external variety with respect to the internal complexity.

Based on (Pine, 1993) and broad implementation experiences, (Salvador, de Holan, and Piller, 2009) argue that for companies to have success with MC requires that their internal operations and supply chain do not get significantly affected by variability in customer requirements. (Salvador, de Holan, & Piller, 2009) express this as “Robust Process Design”. According to manufacturing this is the aim of Modular Manufacturing Systems (MMS) where components, controllers, machine tools, etc. are modularised, and manufacturing systems developed as one particular module configuration tailored to a set of production needs. The ability to reconfigure (change, add, remove modules) entails the capacity and functionality to be adjustable, which imply responsiveness according to changes (Koren, et al., 1999; Koren, 2006; Mehrabi, Ulsoy, and Koren, 2000). Such systems are, therefore, aimed to possess the capacity and flexibility needed when needed (Mehrabi, Ulsoy, and Koren, 2000), and to be the manufacturing paradigm of MC (ElMaraghy, 2005). This will bring the market of manufacturing development/distribution from engineer-to-order (ETO) against configure to order (CTO).

In research MMS is treated in terms of Reconfigurable Manufacturing Systems (RMS), Holonic Manufacturing Systems (HMS), etc. The research effort is mainly focused on the basic principles and enabling technologies, while manufacturing family and systems design have received less or little attention. Based on communalities (Joergensen, Nielsen, and Joergensen, 2010) found a potential to take MMS forward by treating RMS as a MC product and applying Modularisation, Modular Product Architecture, and Product Family Modelling theory and methods.

This paper evaluates the potential of utilising these MC methods and theory in MMS architecture and system design further. To do so, an analysis comparing the basic assumptions of
MC methods and theory with the similar ones of MMS is performed. This analysis includes both product and business characteristics due to the known business influence of MC product success - see MC definition of (Pine, 1993), MC enabling factors (Silveira, Denis, and Fogliatto, 2001), and the guidelines for MC success of (Salvador, Martin De Holan, and Piller, 2009). The background, purpose, and method of the analysis are elaborated in section 2 before the analysis framework in terms of the list of product and business characteristics is constructed in section 3. Section 4 presents the analysis which findings are discussed in section 5 in terms of gaps influence on the potential to utilise these theory and methods on MMS. Finally, section 6 draws up the conclusions.

2. Background, purpose, and method

Based on an identified communality in the general modular approach (Joergensen, Nielsen, and Joergensen, 2010) analyse the potential for RMS to succeed as a MC product, which resulted in a number of gaps. Based on communality in the gap characteristics and comparable issues in MC literature a potential to fill/limit the gaps by applying MC theory and methods have been seen in accordance to:

• Modularisation: Modularisation has been an object for research within MMS and identified as a key characteristic of RMS, and modular controllers and machine/tools as enabling technologies (Koren, et al., 1999). The research focus has mainly been on the decentralisation like the Holonic and Multi Agent approach of HMS, see (Babiceanu and Chen, 2006), (Orozco and Lastra, 2007). From MC it is well known that achieving modular benefits depend on the modular structure which must be designed with the needed variety in a manner that limits the internal complexity. This theoretical background and the related methods, such as Design Structure Matrix, are of relevance to modularisation of MMS.

• Modular Product Architectures: (Erixon, 1998) and (Harlou, 2006) state the importance of modular architecture to describe/define modules, interfaces, etc. to ensure achieving the modular benefits. This is also relevant to MMS and modular architecture theory, definition of terms, and methods such as Modular Functional Deployment (Ericsson and Erixon, 1999) and Generic Organ Diagram (Harlou, 2006) are of relevance for MMS design.

• Product Family Modelling: To work with modular products demands overview of the product family and its possible ways of combining modules into products. Product family models, like Product Family Master Plan (PFMP) (Harlou, 2006) and Object Oriented Modelling, are tools to generate such an overview and one such model is often included in a configuration system. Product Family Modelling is likewise needed to control and configure MMS.

To evaluate the potential of applying these MC theories and methods onto MMS, the basic assumptions and preconditions of the theories/methods must correspond to the characteristics of MMS. In this paper this will be evaluated by comparing the product and business characteristics of the three areas of theory/methods and MMS. The need to include product characteristics in this comparison occurs directly from the basic assumption mentioned earlier – to view MMS as an MC product. The need to include characteristics of the surrounding business is widely supported in the MC literature, presented in term of business and product coherence in the MC definition of (Pine, 1993), in the MC enablers presented by (Silveira, Denis, and Fogliatto, 2001), and from (Salvador, Martin de Holan, and Piller, 2009) extensive study on how to benefit from MC. The relevant sub criteria for product and business characterisation must be identified before the communality analysis can be performed and the related application potential can be evaluated.

3. Characterisation list

A list of criteria characterising a product and its surrounding business setup must be defined in advance to the characterisation and the subsequent evaluation of application potential. Identification of a list of criteria for product and business characterisation is performed separately.

3.1. Criteria for Product Characterisation

The manner of which to categorise a product is coherent with the target goal of the product categorisation. Evaluation of the potential to apply the given theory/methods requires a list of
categorisation criteria in accordance with the viewpoint of the respective theories/methods. It appears from the module drivers presented by (Ericsson and Erixon, 1999) that the main reasons for modularity are related to product development and internal aspects such as manufacturing. No product characterisation model with this perspective has been found - instead a list of criteria is selected based on literature:

- **Product type:** Products are generally divided in terms of mechanical-, electronic-, software, and mechatronic production based on a product’s components, see (Nielsen, Jørgensen, and Petersen, 2009; Nielsen, Petersen, and Jørgensen, 2011). The product type is related to the desired product functionality, the professions involved in product development, the applied development tradition, etc. and is, therefore, found as a criteria for product characterisation.

- **Product complexity:** The complexity of a product affects the product development, manufacturing, market situation, etc. (Petersen, 2008).

- **Design tradition:** Design tradition represents the offset of modularisation in terms of whether a given product is a well known standard product/product assortment to which variation must be created in a controlled way; or if the product is a ETO product which must be standardised towards modularity.

- **Product Volume:** Creating and maintaining volume in production (on module level) is an important argument of modularisation. Production volume holds a strong influence on development investment, production setup, business strategies, etc.

- **Product Dynamic:** There is, as stated in the introduction, a demand in most markets for companies to update their products rapidly and offer product variety. Triggers for product update can be aspects such as technology evolution and changing market trends, while product variety is linked to market segments, seasons, versions, etc. This dynamic is a main driver for modularisation and, hereby, of interest for product categorisation.

- **Customer Involvement:** (Berman, 2002) and (Pine, 1993) stated the importance of postponing the product differentiation which has become generally accepted within MC literature and, hereby, found relevant for product characterisation. Based on a review, (Silveira, Denis, and Fogliatto, 2001) introduce eight levels of customisation seen from a manufacturing perspective. This spans from standardisation (standard products without customer involvement) to Design (ETO products).

The listed criteria are found to be the ones of highest relevance according to the purpose of this paper. In addition to the listed criteria aspects such as price/overhead, lead time, environmental footprint, etc., could have been added.

### 3.2. Criteria for Business Characterisation

Company survival is no longer merely on single entity level, but rather on entire supply chain level (Lambert, 2006). As a part of that, manners of conducting business has expanded from strategic thoughts upon how to enhance the profit of one central company to putting more thoughts into ensuring how the entire supply network of the company can collaborate in discussions concerning organisational structure, processes, systems, and outputs, or, as mentioned by (Lambert and Pohlen, 2001): “Managers can no longer focus on optimising their own firm’s operations. Instead, they need to work collaboratively to generate the greatest mutual gains and savings”. The criteria for categorising a business setup of a MC product must, therefore, be defined from a network perspective. Several scholars have looked into the field of altering the notion of conducting business as collaborative partners amongst companies in networks rather than single entities (Lambert, 2006; Lambert and Pohlen, 2001; Osterwalder and Pigneur, 2010; Cox, 2004; Olsen and Ellram, 1997; Nellore and Söderquist, 2000; Kraljic, 1983). Yet, the different scholars choose to focus upon different aspects that are important to consider in business matters, but seem to be gathered in the following characteristics:

- **Competence Factors:** Organisations must consider how collaborating with other partners can improve the competencies of the organisations, and if those competencies are in fact necessary and useful in accordance to their individual business perspectives (Olsen and Ellram, 1997; Nellore and Söderquist, 2000).

- **Economic Factors:** Includes the internal stability, cost structure, revenue streams, etc. of each individual organisation as well as the financial stability of the entire network and the industry of which the network belongs to. Also, the economic factors include the value
of the exchanges between the partners and if whether or not the exchange is part of the final product or service that the network offers to its end users (Olsen and Ellram, 1997; Cox, 2004; Osterwalder and Pigneur, 2010).

- **Technological Factors:** Focus is put upon the importance of continuously strengthening the technological strength of the individual organisations and the network. Thus, the performance of the partners in terms of delivery, quality, price, ability to cope with technological changes in the industry, design capabilities, development speed, and patent protection is measured in the technological factors (Nellore and Söderquist, 2000; Olsen and Ellram, 1997; Balasubramanian and Baumgardner, 2004).

- **Organisational/Cultural/Strategic Factors:** This factor is indeed a very large and complex aspect. The category includes subjects such as the internal and external integration of partners in each company, thus, the strategic and cultural fit between partners – meaning that the key activities of each partner and the compatibility across levels and functions of partners are of utmost importance to look into. However, this aspect also looks into the significance of top management capability and their attitude and outlook for the future (Kraljic, 1983; Osterwalder and Pigneur, 2010; Olsen and Ellram, 1997; Lambert, 2006; Clegg and Montgomery, 2005).

- **Character of Exchange Relationship:** Looks into the types of exchange that exist between the partners (be that in the manner of products or services), and the importance of these exchanges for the key activities of each of the partners. Hence, the value proposition of the partners, development cooperation, and technical cooperation between the partners are in focus for this characteristic (Olsen and Ellram, 1997; Cox, 2004; Osterwalder and Pigneur, 2010; Stuart and McCutcheon, 1996).

- **Product and Product Development Factors:** A factor that is widely discussed in business perspectives as well. For further insight please see section 3.1.

- **Supply Market Factors:** This factor especially involves the power structure of the market, and looking into the suppliers’ technical and commercial competencies. Thus, this includes the importance of the buyer to the supplier, key channels and partners, supplier segments, and supplier relationship management (Olsen and Ellram, 1997; Clegg and Montgomery, 2005; Cox, 2004; Lambert, 2006).

- **Customer Market Factor:** Whilst the supply marked factor refers to the upstream business processes, this factor focuses upon the downstream process, involving aspects such as the strength of the customers, the technical and commercial strength of the customer, the importance of the supplier to the customers, customer relationship management, and customer segments (Olsen and Ellram, 1997; Stuart and McCutcheon, 1996; Osterwalder and Pigneur, 2010; Lambert, 2006; Cox, 2004). The literature supporting the criteria is, as it appears, tangled across the criteria. This indicates the importance to include all criteria in a business network characterisation. Due to the purpose of this paper, the characterisation is to be performed on a general level. This is not found possible for the criteria “economic factors” and “organisational/cultural/strategic factors” and these criteria are, therefore, not treated further.


The business and product characteristics of the underlying approach of the three areas of theory/methods and the characteristics of MMS are identified and compared. The results are listed in table 1 and the evaluation and experienced gaps are elaborated upon below. In the elaboration Modularisation, Modular Product Architectures, and Product Family Modelling are described together. This is based on the convergence in literature between modularisation and modular product architectures, and the use of modular product families in relation to modularisation and architecture development, see (Ericsson and Erixon, 1999; Harlou, 2006). The product and business characteristics are elaborated upon separately.
4.1. Product Characteristics

- **Product type**: The three theory areas are traditionally treated from a mechanic and partly electrical product development perspective. An example is Modular Functional Deployment whose Module Driver categories “Production” and “Purchase” are directly related to advantages of hardware. This conflicts which modern manufacturing systems and, hereby, MMS which is mechatronic in its nature. Recent research has put focus on mechatronic products according to modularisation and MC, see (Nielsen, Jørgensen, and Petersen, 2009; Nielsen, Petersen, and Jørgensen, 2011). It is here argued that mechatronic products are adaptable into a MC strategy.

- **Product complexity**: The product complexity related to the three theory areas is found to be low to medium compared with manufacturing. This is based on case studies presented and summarised by (Ericsson and Erixon, 1999; Harlou, 2006), and the study on production development presented in (Bellgran and Kristina, 2010). The increase in complexity most likely increases the need to create overview according to modularisation, architecture development, configuration, etc. which will affect related methods – an example is the Product Family Model which must handle the increased complexity in a manner which ensures overview. Another issue is the multiple actors involved over time in manufacturing development and control of the cross profession in mechatronic. This will most likely increase the need for coordination and demand a common language – aspects to be handled by the Modular Product Architecture.

- **Design tradition**: The three areas of theories depict how to create and manage variety in terms of transforming a known product assortment into modular product architecture. This appears from methods such as Generic

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Table 1: Comparison of the characteristics of the three areas of theory and methods (modularisation, modular product architectures, and product family modelling) and MMS

<table>
<thead>
<tr>
<th>Product characteristics</th>
<th>Modularisation, Modular Product Architecture, and Product Family modelling</th>
<th>MMC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Product type</strong></td>
<td>Primarily hardware (mechanical and electronic) but evolve against Mechatronic</td>
<td>Mechatronic</td>
</tr>
<tr>
<td><strong>Product complexity</strong></td>
<td>Low to medium</td>
<td>High</td>
</tr>
<tr>
<td><strong>Design tradition</strong></td>
<td>Well known standard product or product assortments</td>
<td>Custom solutions tailored specific needs (ETO)</td>
</tr>
<tr>
<td><strong>Product volume</strong></td>
<td>One of a kind – scaled production</td>
<td>One of a kind – small numbers</td>
</tr>
<tr>
<td><strong>Product dynamic</strong></td>
<td>High</td>
<td>Medium change rate – tendency are increasing</td>
</tr>
<tr>
<td><strong>Customer involvement</strong></td>
<td>Assembly/configure-to-order</td>
<td>Assembly/configure-to-order</td>
</tr>
</tbody>
</table>

**Business characteristics**

<table>
<thead>
<tr>
<th>Competence factors</th>
<th>Not directly evaluable, but modularity enabler for easy cooperation according to products</th>
<th>Medium to high</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Technological factors</strong></td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td><strong>Character of exchange relationship</strong></td>
<td>Products</td>
<td>Products, services, knowhow</td>
</tr>
<tr>
<td><strong>Supply market factors</strong></td>
<td>Medium</td>
<td>Low to medium</td>
</tr>
<tr>
<td><strong>Customer market factors</strong></td>
<td>High customer focus and customer power</td>
<td>High customer focus and customer power</td>
</tr>
<tr>
<td><strong>Competitor market factor</strong></td>
<td>Not directly in focus</td>
<td>Medium to high</td>
</tr>
</tbody>
</table>
Organ Diagram and PFMP. This contradicts with the traditional ETO approach of manufacturing development. In ETO, product and consumer knowledge are generally more loosely defined which can be a challenge according to existing methods.

- **Product Volume**: The three theory areas focus on creating volume on module and part level and are, therefore, unaffected whether the product is produced as one of a kind or in a scaled production. Manufacturing systems are in general unique or replicated in low numbers in terms of parallel lines. The included equipment can, likewise, be unique or it can be standard produced at higher volume. The low item numbers do not directly affect the methods but in practice the additional cost of forming modules and architectures must be considered against the benefits.

- **Product Dynamic**: The three areas of theory/methods focus, from a product perspective, on how to operate firms under and taking advantages of the new dynamic market conditions – this in terms of fast changing product assortment, need for product variety etc. for elaboration please see (Ericsson and Erixon, 1999). A consequence of the high product and market dynamics is that production demands become affected by changing production volume, product evolutions, strategy changes, and evolvement in manufacturing technologies. The aim of MMS is to provide manufacturers the ability to respond according to such changes in needs. This and the high demands for tailored solutions entail a potential manufacturing platform to be of high variety.

- **Customer Involvement**: By comparing the modular approach of these three theory areas with Silveira’s 8 levels of MC (Silveira, Denis, and Fogliatto, 2001) it appears that these theories are mainly related to level 6 assembly/configure-to-order. It appears from (Joergensen, Nielsen, and Joergensen, 2010) that this is also the case for MMS.

### 4.2. Business characteristics

- **Competence factors**: Company cooperation in the shape of competence factors is not directly discussed in the theories and methods which are in focus of this paper. However, modularity does simplify such cooperation due to clear defined interfaces, functional specification, test options, etc. The competence factor of manufacturing systems is set to “medium to high” according to the multiplied competences and actors involved in manufacturing development (machine builders, system integrators, production engineering, etc.) and their internal cooperation/alliances.

- **Technological factors**: Cost effective and fast product development according to new technologies, trends, etc. are main reasons to apply a modular product structure. This is due to parallel module development, test and debugging at module level and higher overview (less tangled products, reuse across product variants, etc) (Ericsson and Erixon, 1999). The three theory areas and related methods are, therefore, found to possess a high technological factor. Similar benefits are the aim of MMS in terms of adjustment to changes and fast adaption of new technology, trends, etc.

- **Character of exchange relationship**: The three theory areas mainly focus on the products as exchange relation while manufacturing and, hereby, MMS must include the product, associated services and knowledge, e.g. how to operate a system.

- **Supply market factors**: Change at suppliers side affect the product and related internal aspects. The supplier power is, therefore, of interest according to Modularisation and Modular Product Architectures. This is illustrated by the module driver category “Purchase” (Ericsson and Erixon, 1999). The corresponding factor of manufacturing is evaluated to be low. This is found according to the traditional ETO market conditions and the numbers of potential suppliers of most type of manufacturing systems/equipment. The supply market factor can vary according to a suppliers (e.g. machine builders) unique technology, special abilities, high experience, brand, etc.

- **Customer market factors**: An important aspect of MC is to take offset in the customer’s needs which imply a high customer market factor of the three theory areas. This is illustrated by the general acceptance of the need for product demands as an offset for product modularisation and development of modular product platforms, see (Harlou, 2006; Ericsson and Erixon, 1999). The customer market factor of manufacturing is likewise
found to be high – this is due to production firm’s individualities, the cost of leak in effectiveness and quality, traditional offset in ETO, etc. For a manufacturing system, such customer demands can be hard to identify due to complexity, high number of stakeholders, complex internal and external relations, etc.

- Competitive Market factors: The three theory areas mainly focus on market demands and competitors are only indirectly included in terms of changes in market demands, trends, change rate, etc. Competitors are, hereby, not used directly as a source of inspiration (inspiration capture, benchmarking, etc.) as known from other product development approaches such as the method of product development presented by (Ulrich and Eppinger, 2003). Previous manufacturing investments firms generally put effort into an investigation of possible solutions, suppliers, etc. That fact coupled with a high number of actors implies that the competitive market factors are of medium to high relevant to consider.

5. Discussion

The analysis revealed a number of differences regarding product type, complexity, offset, exchange relationship etc. In the following, implications of these differences will be discussed according to the potential to apply theory and methods of the three appointed MC areas onto MMS.

Manufacturing systems are, as mentioned, mechatronic in their structure which conflicts with the traditional hardware focus of modularisation and modular product architectures theory and methods. Recent research has found these extendable in terms of mechatronic products (Nielsen, Jørgensen, and Petersen, 2009; Nielsen, Petersen, and Jørgensen, 2011) – an extension which requires adjustments in module drivers, etc. The adjustments are expected to have an effect on methods, but not on the underlying basic theory of modularity. Including software parts in existing Product Family Models like PFMP and Object Oriented Modelling are not expected to become a problem by itself. This is due to a modelling offset in object oriented thinking as known from software development. Software will, though, be an addition and require some adjustments. In regards to mechatronic, the interrelation between mechanic, electronic, and software is expected to become a challenge. Modelling and controlling such interrelations call for further extensions of existing Product Family Modelling methods of mechatronics. The process of including mechatronics is ongoing within the three appointed areas of MC – a process, which most likely will be beneficial for MMS to join.

The analysis pointed out that manufacturing as a product includes the manufacturing setup, the related/supporting services, and knowledge. These aspects are out of scope of the theory areas analysed in this paper but included elsewhere in MC theory. The potential to utilise theory and methods from these areas is an object for further study.

The mechatronic structure, the complex nature of manufacturing, and the high number of actors involved in manufacturing development entails a high level of complexity – a complexity which extends the complexity level of the three theories/methods. For the theory and methods to be relevant for MMS it is imperial that the complexity of manufacturing do not eliminate the potential of achieving some extent of modularity - a modularity which, according to (Ulrich and Eppinger, 2003), depends on the scheme by which functional elements are implemented in chunks. Architectures can be more or less modular depending on the mapping relation where a modular architecture consists of one-to-one relations between functions and chunks, and integral architectures consist of complex relationships (many-to-one or one-to-many). For MMS this must be evaluated both on system and machine level. On a system level, manufacturing systems are compressed of a number of machines which are target a specific job. This indicates potential for one-to-one relationships on system level. The machine level depends on the individual machines, but the general impression is that one-to-one relationships can be achieved at least to a certain level.

The increased complexity can potentially challenge the ability to gain an overview of the product family and, hereby, the ability to further develop and control the product family and to configure products. Such an overview is traditionally provided by the product family model which tends to become relatively extensive for products of low-to-medium size and complexity. It is, therefore, the expectation that existing product family models need modifications to handle the product size and complexity of a manufacturing system in a manner that ensures an overview. Today, levelling and system theory are applied on
manufacturing in order to limit complexity and divide systems into manageable parts, see (Bellgran and Kristina, 2010). Similar levelling can, likewise, be of interest for product family modelling, where an example for inspiration can be found in (Petersen, 2008; Joergensen K. A., 2010)

Manufacturing systems create value for the customer in its totality but several actors are involved in the manufacturing development and realisation process. This introduces complexity to the customer value/function/chunk relation which most likely becomes a challenge for both product family models, and methods for modularisation and modular product architecture development. On a system level, this calls for interface standards, a common language, etc.

It is well known in MC literature that achieving of the modular benefits requires a modular structure which meets customer needs in a manner which limiting the internal complexity. Designing and maintaining one such structure requires an overview of the customer needs and the internal aspects/consequences – overviews which are hard to archive for manufacturing. Overview of internal consequences is generally hard to achieve; a task, which become more complex due to the multiple actors involved in developing manufacturing systems. The customers of manufacturing expect solutions that are tailored to their needs and performance demands. This factor coupled with the indirect demands and a high number of stakeholders (production engineering, managers, service, operators, etc.), makes customer demands hard to identify, and a challenge for traditional modelling methods.

Modularisation and modular product architecture development literature takes, as argued in the analysis, offset in product assortments of standard products. This contradicts with the ETO offset of manufacturing development which limits the direct applicability of associated methods. This limitation occurs according to a leak in customer and product knowledge, which are a precondition of most existing methods. Similar knowledge is used for design of standard products and discussed in other areas of product design literature. One example is the early design phases of the method presented by (Ulrich and Eppinger, 2003), here knowledge is captured in a structured manner based on own ideas, customer involvement, active involvement (analysis, benchmarks, etc.) of competing products, etc. The potential to fill the knowledge gap based on related design theory is an object for further research. In regard to this, it is worth noticing the un-formalised customer knowledge related to earlier ETO projects and the high competitor factor of manufacturing which indicates a potential to search for inspiration and benchmarks among competitors’ products. If the competitors’ products are used for inspiration and benchmarks, it must be noticed that a products modular structure depends on internal aspects (Ericsson and Erixon, 1999) and is, hereby, not directly comparable.

6. Conclusion

This paper evaluates the potential to apply theory and methods of Modularisation, Modular Product Families, and Product Family Modelling onto Modular Manufacturing Systems (MMS) and, hereby, the potential to utilise Mass Customisation to bring MMS forward. An analysis comparing the basic approach of the listed theory areas and MMS is performed and based on this, the potential to apply the listed theory and methods is evaluated by discussion. It occurs that the theories, in general, are applicable for manufacturing systems, but that an application is challenged by a number of obstacles which demand supplements to the theory and modifications of the methods. The identified obstacles are the mechatronic nature of manufacturing, the high complexity, and the offset in engineer-to-order.

7. Acknowledgments

Adept Technology Denmark is grateful for their support and involvement in this research project.

8. References


Paper 4

Designing modular manufacturing systems using mass customisation theories and methods

Steffen Nordahl Joergensen*, Mads Hvilshøj and Ole Madsen

Department of Mechanical and Manufacturing Engineering, Aalborg University, Fibigerstraede 16, DK-9220 Aalborg East, Denmark
E-mail: snj@m-tech.aau.dk
E-mail: mh@m-tech.aau.dk
E-mail: om@m-tech.aau.dk
*Corresponding author

Abstract: Today, manufacturing systems are developed as engineered to order (ETO) solutions tailored to produce a specific product or a limited product mix. However, such dedicated systems are not consistent with the current market demands for rapid product changes, high product variety, and customisation. In response, modular manufacturing systems (MMS) are evolving, which are aimed to possess the required responsiveness and to be the manufacturing paradigm of mass customisation (MC). Hereby, MMS brings the development process of manufacturing systems against configured to order (CTO). Up to now, research in MMS has primarily focused on potential benefits, basic principles, and enabling technologies, while the approaches of actually designing and creating modular architectures have received less attention. A potential to fill these gaps by applying MC theories and methods is identified based on the commonalities in the basic modular approaches of MC and MMS. This paper analyses this potential and evaluates it through three conducted cases within the domain of industrial automation and robotics. Based on the results, the paper discusses the prospective to form an MMS design framework by utilising selected MC theories and methods.

Keywords: modular manufacturing systems; MMS; mass customisation; MC; modularisation; modular product architectures; product family modelling; PFM; changeable manufacturing systems.


Biographical notes: Steffen Nordahl Joergensen holds an MSc in Mechanical and Manufacturing Engineering and is currently working on an industrial research project as a PhD student at Aalborg University. The project is carried out in cooperation with Adept Technology Denmark and Grundfos. Furthermore, he is affiliated to the Automation and Robotics Group and the Product Configuration Group at the Department of Mechanical and Manufacturing Engineering, Aalborg University, which carries out research within the domain of adaptive automation and product configuration, respectively. His research is focused on developing economically and practically meaningful modular and (re)configurable architectures for automated manufacturing systems.

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Mads Hvilshøj holds an MSc in Mechanical and Manufacturing Engineering and is engaged as a PhD student in the research project ‘AIMM – implementation, maturation and exploitation’. The project is carried out in cooperation with Grundfos and is related to the EC FP7 projects GISA and TAPAS. He is employed by the Automation and Robotics Group at the Department of Mechanical and Manufacturing Engineering, Aalborg University. The group carries out research activities within adaptive automation by focusing on: automation, scalability, and cost/diversity. His current research is focused on developing modular and (re)configurable architectures for autonomous mobile manipulators in manufacturing environments.

Ole Madsen holds a PhD and an MSc in Mechanical and Manufacturing Engineering and is a Professor at Aalborg University, where he heads the Automation and Robotics Group at the Department of Mechanical and Manufacturing Engineering. In the past, he has worked for Odense Staalskibsværft A/S as Consultant and at IWA (Intelligent Welding Automation) A/S as Co-founder, System Developer, and Manager. Recently, he has worked at Grundfos A/S, where he focused on the development of automation equipment. Additionally, he has participated in a number of EU-funded research projects under the FP4, FP5, FP6, and FP7.

1 Introduction

Most markets have become dynamic and demand products, which satisfy individual customer needs. These conditions require rapid product changes, high variety, and customer involvement in the product realisation. Mass customisation (MC) focuses on how to operate in such market conditions and is aimed to satisfy individual customer needs, while taking advantage of mass production efficiency (Pine, 1993). Salvador et al. (2009) argue that for manufacturing companies to have success with MC, it is necessary that their internal operations and supply chains do not get significantly affected by variability in the customer requirements. Within manufacturing, this is the aim of modular manufacturing systems (MMS), where components, controllers, and machine tools are modularised, and manufacturing systems developed as one particular module configuration tailored to a specific set of manufacturing needs. The ability to (re)configure, i.e., to change, add, and/or remove modules, entails the capacity and functionality to be adjustable, which imply responsiveness according to changes (Koren et al., 1999). Therefore, MMS are aimed to possess the capacity and flexibility needed when needed (Mehrabi et al., 2000), and to be the manufacturing paradigm of MC (ElMaraghy, 2005). This brings manufacturing development from engineered to order (ETO) against configured to order (CTO).

In research, MMS has been treated in terms of reconfigurable manufacturing systems (RMS) (Koren et al., 1999), holonic manufacturing systems (HMS) (Christensen, 1994), and evolvable production systems (EPS) (Frei et al., 2007). When looking in the literature, the research effort in MMS is mainly focused on potential benefits, basic principles, and enabling technologies, while the approaches of actually achieving modular manufacturing architectures have received little attention. However, based on the basic similarities of MMS and highly customised MC products, Joergensen et al. (2010) have identified a potential to move MMS forward by treating the manufacturing
Designing MMS using mass customisation theories and methods

This paper further evaluates the potential of utilising well-established MC theories and methods within MMS. Therefore, the work takes offset in the objective that MC creates a useful framework for MMS design and constitutes a contribution towards a development framework for MMS. As a starting point, the paper evaluates this objective by analysing the offset for actually applying MC within the manufacturing domain. Based on this, the paper examines the possibilities for utilising MC theories and methods in the design and development of modular and (re)configurable automatic manufacturing equipment through three conducted industrial cases. The paper is organised as follows. Section 2 presents a general framework for MMS, including a description of the background and related work. Section 3 introduces the development within MMS and elaborates on relevant theories and methods from the MC domain. Section 4 presents results from performed cases with the purpose of utilising MC theories and methods within the field of MMS. Finally, the paper discusses (Section 5) and concludes (Section 6).

2 Modular manufacturing systems

2.1 Manufacturing levels and levels of manufacturing changeability

Nowadays, reliable delivery of customised products has the highest priority in the globally distributed markets. Therefore, the next generation factories are described as adaptive, transformable, and intelligent, as highlighted in the EU ManuFuture strategy. Wiendahl et al. (2007) appoint that the key to create products that can meet these diversified customer demands is manufacturing changeability, which is defined as characteristics to accomplish early and foresighted adjustments of the factory’s structures and processes on all levels. Also, Wiendahl et al. (2007) distinguish not only the factory levels but also the views on the factory levels; the resource view and the space view, as illustrated in Figure 1 (left). The resource view looks for the technical and human resources, which maintain the processes, whereas the space view considers the architectural objects, which have to be designed in accordance with these resources. Overall, the basis for both views is given by the processes, which are performed by either machines and/or workers.

Interesting for MMS, Wiendahl et al. (2007) combine the structuring levels with the associated product levels. From this, a hierarchy emerges that allows a definition of five types of changeability [Figure 1 (right)]. The hierarchy of product levels starts from the top with the product portfolio a company offers to the market. Then the product or a product family follows downwards. The product is usually structured into sub products or assembly groups that contain work pieces. Overall, any changeability type at a higher level subsumes the types below it.

The above description is used for specifying the focus area of this paper. The paper focuses exclusively at the manufacturing system level and levels below (cell, station, and processes), as shown by the red markings in Figure 1. This is a deliberately ‘bottom-up approach’, as elaborated in Section 4. Therefore, the focus is on the changeability levels of:
• **changeover ability:** the operative ability of a single machine or workstation to perform particular operations on a known work piece or subassembly at any desired moment with minimal effort and delay

• **reconfigurability:** the operative ability of a manufacturing system to switch with minimal effort and delay to a particular family of work pieces or subassemblies through the addition or removal of functional elements.

**Figure 1** Structuring levels and views of a factory (left) and classes of factory changeability (right) (see online version for colours)

Source: Wiendahl et al. (2007)

2.2 Manufacturing paradigms

Traditionally, automatic manufacturing systems have been developed as dedicated manufacturing lines (DML), i.e., fixed automation systems dedicated to produce company core products at a high volume and good quality in a cost-effective manner. However, DML’s are only profitable as long as demand exceeds supply and if they operate at their full capacity (Koren et al., 1999). In response to the shortcomings of DML and the increasing needs for manufacturing flexibility, flexible manufacturing systems (FMS) evolved in the mid-eighties. FMS consists of multi-purpose machines (e.g., CNC machines and other programmable automation) and aims to increase the variety of parts produced. Despite this advantage, FMS has never been adopted in industrial environments, because of low system output (Koren, 2006), high complexity (Setchi and Lagos, 2004), and a high cost of general flexibility (Mehrabi et al., 2000). Today, the trend points towards MMS, i.e., manufacturing systems and equipment consisting of standardised modules with well-defined interfaces. The modular approach entails the functionality and capacity of the MMS to be changeable, so that systems only possess the required properties and are able to evolve rapidly according to changing manufacturing demands. A comparison between the manufacturing paradigms is provided in Figure 2.
MMS compromises the high throughput of DML with the flexibility of FMS. The rationale is that by using standardised modules, it is possible to (re)configure (update, add, remove, and/or exchange modules) the manufacturing system to a specific set of manufacturing needs. In this way, MMS provides high responsiveness, in terms of evolving the manufacturing setup together with the company’s products and manufacturing needs. In general, the modular approach brings volume into the manufacturing systems, with the benefits of lower unit cost, lower delivery time, higher reuse, focused product(ion) development, and certainty on cost and performance. The main principles of MMS are illustrated in Figure 3, which can be applied on system, cell, and/or station level, as indicated by the red markings in Figure 1.

In the literature, MMS have been treated in terms of RMS, HMS, and EPS, to which MMS appears as a super category, as shown in Figure 2. Before discussing how to actually design and develop MMS, each of the underlying theories is briefly compared and summarised in Table 1.
Table 1 Comparison of the underlying MMS theories; RMS, HMS, and EPS

<table>
<thead>
<tr>
<th>Reconfigurable manufacturing systems (RMS)</th>
<th>Holonic manufacturing systems (HMS)</th>
<th>Evolvable production systems (EPS)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Main concepts</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RMS was introduced in the mid-nineties and is designed for rapid change in structure, as well as hardware and software components, to quickly adjust production capacity and functionality to sudden changes (Koren et al., 1999).</td>
<td>HMS emerged in the early nineties and is designed to attain stability in the face of disturbances, adaptability and flexibility in the face of change, and efficient use of available resources (Brussel et al., 1998).</td>
<td>EPS was introduced around the turn of the millennium and is a holistic approach to support product/shop floor co-evolution and to ensure a balanced solution for sustainable enterprise development (Onori and Barata, 2010).</td>
</tr>
<tr>
<td>RMS is customised around a product family to provide only the features and flexibility needed when needed. RMS is designed at two levels: system (machine interfaces, link to ERP, and etcetera) and machine (internal machine/tool modularity, interfaces, and etcetera) (Koren, 2006).</td>
<td>HMS is based on holons; autonomous and cooperative building blocks (modules). The holons assist the operators in controlling the system, i.e., holons autonomously select appropriate parameter settings, find their own strategies, and build their own structures (Bongaerts, 1998).</td>
<td>EPS is focused on manufacturing adaptation through modularity and stepwise evolution. However, EPS is not a generic solution, but is rather a specific approach that may be adopted by several products of the same class (Neves and Barata, 2009).</td>
</tr>
<tr>
<td><strong>Enablers and characteristics</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In RMS, the modular approach is essential, and is enabled by: open-architecture modular controllers (reconfigurable software) and modular machines/tools (reconfigurable hardware) (Bi et al., 2008).</td>
<td>The features of holons as autonomous agents and their relationships make Multi Agent Systems (MAS) and Artificial Intelligence (AI) suitable for HMS implementation (Babiceanu and Chen, 2005).</td>
<td>The cornerstones are process-oriented modules with embedded intelligence. Overall, EPS is inspired by biology and complexity theory, with main influences from AI and MAS (Frei et al., 2007).</td>
</tr>
<tr>
<td>The key characteristics are: modularity, integrability, customisation, convertibility, and diagnosability. To ensure a high level of reconfiguration, the system and machine level must be represented by the key characteristics (Koren, 2006).</td>
<td>The key concepts of HMS are (Bongaerts, 1998): holon, autonomy, cooperation, and holarchy. Overall, HMS is a holarchy that integrates the entire range of manufacturing activities in order to realise the agile manufacturing enterprise (Brussel et al., 1998).</td>
<td>By using a concept similar to the well-known LEGO’s, together with local intelligence, EPS allows the user to build and (re)configure the required manufacturing systems integration (Ribeiro et al., 2010).</td>
</tr>
</tbody>
</table>
From the literature and Table 1, it occurs that the main focus of the underlying MMS theories is the potential benefits, basic principles, and enabling technologies. However, how to actually design the manufacturing modules, how to obtain the modular structure, and how to create customer specific solutions based on modules, are not answered in the literature. In this paper, answers to these questions are sought in MC domain, see Section 3.

3 Developing MMS

Modular Product Design is well known from the domain of MC and related product design theories, where it is widely accepted that achieving modular benefits depend on the applied modular structure. As argued by Harlou (2006), Ulrich and Eppinger (2003), and Ericsson and Erixon (1999), a modular structure must be designed with the needed variability in a way that limits the internal complexity of the product realisation. By comparing the modular approaches of MC and MMS, high commonalities are seen in the basic procedures and reasons for applying a modular approach (Joergensen et al., 2010). In general, MC covers comparable issues and, hereby, possesses a potential to bring MMS development forward – this in terms of theories and methods within modularity and modularisation, modular product architectures, and PFM. However, transferring theories and methods from one domain to another demands commonality, not only in the focus areas, but also in the underlying assumptions and preconditions. To form a basis for evaluating the MMS applicability, the appointed areas of MC is shortly revised.

3.1 Elaboration of MC theories and methods

3.1.1 Modular product architectures

The concept of architecture constitutes the layout, configuration, and/or topology of functions (Ulrich, 1995), chunks (Ulrich and Eppinger, 2003), modules (Ericsson and Erixon, 1999), or standard designs (Philips, 2000) of a product assortment, a product family, and/or a product (Harlou, 2006). A widely accepted definition is; “a product architecture can be defined as the way in which the functional elements of a product are arranged into physical units, and the way in which these units interact” (Ulrich and Eppinger, 2003). In the literature, substantial work has been carried out within the domain of product architectures, ranging from single products to product families. A review can be found in Jiao et al. (2007). Based on the mapping relations between functional elements and physical units, product architectures are more or less modular. At the one extreme, modular architectures consist of one-to-one mappings, and at the other extreme integral architectures consist of complex (many-to-one or one-to-many) mappings. In practice, products are rarely strictly modular or integral. Modular structures contain well-defined interactions (interfaces) between modules, interactions which are fundamental to the product functionalities. Hence, modules must be developed such that interactions between modules are minimal, while internal interactions can be high (Ulrich and Eppinger, 2003).

Mortensen and Andreasen (1996), Erixon (1998) and Harlou (2006) state the importance of architectures as a tool to develop, maintain, and manage a product assortment. The development of architectures comprise five domains; customer,
functional, physical, process, and logistics, which involves a series of mappings, as inspired by the theory of domains (Andreasen, 1980) and axiomatic design (Suh, 2001). Architectures are compressed by standard designs and design units and exist on three levels; assortment (portfolio), family, and product. Furthermore, Harlou (2006) makes a firm distinction between architectures and platforms, where a platform constitutes a subset of an architecture, including only existing standard designs and their interfaces.

3.1.2 Modularisation and architecture development

In the literature, there exist numerous methods and tools for modularisation and architecture development. The design structure matrix (DSM) (Steward, 1981) is a widely used method to examine interfaces and interactions among system components in order to identify structures with limited interactions (module candidates). Another approach is design for variety (DFV) (Erens, 1996), a domain oriented approach, which is closely related to the theory of domains (Andreasen, 1980). In DFV, relations between the functional, technological, and physical domains must be understood. Therefore, a product model for each domain is developed and standard interfaces defined. Modular functional deployment (MFD) (Erixon, 1998) is a pragmatic and stepwise approach, which utilises QFD principals to clarify customer requirements, which form the input to define functionalities and technical solutions of the products. Based on these technical solutions, MFD identifies module candidates from a set of module drivers (Ericsson and Erixon, 1999).

3.1.3 Product family modelling

A PFM is a generic model of product families, describing which modules are parts of the product family and how the modules can be combined into products. Furthermore, a PFM provides overview of the architecture. PFM is treated by several authors and a number of methods and tools exist. A pragmatic method is the product family master plan (PFMP) (Harlou and Nielsen, 1999), which has its origin in the object oriented paradigm (Coad and Yourdon, 1991), system theory (Klir and Valach, 1965), theory of technical systems (Hubka and Eder, 1988), and theory of domains (Andreasen, 1980). The PFMP modelling formalism consists of three types of elements (classes, attributes, and constraints) and architectures are modelled hierarchically in terms of part-of and kind-of structures. In the PFMP, architectures are viewed from the customer, engineering, and part view. Application examples can be found in Mortensen et al. (2008). Another PFM approach is the generic organ diagram (GOD) (Harlou, 2006), which model the structure and interfaces of architectures. The GOD utilises a block diagram, where each block represents an organ or a group of organs, and interactions (interfaces) between organs are drawn as connecting lines.

3.2 MMS applicability (from MC to MMS)

Application of theories and methods from one domain to another requires either adjustments to the theories and methods or a complete fulfilment of the underlying assumptions and preconditions. An analysis is conducted to identify such obstacles of applying the listed MC theories and methods onto MMS. The analysis reveals a number
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of differences, where the main ones are listed below. For a detailed exposition, see Joergensen et al. (2011a).

3.2.1 Design tradition

In general, the MC literature focuses on how to transform product assortments into modular products and/or product architectures, as a response to market demands for product variety, customisation, and rapid product updates. This assumes well-known products and market conditions, a precondition, which contradicts the knowledge state of ETO-based products such as manufacturing systems and equipment. This leak in product and customer knowledge could potentially limit the direct application of MC theories and methods onto the MMS domain.

3.2.2 Product type

Overall, manufacturing systems consist of a combination of hardware, electronics, and software. This mechatronic structure contradicts the traditional hardware focus in the literature of modularisation and modular product architectures. However, Nielsen et al. (2011) found these areas extendable in terms of mechatronic products – an extension, which requires adjustments in the module drivers and related areas. This indicates applicability of the basic MC theories, but a potential need for adjustments and/or elaborations of the methods.

3.2.3 Product complexity

Due to the complex nature of manufacturing systems, the mechatronic structure, and the high number of actors involved in manufacturing, the complexity of manufacturing extends the complexity level of products traditionally treated in the MC literature. According to the applicability of MC theories and methods, it is essential that the complexity of manufacturing systems does not eliminate the potential to achieve direct functional relations, i.e., modular structures. The design of a modular structure demands overview, which traditionally is provided by PFM tools. For products of low-to-medium size and complexity such models tend to become extensive. However, the size and complexity of manufacturing might challenge the ability of these modelling methods to provide overview. Also, the complexity is a challenge in collecting the information needed to build such models. For instance, the customer demands of manufacturing systems consist of both direct and indirect demands, expressed as the needs of multiple stakeholders. Collecting and formalising such knowledge can be a challenge for applying the MC methods.

4 Industrial cases

In this section, three conducted industrial cases for applying MC theories and methods onto MMS are presented. The cases have the overall scope of moving the design and development process for industrial automation equipment from ETO against CTO to achieve economic and competitive advantages. Depending on the specific case, this corresponds to either a manufacturing station and/or cell. This ‘bottom up’ approach to
MMS design and development is purposefully chosen to ensure achievement of lower level manufacturing changeability, which according to Wiendahl et al. (2007) are subsumed in the higher changeability levels and, hereby, required to achieve these levels. Furthermore, manufacturing stations and cells constitute a fundamental linkage to the products of a company, as they are the direct implementations of transformation processes for producing a product, a product family, or a product assortment. This corresponds to the processes in Figure 1, which are performed by stations or cells in the industrial cases.

4.1 The proposed and applied design approach

In Figure 4, a general design approach for applying MC theories and methods onto MMS is proposed, as inspired by modular product development. The circular arrows show the mutual interactions between the different phases and indicate the iterative design process. In the following sections, the approach is applied to three distinct cases.

The industrial cases have the same overall scope of moving the design and development of manufacturing equipment from ETO against CTO. However, within the individual cases, we apply different MC theories and methods. Because of imposed confidentiality issues, only excerpts from the conducted industrial cases are presented in the following.

4.2 Scape Technologies A/S – industrial bin-picking cells

Scape Technologies A/S develops industrial bin-picking systems (Scape Technologies A/S, 2011). Bin-picking is the process of picking randomly placed parts from boxes or bins, and feeding them precisely to manufacturing machinery for further processing. The Scape Technologies bin-picking systems typically consist of one or two industrial robots equipped with bin-picking vision system(s) and gripping tool(s). In an industrial part feeding workstation, the Scape Technologies bin-picking system constitutes a functional subsystem in terms of the process of identifying and handling the objects. Since no generic robot tool has been developed, which can grip all parts, different tools suited for picking and placing particular part geometries are used. Figure 5 shows the main components of the bin-picking process, including the robot controller, robot arm, robot tool, vision system, bin unit, and robot base (Saboori et al., 2011).
Scape Technologies is a rather new company, therefore their products (bin-picking systems) are under continuous development. The design process at Scape Technologies is generally ETO-based, as main parts of the bin-picking cells are engineered after a customer order takes place. To become more competitive, in a highly dynamic market, Scape Technologies wants to move towards CTO. This is realised by applying modular family architectures and platforms.

4.2.1 Family and architecture scope

The work on transforming the bin-picking systems into modular platforms is performed with offset in a preliminary market analysis, incoming leads, and the company’s history of related projects. I.e., projects, which has formed the current bin-picking concept and clarified the target customer group. This is further elaborated in Saboori et al. (2011).

4.2.2 Module candidates

Initially, a PFMP is conducted to create an overview and a communication platform, i.e., an offset for identifying module candidates with the needed span of variety to fulfil the individual customer needs within bin-picking. According to the theory of domains (Andreasen, 1980), three viewpoints are needed to describe a product family: customer, engineering, and part view, which are contained in the PFMP tool. The views are related in the sense that the product family (the engineering view) shows variety to the market (the customer view) and commonality to the production system (the part view). An overview of a product family, based on these three views, enables reduction of non-value-adding variety and identification of potential standard designs (Harlou, 2006). At Scape Technologies, the customer view contains properties of the bin-picking process, which are interesting from the customers perspectives, i.e., production cost, price, cycle time, picking-part specifications, etcetera. These features are defined on the basis of the family and architecture scope, i.e., through a preliminary market analysis and discussion with people familiar with market demands and customer requirements. In the engineering view, a functional decomposition of the bin-picking process is modelled, i.e., robot manipulator unit, tool unit body, bin unit, etcetera. At this point, it is not possible to model the part view due to the development state of the technology and the related leak.
of detailed product knowledge. Extracts of the PFMP are shown in Figure 6, where the customer view is focused on the picking-part specification and the engineering view is concentrated on the standard variant of the tool unit body.

**Figure 6**  Customer view (left) and engineering view (right) of the PFMP (see online version for colours)

Notes: The blue circles represent the general structure (part-of structure), whereas the yellow circles represent the variety (kind-of structures), as inspired by object oriented modelling.

In general, it was experienced that modelling the customer and engineering views helped to define standard terminologies (e.g., tool unit body), to create a common overview of the product (system) and market, and to provide indication of the required variance (e.g., in terms of customer specific part geometries). From the customer and engineering views, it is possible to define the overall modular entities (module candidates) of the bin-picking process, which serves as input to the architecture modelling and hereby the subsequent product design/redesign phase related to the implementation. It is important to include design restrictions and confinements of the functional parts, in terms of PFMP-specific design rules, to define how the bin-picking equipment can be (re)configured. A successfully applied tool for describing such rules is combination tables. An example is provided in Table 2, showing a correlation between the robot manipulator type and tool unit type with respect to various picking-part specifications (Saboori et al., 2011).

**Table 2**  Combination table; linking various picking-part specifications (customer needs) to the manipulator and tool unit type

<table>
<thead>
<tr>
<th>Picking-part weight (kg)</th>
<th>Manipulator type</th>
<th>Tool unit type</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–1</td>
<td>KUKA Kr5_sixx/Kr5-arc</td>
<td>Compact</td>
</tr>
<tr>
<td>1–5</td>
<td>KUKA Kr16</td>
<td>Standard</td>
</tr>
<tr>
<td>5–15</td>
<td>KUKA Kr30/Kr60</td>
<td>Standard/large</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

**4.2.3 Modular manufacturing architectures**

The GOD (Harlou, 2006) has been applied to model the structure and interfaces of the modular bin-picking family architecture. The GOD utilises a block diagram formalism,
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where each block represents an organ or a group of organs, and interfaces between organs are drawn as connecting lines. As a starting point, the modular entities of the engineering view are represented as blocks in the GOD. In this way, it is possible to sketch the GOD for each bin-picker product variant or family by specifying suitable interfaces among the organs. By comparing the GOD’s for the various products and/or product families, one can identify the standard designs and, hereby, the family architecture. An extract of the GOD is shown in Figure 7, where an example of a standard design is the robot picker unit (robot manipulator, Scape controller, and bin-picker kit), while an example of a design unit is the customised bin unit.

**Figure 7** Family architecture model of the bin-picking process represented by a GOD (see online version for colours)

Based on the GOD(s), it is possible to specify modular platforms for the bin-picking family, i.e., a formalisation and realisation of the family architecture. To obtain useful modular platforms, a more detailed market analysis is performed, which may reveal non-value-adding elements (unnecessary variety) in the product assortment. Here, the market analysis focuses on highly demanded processes. Based on this, it is possible to assess available modules with respect to more precise market demands and specify modular platforms with consistent details. Platforms can be defined in different levels; component-, unit- (collection of components), and/or workstation/cell-level (collection of components and/or units). From the conducted market analysis, it is experienced that achieving reuse requires focus on modules at the component- and unit-levels, respectively. Modules and basic configurations (combinations of module variants) is defined by relating market information to the structural information of the GOD – this in an iterative process supported by use of combination tables. An extract of the specified modular bin-picking platforms are shown in Table 3. The robot picker unit is a modular platform, in the unit-level, with three variants (A, B, and C), consisting of the modular subunits (components); robot manipulator, robot controller, tool unit, and tool control unit.
### Table 3 The robot picker unit platform; units and components

<table>
<thead>
<tr>
<th>Robot picker unit</th>
<th>Robot manipulator</th>
<th>Robot controller</th>
<th>Tool unit</th>
<th>Tool control unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>KUKA Kr30/Kr60</td>
<td>KUKA Krc Standard/large</td>
<td>Attached</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>KUKA Kr16</td>
<td>KUKA Krc Standard</td>
<td>Attached</td>
<td></td>
</tr>
</tbody>
</table>

4.3 Grundfos A/S – the AIMM ‘little helper’

Grundfos A/S (Grundfos A/S, 2011), the world’s leading pump manufacturer, wants to expand their automation toolbox by means of autonomous industrial mobile manipulators (AIMM). A project has been running since 2007 with the aim to develop the AIMM ‘little helper’, which is a flexible manufacturing assistant on workstation level (Hvilshøj and Bøgh, 2011). Figure 8 shows the main systems of ‘little helper’: mobile platform, manipulator, vision, and tooling.

As the AIMM technology is a versatile automation solution, covering the application areas of logistics, assistance, and service, it is necessary to maximise the operational flexibility of the system. However, it is not technically and/or economically feasible to create a universal AIMM system that can solve all potential tasks. Furthermore, it is unacceptable to have a specific AIMM configuration for every single task. By creating modular and (re)configurable family architectures, the AIMM system(s) can be adapted to various manufacturing applications and tasks (customer requirements).

4.3.1 Family and architecture scope

To clarify the family and architecture scope for the AIMM technology, it is necessary to identify suitable manufacturing applications for this emerging technology. In the literature, there exist many methodologies for analysing manufacturing facilities. However, these methodologies are concentrated on evaluation of the production performance and are not suited for identifying application areas for emerging
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Technologies. Therefore, the TPMT methodology has been developed, which can be used for identifying, classifying, and evaluating applications and opportunities for technology-push automation and robotics technologies in industrial environments. Overall, the TPMT methodology is based on a comprehensive analysis at manufacturing task level (input/output, environment, technology, and process), as elaborated in Bøgh et al. (2011b). In this specific case, we explore the suitability of AIMM applications by applying the TPMT methodology at the Grundfos manufacturing facilities in Bjerringbro (five distinct factories). In this way, it is possible to map representative industrial applications (customer needs) to the AIMM technology (functionalities). Results from the conducted TPMT analysis, based on 566 manual manufacturing tasks, are shown in Figure 9. In general, it is observed that the AIMM technology, at its current stage, finds most suitable applications within the logistics area, moving towards assistive tasks, and in the future more service-minded and other non-production related tasks.

Figure 9  AIMM suitability according to representative manufacturing applications at Grundfos (see online version for colours)

Based on the TPMT analysis, it is possible to classify and generalise the identified customer needs and requirements. While each manufacturing task has specific requirements, e.g., in terms of parts, tact times, communication protocols, and environmental characteristics, it is important to identify similarities and common challenges to realise a modular and (re)configurable AIMM architecture. For instance, industrial part feeding tasks have a lot of similarities, e.g., the same overall structure for material handling: pickup → transportation → empty at feeder → transportation→ place, but at the same time they differ in other aspects, e.g., the parts to be handled, the feeders to be serviced, and the workstations to be operated. To address this, application scenarios are generated, which take advantage of the similarities within and in-between application categories. An application scenario for the logistics area is shown in Figure 10 (left). To formalise this knowledge, a PFMP model has been created. An extract is provided in Figure 10 (right).
Figure 10 Application scenario for the logistics area (left) and identification of commonalities by a PFMP model (right) (see online version for colours)

Figure 11 General mapping ideas between AIMM modules and skills (up) and an extract of a detailed mapping table (bottom)

<table>
<thead>
<tr>
<th>Task description</th>
<th>Tasks</th>
<th>Skills</th>
<th>Modules</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fetch container X from storage</td>
<td>Go to storage</td>
<td>Move arm to home position</td>
<td>Robot manipulator</td>
</tr>
<tr>
<td>Localise X</td>
<td>Platform move to station</td>
<td>Move arm to localise location</td>
<td>Mobile platform</td>
</tr>
<tr>
<td>Pick up X</td>
<td>Acquire and process image</td>
<td>Move arm to ‘pick’ location</td>
<td>Vision system</td>
</tr>
<tr>
<td></td>
<td>Move arm to ‘place’ location</td>
<td>Close gripper</td>
<td>Robot manipulator</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Open gripper</td>
<td>Tooling system</td>
</tr>
</tbody>
</table>
4.3.2 Module candidates

Specifying the customer needs by a PFMP model (Figure 10, right) makes it possible to identify the commonality and variety of the manufacturing tasks (processes). Within the manufacturing domain, the functions of products (MC) correspond to the skills of manufacturing equipment (MMS). Therefore, a module is characterised by its skills, which represent the functionalities in relation to the process. In this case, module candidates are identified by extracting the required skills and by relating these to the individual systems (modules). This is inspired by axiomatic design (Suh, 2001) and theory of domains (Andreasen, 1980). In Figure 11, examples of AIMM modules and skills are provided, by the general mapping ideas (up) and an extract of a detailed mapping table within the logistics domain (bottom).

In the long run, the necessary AIMM skills (functionalities) must be identified for all potential tasks and applications within logistics, assistance, and service. By comparing the different application scenarios, it is possible to discover their similarities and varieties, and, hereby, to find a modular and (re)configurable AIMM family architecture and platform.

4.3.3 Modular manufacturing architectures

The above steps provide substantial information for architecture modelling, making it possible to formalise the module candidates (building blocks) into modular AIMM architectures. To realise this, a GOD has been created, as shown in Figure 12 (right). Currently, the application scenarios from Grundfos are being further analysed to identify specific AIMM standard designs and, hereby, suitable AIMM family architectures and platforms.

Figure 12 Main AIMM building blocks (left) and an initial ‘little helper’ architecture, including modules and interfaces (right) (see online version for colours)

4.4 Adept Technology Denmark – modular automated manufacturing cells

Adept Technology Denmark is part of the automation manufacturer Adept Technology Inc. (Adept Technology Denmark, 2011). The activities of the Danish department are concentrated on the automation platform OctoMation, which is tailored for handling
applications within the food industry. Typical applications are packaging of food items into boxes or loading such items into third part process equipment. In practice, OctoMation is implemented as the driving station in a manufacturing cell and interface both internally to other stations (own or third part) of the cell and to the surrounding manufacturing lines/systems. In general, the customers of OctoMation expect a system, which comply with their specific requirements concerning products, layout conditions, sanitation, flexibility, and etcetera. In order to become more competitive in a highly dynamic market, Adept Technology Denmark wants to develop the OctoMation systems as a combination of standard modules; moving from ETO towards CTO, as illustrated in Figure 13.

**Figure 13** Typical material handling cells (OctoMation) from Adept Technology Denmark (see online version for colours)

Source: Adept Technology Denmark (2011)

4.4.1 Family and architecture scope

The work on transforming OctoMation into a modular platform is performed with offset in Adept Technology Denmark’s history of related projects. I.e., projects, which has formed the OctoMation concept and clarified the target customer group, the utilised technical solutions, the physical capabilities, and etcetera.

4.4.2 Module candidates

From these earlier projects, experience and understanding are obtained concerning customer needs, how to construct the systems, and how to utilise involved technologies – i.e., tacit knowledge of the project participants fundamental to form module candidates and develop the subsequent modular architecture(s). In this specific case, a bottom-up approach utilising the part view of the PFMP tool (Figure 14, left) is applied to extract and formalise this knowledge. The work is performed in numerous workshops, where the part view is established gradually, by discussing the reasons behind the existing designs, selected technologies, component groupings, variations, and etcetera. To get an AS-IS overview of the overall OctoMation system and its potential module candidates, the customer and engineering view of the PFMP are constructed directly from this knowledge. Based on the PFMP views, inexpediencies in the existing mapping relations
between the three views (customer, engineering, and part) appear - inexpediencies, which serve as input for redesigning the engineering and part view, and to form a preliminary version of the modular structure.

**Figure 14** Extracts from the PFMP part view (left) and abstraction levelling (right) of the OctoMation systems (see online version for colours)

Furthermore, a modular function deployment (MFD) analysis is performed to evaluate the modular structure and generate documentation cards on the module candidates. The MFD showed difficulties regarding completing the first two steps – steps which require extensive customer and product knowledge. By completing these steps in-between workshops, the table knowledge representation, the module drivers, and the interface matrix formed a nice offset for evaluating the PFMP results by new discussions and related knowledge extraction. However, the work of identifying module candidates showed difficulties regarding obtaining and maintaining the required overview across the company divisions. In response, abstraction levelling is introduced to the PFMP and MFD models to reduce complexity, in terms of top-level modules by which internal modularity is analysed and build separately, as shown in Figure 14, right.

The obtained modular structure is tested against new incoming project proposals, a test which tend to introduce refinements to the customer view, and consequently to the overall modular structure (architecture). To establish a solid basis for the modular structure, additional market knowledge is encapsulated by a holistic analysis of the manufacturing needs. The analysis takes offset in the customer’s market situation and includes both the directly given demands and the indirectly given demands (e.g., the stakeholder interests). The analysis framework and a general analysis of the production demands related to today’s dynamic market conditions can be found in Joergensen et al. (2011b). Introducing such manufacturing needs in the PFMP and MFD tools reveal a leak of knowledge regarding corresponding technical solutions, product parts, and properties – a leak, which complicates the utilisation of the applied tools.

### 4.4.3 Modular manufacturing architectures

In this case, a modified version of the GOD tool is applied to clarify interfaces and to generate a communicational overview. The method utilises a block diagram formalism of the GOD, but models on a functional level and introduces further levelling. The method is applied on a product segment (the air system of the OctoMation platform – Figure 15), which until now has been considered too complex and too project dependent to be
standardised. The model provides a graphical overview of the functions, which serves as a strong platform to discuss product variety, standardisation, functional grouping, and etcetera. In this particular case, the method resulted in successful modularisation and standardisation of the air system of the OctoMation platform. An excerpt is shown in Figure 15.

Figure 15  A modified GOD of the air system of the OctoMation platform (see online version for colours)

4.5 Experience and results

The architectural work in the industrial cases, the subsequent practical implementations, and later sales projects have shown general increase of reuse, lowering of project lead times, improved quotation and project proficiency, increased development speed, and strategic development focus. This indicates that decomposition of manufacturing by the modular characteristics of MC enables modular benefits. Furthermore, it is learned that achieving MC benefits, require a MMS structure developed with offset in the customer needs and concurrent involvement of technical issues. This indicates a general compliance with the domain-based design theories of modularity such as axiomatic design (Suh, 2001) and theory of domains (Andreasen, 1980) and, hereby, the methods of PFMP (Harlou and Nielsen, 1999) and modular function deployment (Erixon, 1998).

Based on the conducted industrial cases, it is the general impression that the MC methods are meaningful for MMS development, but that modifications and extensions are required, such as surrounding methods for knowledge gathering. In addition to the architecture development, the MC theories and methods establish a common understanding and vocabulary, which improve the communication of the MMS design and development process. Finally, the performed cases illustrate the importance of architectures in the design, development, and maintenance of MMS by formal structures, overviews, and design rules.

When applying MC methods in the manufacturing domain (the cases in Section 4), a leak in knowledge and overview is experienced, corresponding to the theoretical appointed gaps of design tradition and product complexity (Section 3). As an offset for modularisation and architecture development, it is found that machine builders can benefit from knowledge and experience from previous projects and leads within the same market and/or product scopes. The development process and knowledge level is iterative and, hereby, also the fundament for the modular structure. Therefore, a solid knowledge state must be obtained before the architectures are formalised and interfaces frozen. From
the conducted cases, it is our general impression that a substantial part of the required knowledge for modularisation exist, at least to an extent where qualified assumptions can be presented. This is in terms of tacit knowledge among technical experts, designers, salesmen, customers, and business partners, which needs to be extracted, formalised and merged. Involving work approaches (e.g., workshops and seminars) are found suitable for this, where the applied MC methods (e.g., the PFMP) form a useful offset for communication regarding modularity and architectures. It is experienced that the various MC methods must be adapted and mixed according to the specific case, i.e., the conditions, the current states, the type of people involved, and etcetera. From the applied methods, it is observed that PFMP provides a useful framework for knowledge gathering through communication and discussing, especially regarding the early stages of the modularisation process. Furthermore, the GOD complements PFMP in relation to graphical representations, a quality which tent to create alternative views in the discussions, by which further information appear. MFD has an extensive initial knowledge demand, but when overcoming this, the method shows usefulness regarding module discussions, questioning based on module drivers and interface matrices, and documentation by making the architectural decisions explicit accessible. In general, it is important not to view the methods as competitors, but rather as complementary methods to be mixed, adjusted, and/or extended according to the needs of the specific situation. Sometimes, the existing methods fall short, which calls for new methods, like the TPMT methodology applied at Grundfos. Finally, additional inspiration for supporting tools and methods can be found in manufacturing development theory (e.g., Bellgran and Kristina, 2010) and ETO-based product development theory (e.g., Ulrich and Eppinger, 2003).

From the industrial cases, it is observed that both direct and indirect customer demands are required to design the MMS and, hereby, that a broad view on stakeholders are needed. The increased complexity of manufacturing entails a limit in the applied MC methods’ ability to provide the required overview and to develop modular manufacturing architectures. In general, levelling and system theories are well-known tools to limit complexity of manufacturing systems and to divide these into manageable parts (Bellgran and Kristina, 2010). All the conducted cases show positive results of introducing levelling to existing MC methods. Inspiration for further research, in this area, can be found in the multi abstraction levelling approach for PFM, as presented by Petersen (2008) and Joergensen (2010).

5 Discussion

The industrial cases concentrate on development of industrial automation equipment. Therefore, further research is recommended to analyse implementation of the proposed methodologies for other types of manufacturing equipment and for the higher structuring levels of manufacturing. Furthermore, to make the results directly applicable for industry, a general design framework is needed. It is our general impression that the proposed three step architecture development model (Figure 4) is a suitable basic approach, but the methods within the steps must be further formalised and refined, e.g., in terms of a library of tools to be adapted to the specific case. Contrary to traditional architecture development, where standard designs are developed up-front, a user driven design approach is needed within the manufacturing domain. This is due to the knowledge gaps,
high diversity of manufacturing systems and equipment, and related low sales volume in comparison to traditional MC products. To obtain a user driven design paradigm, MMS architectures must be developed as architectures with planned standard designs and design units – i.e., units defined by black boxes, which are developed as projects come along. In coherence to the architectural terms of MC, MMS architectures define the way functional elements are arranged into units, and the way in which these units interact. Hereby, the MMS architectures form a skeleton for development, which defines the grouping of functions into units, interfaces, design rules, compatibility, reuse, and etcetera. Based on this, it is possible to achieve the aimed benefits, such as responsiveness to evolve manufacturing systems according to the production and product needs.

6 Conclusions

Today, most manufacturing systems are developed as ETO solutions tailored to produce a limited product mix. However, such dedicated systems are not consistent with the current market demands. In response, MMS are evolving, which are aimed to possess the required responsiveness and to be the manufacturing paradigm of MC. Hereby, MMS brings the design and development process of manufacturing systems against CTO. Up to now, research in MMS has primarily focused on potential benefits, basic principles, and enabling technologies, while the approaches of actually designing and creating modular architectures have received less attention. A potential to fill these gaps by applying MC theories and methods is identified, by regarding manufacturing systems and equipment as products. This paper has analysed this potential and explored it through three typical cases within the domain of industrial automation by proposing and applying a three steps approach: family and architecture scope, module candidates, and modular manufacturing architectures. From this, MC is found to possess a potential to bring MMS development forward – this in terms of application of theories and methods within modularisation, architecture development, and PFM. The domain differences have shown a need for modifications of existing MC methods, as a consequence of a changed development offset (from standard products to ETO) and an increase in product complexity. The conducted cases illustrate that MC methods are relevant for MMS development, but require modifications and extensions, such as surrounding methods for knowledge gathering and levelling. It is observed that inspirations for such modifications and extensions can be taken from traditional manufacturing development and ETO-based product development theory.

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