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# DESIGN OF RECONFIGURABLE MANUFACTURING SYSTEM ARCHITECTURES

## METHODOLOGY FOR LOW VOLUME INDUSTRY

BY
MADS BEJLEGAARD

DISSERTATION SUBMITTED 2017

AALBORG UNIVERSITY
DENMARK

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Dissertation submitted

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# PREFACE

The dissertation at hand is a result of an Industrial PhD project conducted in the period from August 2014 to August 2017. The PhD project was conducted as a joint project between Department of Materials and Production at Aalborg University and a Danish SME. The latter is a manufacturer of construction machinery and served as industrial partner throughout the three-year project period. The project has been funded by the Danish Ministry of Higher Education and Science and by the industrial partner.

As an Industrial PhD student, you act as a link between the academic world and industry. Hence, both the interests of academia and industry are reflected in the research related to this project. This means that the project contributes to both academia by creating new knowledge but also by producing applicable and implementable results useful to the industrial partner. The interests of the two partners are thus reflected in the dissertation. The dissertation is structured in two parts; an extended summary followed by a collection of some of the papers resulting from this project.

When I look back on the past three years, it leaves me with many good experiences and memories. Now, numerous educational commitments at the university and at the industrial partner, a number conferences participations, and numerous industrial visits both national and international later, the project has come to an end. I will look back at an exciting journey that brought new insight, and many new friendships and new professional relations.

I would like to thank my supervisor, Associate Professor Thomas Ditlev Brunø, and co-supervisor, Associate Professor Kjeld Nielsen, for giving me the opportunity to conduct this research first of all. Secondly, I would like to thank you both for your sustained support and for inspiring, guiding and encouraging me throughout the project. Your support has been highly appreciated. In this regard, I would also like to thank the members of the entire Mass Customization group for being the best colleagues I could hope for.

I would also like to express my gratitude towards Professor Hoda ElMaraghy and Professor Waguih ElMaraghy for the opportunity to take part in the research environment at the Intelligent Manfacturing System Centre, University of Windsor, and for providing me with invaluable insight into the world of Reconfigurable Manufacturing Systems. In this regard, I would also like to thank the entire group at the IMS Centre for making my stay to a wonderful experience that gave me the best memories.

I would also like to thank my industrial supervisor, R&D Manager Thorkil K. Iversen, for sharing your experience from practice, and for challenging me to keep an operational focus.

Last but not least, I would like to express my deepest gratitude for the moral support, love, and understanding from my family. Your enduring support and sustained encouragement has meant a lot to me. Although it is only a humble expression of my deepest gratitude, I would like to dedicate this dissertation to you.

Aalborg, August 2017

Mads Bejlegaard

# ENGLISH SUMMARY

This dissertation presents two novel methodologies, which enables low volume companies to design reconfigurable manufacturing system architectures on two different factory structuring levels.

In order for manufacturers to be able to compete in today's global market, they should be in a position where they are able to rapidly change to the present required functionality and capacity. Such demands can be met by the responsive Reconfigurable Manufacturing System, which has been referred to as the new manufacturing paradigm. However, the transition towards a reconfigurable manufacturing system in low volume industry is largely unexplored. Consequently, two methodologies for Reconfigurable Manufacturing System architecture design for low volume industry is provided in this dissertation. These methodologies enables low volume manufacturing companies to reach increased responsiveness through reconfigurability, which provides them with competitive advantages.

The two methodologies are concerned by architecture design on two interdependent factory structuring levels; machine level and system level. Hence, one of the two methodologies addresses architecture design of Reconfigurable Machines, whereas the second methodology addresses architecture design of the system into which the machines are arranged and interlinked with the specific context of high variety low volume production. The two methodologies has been synthesised based on existing literature on Reconfigurable Manufacturing System design, and subsequently design issues within each design phase has been related to low volume industry. The constituent publications of this dissertation addresses both isolated design issues related to one or a few design phases, and the entire sequence of design phases for architecture design on each of the two system levels.

Design of such Reconfigurable Manufacturing Systems has been scarcely described in literature, particularly in relation to low volume industry. At the same time practitioners in industry have expressed a need for practical guidance to design systems with increased responsiveness. Thus, the origin of the methodologies is based on a specific need in industry and a gap in literature. By applying the methodologies to an industrial case they proved to be practically applicable and the results of applying the methodologies revealed a promising potential of increased reconfigurability to the case company.

# DANSK RESUME

I denne afhandling præsenteres to ny metoder, som gør det muligt for lavvolumen producenter at designe rekonfigurerbare produktionssystemarkitekturer på to forskellige systemniveauer.

For at produktionsvirksomheder kan konkurrere på dagens globale marked, bør de være i en position, hvor de er i stand til hurtigt at tilpasse deres funktionalitet såvel kapacitet. Sådanne krav kan imødekommes med det rekonfigurerbare produktionssystem, som er blevet omtalt som fremtidens produktionsparadigme. Transformationen mod et rekonfigurerbart produktionssystem i lavvolumenindustrien er dog stort set uudforsket. Derfor præsenteres der i denne afhandling to metoder til at designe reconfigurerbare produktionssystemarkitekturer i lavvolumen industrien. Disse metoder vil gøre produktionsvirksomheder i lavvolumenindustrien i stand til at reagere på ændrede krav til funktionalitet og kapacitet hurtigt, hvilket vil give dem en konkurrencefordel.

De to designmetoder er fokuseret omkring arkitekturdesign på to indbyrdes afhængige systemniveauer, maskinniveau og systemniveau. Den ene af de to metoder adresserer således arkitekturdesign af rekonfigurerbare maskiner, hvorimod den anden metode adresserer arkitekturdesign af det system maskinerne indgår i. Metoderne er udledt med udgangspunkt i eksisterende litteratur om rekonfigurerbare produktionssystemer. Hernæst er de enkelte designmæssige problemstillinger i hver fase af designmetoderne sat i relation til lavvolumenproduktion. De publikationer som udgør afhandlingen adresserer både isolerede designmæssige problemstillinger, som vedrører en eller få designfaser, men også den samlede sekvens af designaktiviteter for arkitekturdesign på hver af de to systemniveauer.

Design af rekonfigurerbare produktionssystemer er kun overfladisk beskrevet i litteraturen, og specielt litteratur relateret til lavvolumenproduktion er mangelfuld. Desuden har industrien udtrykt et behov for praktisk anvendelige metoder til at designe systemer, som indeholder egenskaberne fra det rekonfigurerbare produktionssystem. Baggrunden for at fremsætte de to metoder tager derfor dels udgangspunkt i mangelfuld litteratur men samtidig også i et behov fra industrien. De to metoder er blevet afprøvet i industrien og de har vist sig praktisk anvendelige. Samtidig har resultaterne ved at anvende metoderne vist et lovende potentiale, da det medførte succesfuldt design af reconfigurerbare produktionssystemsarkitekturer.

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# CHAPTER 1. INTRODUCTION

*This chapter introduces the general context and the specific background of this dissertation. This includes a description of both the scientific motivation and the industrial motivation. The description of the latter will include an introduction to the industrial partner as well.*

Today's global, integrated markets put manufacturers in a position characterised by greater competition leading to limited time frames to enter potential markets, more frequent introduction of new products, and rapid changes in product demand (Koren, 2010a). In order to compete on a global market and hence gain the benefits of a global market, manufacturers should be in possession of manufacturing systems that can be rapidly changed to the present needed functionality and capacity. Thus, this new generation of manufacturing systems should have the capabilities to reconfigure its functionality to the current product mix and its capacity to the demanded product quantities (Koren, 2010a). These needs are met by the Reconfigurable Manufacturing System (RMS). It is capable to adapt its capacity and functionality to changes in volume and variety, and has with its responsiveness been referred to as the new manufacturing paradigm (Koren, 2010a; Mehrabi, Ulsoy, & Koren, 2000a; Mehrabi, Ulsoy, & Koren, 2000b). According to Megginson (1963) Charles R. Darwin wrote in "The Origin of Species":

> *"It is not the most intellectual of the species that survives; it is not the strongest that survives; but the species that survives is the one that is able best to adapt and adjust to the changing environment in which it finds itself"*

This statement apparently also applies to manufacturers of today's global markets. In any case, responsiveness is widely recognized to enable manufacturers to compete on a global market (H. A. ElMaraghy, 2005b; Koren, 2010a).

This dissertation aims to present two novel methodologies to guide practitioners in the process of designing Reconfigurable Manufacturing Systems in low volume industry, which allows manufacturing companies with such characteristics to reach increased responsiveness through reconfigurability (i.e. ability to adapt to new functionality or change for new capacity in profitable way). The suggested methodology focuses on architecture design on two interdependent factory structuring levels (i.e. both the manufacturing system and the included machines). An additional focus is put on low volume industry due to previous limited interest in academia and a need for guidance to practitioners in industry. Thus, the origin of the methodology builds on both an academic and an industrial demand for a practical, applicable methodology for reconfigurable manufacturing system design. This claim is supported by the following introduction to the state-of-the-art of this research field and by the empirical context. The latter describes how the industrial partner is motivated by this research project.

Throughout the dissertation reference will be made to the constituent publications, which are enclosed in the appendix, e.g. by referring to Paper 1, Paper 2, and so forth.

## 1.1. SCIENTIFIC MOTIVATION

The need for a methodology to design reconfigurable manufacturing systems have motivated the research reported in this dissertation. In this section, the Reconfigurable Manufacturing System (RMS), current practices for design of RMS, and its relation to low volume industry, is introduced.

### 1.1.1. RECONFIGURABLE MANUFACTURING SYSTEMS

The responsive RMS is characterised by the capabilities to adjust the capacity to the volatility of product volume and to adapt the functionality for new product introductions or product variety in general (Koren & Shpitalni, 2010). Thereby, the traditional, dominating systems as flexible systems and dedicated manufacturing lines are ill suited to meet the new requirements to responsiveness at a reasonable cost, in contrast to RMS (Koren, 2006). The dedicated lines operate with fixed automation and produces only one or a few parts or products over a long time period and is intended for high volumes. Thus, the cost per part can be relatively low when product demand is high. However, dedicated lines do not necessarily operate at full capacity in today's dynamic markets (Koren, 2006; Koren & Shpitalni, 2010). Thereby, the dedicated lines may operate with excess capacity during their lifetime (Andersen, Bejlegaard, Brunoe, & Nielsen, 2017) and with their rigid structure they will get obsolete before more flexible systems. At the other extreme, flexible systems are characterised by the capabilities of producing a high variety of products in different orders on general-purpose machines. However, these systems are also rather expensive and provides a low throughput, why the cost per part or product is relatively high, the capacity is in most cases lower than that of the dedicated lines (Koren, 2006; Koren & Shpitalni, 2010), and it provides excess flexibility (Mehrabi, Ulsoy, Koren, & Heytler, 2002; Zhang, Liu, Gong, & Huang, 2006). RMS combines the high throughput from the dedicated systems and the flexibility from the flexible systems (Koren, 2006). It holds the capabilities to rapidly and cost efficiently adapt the systems elements for new functionality and capacity as a response to market change (Koren & Shpitalni, 2010). This reconfigurability is enabled through the six core characteristics, namely customization, convertibility, scalability, modularity, integrability, and diagnosibility (Koren, 2010a). Customisation refers to the fact that reconfigurable manufacturing system should be design across a part or product family to enable customised flexibility, which essentially is about making a trade-off between efficiency and flexibility. Convertibility and scalability refers respectively to functionality change and capacity change, which is enabled through modularity (i.e. modular system elements) and integrability (i.e. interfaces for rapid integration). Diagnosability refer to a system that is designed for easy diagnosis and rapid correction of operational defects. These characteristics allow the RMS to reuse system elements and thus extent the lifetime of the system, and keep a relative high throughput across a relative high variety of parts or products (Koren & Shpitalni, 2010; Mehrabi et al., 2000a; Mehrabi et al., 2000b).

In literature, reconfigurable manufacturing has mainly been describe through the RMS concept, but other concepts with similar characteristics has been introduced. Though the research lacks in a thorough comparison Brunoe et al. (2017) describes how holonic manufacturing, modular manufacturing systems, and focused flexible systems have in common that manufacturing system modularity is applied as a means for reconfigurability. However, the RMS concept is largely described in literature through the RMS concept.

### 1.1.2. RECONFIGURABLE MANUFACTURING SYSTEM DESIGN

RMS have gained growing attention since the concept was first published in the late 90's (Koren et al., 1999). However, despite that numerous contribution exist on RMS, a systematic design methodology for RMS is lacking (Andersen, Brunoe, Nielsen, & Rösiö, 2017). Additionally, only few practical examples with an industrial application of RMS has been provided. One example is provided by Harder & Bilberg (2014) but a design methodology does nor in this case explicitly appear. With regards to RMS design, various research issues are being covered in publications. Generally, these are relevant to different stages of the design process (Andersen et al., 2017) and can furthermore be divided on a number of factory structuring levels (Andersen, Brunoe, & Nielsen, 2015b).

The conventional methods for manufacturing system design do not fully support the design of RMS (Andersen et al., 2017; Rösiö & Säfsten, 2013). They are not applicable for RMS design, as they do not consider important design issues like those that are described in following. First, since the RMS should be designed to cope future product generations to extend the lifetime of the system, it requires a long-term view in the design process predicting how the markets may evolve (i.e. identifying changeability requirements). Secondly, these requirements imply that the design of RMS is integrated with product design (i.e. co-developed) and that product and production systems are designed to evolve coordinated (i.e. co-evolved). This will help to succeed in production of multiple product variants and future product variants using the same manufacturing equipment. Finally, the manufacturing system design influences the configuration opportunities during the lifetime of the system, which is also related to finding the optimal configuration (i.e. optimal configuration and granularity levels for reconfigurations). These three design issues are not supported in conventional manufacturing system design methods. Additionally, conventional methods do not treat reconfigurability characteristics (Rösiö & Säfsten, 2013). It has been commonly agreed that a method for RMS design has been lacking (Z. Bi, Lang, Shen, & Wang, 2008; H. A. ElMaraghy, 2005a; Rösiö & Säfsten, 2013). However, a recently published article by Andersen et al. (2017) presents a first attempt to put forward a generic method for RMS design based on synthesis of existing publications on RMS design. The literature is divided into phased design methods and cyclic design methods, which respectively cover sequences of design phases and the logic of problem solving within phases. These are all synthesised into a generic design method that cover the entire design process for reconfigurable manufacturing system design, though some areas are better covered than others. Of the phased design methods, the following can be mentioned. The RMS design approach by Rösiö et al. (2012a; 2012b), covers three phases, namely initiation, preparatory design, and detailed design. The design method by Schuh et al. (2009), is divided into identification and clarification of change drivers, describing change profiles linking change drivers with properties of system elements, determination of interdependencies between system elements, and creation of modules. Heisel and Meitzner (2006) presents eight steps, which among the others cover identification of reconfigurability requirements, quantifying the reasonable extent of reconfigurability, and identification of characteristics of modules for reconfigurability. Deif and ElMaraghy (2006) presented an RMS design architecture consisting of three layers; a market capture layer in which functionality and capacity requirements are derived, a system-level reconfiguration layer in which suitable configurations are suggested based on requirements from the market layer, and a component-level reconfiguration layer which addresses the effect on systems components (i.e. physical, logical, and human) and thereby the implement the suggested configuration. Tracht and Hogreve (2012) presents five phases focusing on both conventional design steps but also decision related to modular systems that has to be made during design, implementation, and reconfiguration. Of design methods for RMS design, which implies a problem solving cycle the following can be mentioned. Francalanca et al. (2014) presents a design approach consisting of a requirements clarification with a subsequent analysis to identify the consequent criteria. This is followed by a synthesis of changeability levels, enablers, and design elements followed by a simulation and an evaluation. Abdi & Labib (2004; 2003; 2004) proposed a method based on a RMS design cycle containing system selection among alternative systems, grouping of products and selection of the configuration period they should be produced, and evaluation of configuration selection. Al-Zaher et al. (2013) presented a framework based on a life-cycle view of the manufacturing system and applied it to a case based on an automotive framing system. The framework includes four stages; manufacturing system analysis, manufacturing systems design, manufacturing systems operation and maintenance, and reconfiguration throughout the system's lifecycle. AlGeddawy and ElMaragy (2009) proposed a framework in which they emphasize the need for bi-directional design of products and productions systems, and thus it can be considered as continues design loop. Benkamoun et al. (2014a) specifies the manufacturing system from various levels and dimensions, and the design activities consist of requirements analysis, definition of functional components, designing of physical components, definition of the functional architecture, and design of the physical architecture. Though it is not presented as a design method, Bi et al. (2008) divided the RMS design process into three design issues. These issues represent a logical view on the RMS design process and can be considered as a phased design method. These three issues are categories in architecture design (i.e. involved in the phase of system design), configuration design (i.e. concerns the phase of system application), and control design (i.e. concerns the phase of operation). On the basis of the same understanding of the RMS design process, this dissertation focuses on architecture design and not the two remaining, which is concerned by design issues involved at phases after the system's implementation.

Though all these different approaches are focused around RMS design, they differs in a number of areas (Andersen et al., 2017). Firstly, the body of terms applied varies contexts although the ideas behind may be the same (Andersen et al., 2017). Secondly, the focus area of the design process differs comparing the different approaches. Whereas some start quite early by justifying the need for reconfigurability (M. R. Abdi & Labib, 2003), others considers rather late decisions, namely regarding the reconfiguration process after the system's implementation (Tracht & Hogreve, 2012). Nevertheless, there is a main focus on the actually design activities, though the structure of activities is not clear. Thirdly, some approaches have more focus on the actually reconfiguration of the system after its implementation, which implies integrated development of product and production systems, since changes in the product portfolio triggers reconfigurations of the manufacturing system. This area is reflected in a number of articles on co-evolution (H. A. ElMaraghy, 2007) and co-development of product and production system platforms (Gedell, Michaelis, & Johannesson, 2011). Fourthly, not much attention have been given to the first of the six reconfigurability characteristics, namely customized flexibility. This particular characteristic implies that systems are designed around a family but this issues is mostly treated in separate literature focusing entirely on this specific issue and not in a context. Fifthly, the different design steps and related procedures and tools are treated on different factory structuring levels in publication on RMS. Some contributions are mostly focuses on system level and does not consider the design of the lower levels, and thereby essential design decisions regarding levels, type, and degree of reconfigurability is neglected (Andersen et al., 2017). Sixthly, there can be seen a dominating focus on high volume industry, and not much attention have been given to reconfigurability in low volume industry. This is highly relevant since the level of which the potential is realized is not the same though the potential may be significant in both cases (Brunoe et al., 2017).

Even though these different approaches to RMS design are different in a number of ways a generic method is synthesized by Andersen et al. (2017), which includes five phases (i.e. management and planning, clarification of design task, basic design, advanced design, and reconfiguration). This common structure builds on a number of publication in which also different procedures and tools are suggested for different purposes along the design process. However, it is not evident from this work how design issues are addressed across companies with different characteristics and thus which methods, procedures, techniques, or tools to apply to implement RMS in different kinds of companies (e.g. transforming from a more rigid or more flexible system) or on the different system levels (e.g. machine level or system level).

In order to overcome the various design challenges reflected in the design phases, which can be derived from the literature above, supportive methods, procedures, techniques, and tools suitable for the specific design phase must also be identified. In 0 and 0 the two suggested design methodologies for machine level and system level are presented together with methods, procedures, techniques, and tools, which are suitable for design of reconfigurable manufacturing system architectures in low volume industry on the two respective levels.

### 1.1.3. RECONFIGURABILITY ON DIFFERENT FACTORY LEVELS

Publications on RMS design refer to different system levels. It is common to apply the factory structuring levels presented by Wiendahl et al. (2007). All levels do not necessarily exist in all companies but it is based on this terminology that this dissertation is demarcated, just as most literature within this field is. From the highest level to the lowest level they are divided in seven levels; network, site, segment, system, cell, workstation machine (Figure 1-1). Of these levels, this dissertation focuses on the two levels highlighted in Figure 1-1. These systems levels are relevant since reconfigurability is more relevant to some system levels than others depending on company characteristics. This will be elaborated in the following. A reconfiguration can either be physical or logical (Wiendahl et al., 2007), which refer to what is also known as hard and soft changes. Hard changes are dominating at lower structuring levels, whereas the soft changes are dominating at higher structuring levels. This dissertation reflects both soft and hard changes on two levels, which will be referred to as system level and machine level. Since the space view of system level and cell level is the same (Wiendahl et al., 2007) it can be argued that the methodology for system level suggested in this dissertation also will be applicable to cell level.

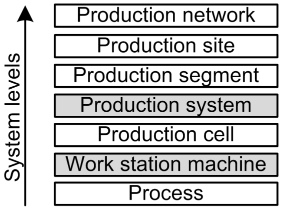


*Figure 1-1 Factory system levels (Wiendahl et al., 2007)*

Hard changes refer to adding, removing, or exchanging the physical system elements (i.e. changing the modular structure). Such changes are conducted on lower structuring levels, e.g. by reconfiguring a line or a machine for new capacity or functionality. One of the dominant research issues on lower structuring levels is how to design reconfigurable machines (RMs) (Z. Bi, Lang, Verner, & Orban, 2008). Embedding the characteristics of the RMS, RMs can achieve the capabilities to rapidly convert to new functionalities enabled by a modular structure in order to cope with product variety within a family or new product introductions (Z. Bi et al., 2008).The term Reconfigurable Machines cover different manufacturing equipment, both reconfigurable assembly systems, reconfigurable material handling systems, reconfigurable inspection machines, reconfigurable fixturing systems, and Reconfigurable Machine Tools (RMTs) (Z. Bi et al., 2008). RMs are key enablers to realize customized flexibility and thus the capabilities to reconfigure manufacturing equipment through configurations of its modules, which are restricted to a part or product family (Katz, 2007). Yet, effective implementations lack and RM are still not broadly available (Z. Bi et al., 2008). This statement is supported by a review conducted in relation to Paper 1. It is thus also important to see that reconfigurability can be achieved not only through RMs but also by adding, removing, and exchanging machines in general on system level. As it will be apparent from the following section with focus on the industrial motivation the commercial perspective of this dissertation leads to a focus on reconfigurable fixtures in regards to machine level. Limited research has been carried out on reconfigurable fixtures and only a few prototyping systems have been developed and those that exist are designed intuitively and a systematic design methodology is still lacking (Paper 1).

Soft changes refer to logical reconfiguration, which can include re-routing and re-planning and will most often be associated with higher structuring levels (Andersen et al., 2015b; Wiendahl et al., 2007). As it is mentioned above, reconfigurations on system level is achieved by adding, removing, or changing the modular system elements in order to obtain the capacity and functionality needed to respond on market demands (Koren, 2010b). Research issues on system level includes various topics which are relevant to different phases of the design process for RMS (Andersen et al., 2017) and the different methods, procedures, and tools suggested for the different design stages are not necessarily generic and thus not applicable in all cases (Paper 1 & Paper 2). That is particular important since it has influence on how design methods for RMS in different application areas may end up, since it may not be the same procedures and tools that is relevant to all types of companies. Nevertheless, RMS design in general is a particular important research issue that needs to be addressed, since it precedes all the remaining design issues on RMS design (M. R. Abdi & Labib, 2003; Andersen et al., 2017; Benkamoun, ElMaraghy, Huyet, & Kouiss, 2014b; Rösiö & Säfsten, 2013).

### 1.1.4. RECONFIGURABLE MANUFACTURING SYSTEMS IN LOW VOLUME INDUSTRY

As it is indicated by Brunoe et al. (2017), tools and methods, which are applicable to large companies, are not necessarily useful in Small and Medium enterprises (SMEs). The same reasoning can be transferred to industries with different volume characteristics. The vast majority of literature presents high volume examples, though it is likely that tools and methods must be adapted and implemented in a different way in low volume industry. However, Brunoe et al. (2017) reveal a potential benefit of implementing reconfigurability on machine level in SMEs with low volume, and thus that RMS is not reserved for high volume industry. The same conclusions can be drawn from Paper 1 and Paper 5.

Low volume industry will often be associated with flexible manufacturing systems, since such systems helps to avoid excess capacity, and dedicated systems will often require a major initial investment that cannot be justified. Thus, the transformation towards reconfigurability for low volume companies will likely be from a more flexible system. Conversely, high volume industry is associated with dedicated manufacturing systems, since this helps to keep high efficiency, why a transformation towards reconfigurability for high volume industry can be expected to be from a more rigid system. However, as stated by Andersen et al. (2017) the task of modifying existing systems does not change the design task considerably, whether it is from a more flexible or a more rigid systems. Supporting this statement, Wu (2012) argues that it rather sets the objectives of the design, while it is the same activities that should be conducted. However, it is reasonable to expect that tools and methods in each of these design activities may differentiate, whether it concerns the transformation from a more flexible system or from a more rigid system (Brunoe et al., 2017). Actually, the way to accomplish reconfigurability is quite different for high volume industry compared to low volume industry. One example often depicted in literature, is a reconfigurable manufacturing system with parallel lines, which produces components of the same part or product family. These lines can react to market changes by reconfiguring the system to produce another variant and thus share capacity (Andersen, Brunoe, & Nielsen, 2015a). However, it requires sufficient volumes to gain the benefit of sharing functionality and capacity across lines. This is typically not the case in low volume industry, since the volume is not nearly high enough to justify one line dedicated to one part or product family.

## 1.2. INDUSTRIAL MOTIVATION

As it has been mentioned, the research presented in this dissertation has been conducted in collaboration with an industrial partner. Thus, the related challenges of the industrial partner have also motivated the accomplishments of the research. Thereby, the industrial partner has been subject for data collection, case studies, interviews, etc. In the following section an introduction to the industrial partner and its related challenges is presented. This section will illustrate that the industrial partner seeks increased responsiveness, i.e. reconfigurability, which evidently shows that there is a match between the two gaps in academia and industry.

### 1.2.1. INTRODUCTION TO THE INDUSTRIAL PARTNER

The industrial partner Hydrema, is a Danish mid-sized manufacturer of construction machinery currently employing around 160 people at the facility subject to this project. Products are manufactured using assembly-to-order strategy. The majority of steel components are manufactured in-house at the same location. Other components, such as plastic components, engines, and electronics, are sourced from sub-suppliers. Similar to competitors and comparable industry, the steel components follow a common operation sequence applying commonly used process technology (i.e. general-purpose machines supported by auxiliary equipment) starting with cutting of metal plates followed by welding and machining. The production volume is to some extent influenced by seasonal variations but a large degree of customized solutions means that it is not possible to level out the production by manufacturing to stock. The industrial partner has an ambition to reduce stock and to reduce the lead time of manufactured components. Therefore, they wish to investigate how to reduce batches to one-piece flow, since manufacturing of large batches results in undesirable large stock. The annual production volume is approximately 200 machines, which can be divided evenly on two product families (see Figure 1-2) that each comes in a number of variants. Consequently, almost 2,000 different part numbers are active in order to produce these products. Thereby, to the industrial partner large batch sizes will result in undesirable large stock. However, with the current setup it has been proven impractical to reduce the batch sizes to one-piece flow, since the changeover times simply are too time consuming.

*Figure 1-2 Hydrema's wheeled excavator and backhoe loader*

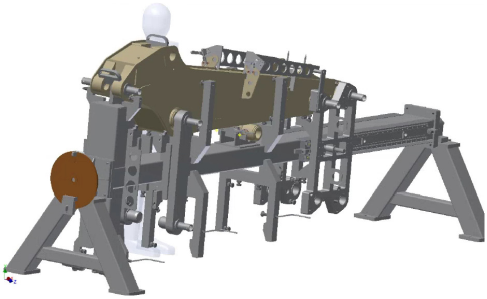


*Figure 1-3 Dedicated tack-welding fixture*

This industry is particular known for the use of large and heavy fixtures in the welding process of steel components (see Figure 1-3). However, handling of such fixtures is time consuming and influences the changeover time between the production of different variants because there is typically one fixture per product components. In this particular case, a changeover involves that the previous fixture is removed by forklift and transported to a warehouse after which the new fixture is located and transported to the welding station and set up for welding of the next product components. These changeovers can take as much as approximately 20 % of the process time. This may seem as a problem of balancing productivity and stock sizes, but such an approach will not eliminate the fact that these fixtures are difficult and time consuming to handle, which means that a lot of hours of payed work is tied up in transportation of fixtures.

### 1.2.2. TRANSITION TOWARDS RECONFIGURABILITY

Currently the industrial partner uses dedicated auxiliary equipment (e.g. fixtures), which is why it is highly relevant to the case company to investigate the potential of reconfigurable machines; especially reconfigurable fixtures, which seems to constitute a potential for reconfigurability at the origin of the project. The rationale behind replacing the existing dedicated fixtures with reconfigurable fixtures is the expectation that fixtures can be reconfigured rather that replaced to cope with part or product variety. This could potentially result in a reduction of the time spent on changeovers and it may also influence the time and resources spent on the introduction of new parts or products, since reconfigurable fixtures may be reused across product generations. Not only the operational benefits but also the potentially increased reuse of manufacturing equipment is a crucial argument for the industrial partner to invest in reconfigurability.

As explained above, the transition towards increased reconfigurability of the industrial partner will imply a transition from a more flexible system in general. This brings forward two important concerns. Firstly, as a low volume manufacturer producing products with relative high variety, the number of reconfigurations must be expected to be much higher in this industry compared to high volume industry. Reconfigurations can be expected to be a daily event in in the industrial partner, why it is important to reduce the changeover time when designing the equipment. Conversely, high volume industry may experience sequence of months or even years between reconfigurations and therefore they can accept a reconfiguration period of several hours or even days. Secondly, the low volume and the relatively high variety means that the variety handled in a workstation or at a machine is presumably higher than that of a high-volume manufacturer, which have a demand high enough to fill in the capacity on one part of the manufacturing system with parts or products with only limited variety. Thus, it can be expected that reconfigurable machines, including reconfigurable fixtures, need to be designed with enough functionality to reconfigure across much larger part variety than in high volume industry.

Reconfigurable machines are designed around a part or product family. Thus, by grouping parts and products into families in order to have a starting point for the design process may set the stage for a more focused factory. Conversely to the more flexible existing setup, a focused factory with machines dedicated to a family may also suggest that the relative distance between related machines is reduced. Thus, implementation of reconfigurability on machine level may open for increased efficiency on system level.

# CHAPTER 2. SCIENTIFIC APPROACH

*The scientific approach will be described in this chapter. The dominant scientific paradigm is the basis for selecting the methodological approach. This leads to the description of the related research methods and the methodological procedure applied. Then a framework based on the methodological procedure is applied to position the research questions and where they contribute to the research. Finally, the research questions are presented along with an argument for why they are included. Finally, the delimitations and the structure of the dissertation is presented.*

## 2.1. RESEARCH METHDOLOGY

Arbnor & Bjerke (2008) argue that it is wrong to state that there is one research methodology, which can be applied regardless the studied area. Instead, Arbnor & Bjerke (2008) presented a methodological framework for creating business knowledge, which relates to different types of research activities. The framework is illustrated in Figure 2-1. The framework illustrates how the ultimate presumptions constituting the paradigm are the basis for determining a methodological approach through theory of science. Then the operative paradigm is derived from the methodological approach. The operative paradigm contains different procedures and methods, which can be applied to the studied area. Following this logic, each of the elements will be addressed throughout this chapter in relation to this project.

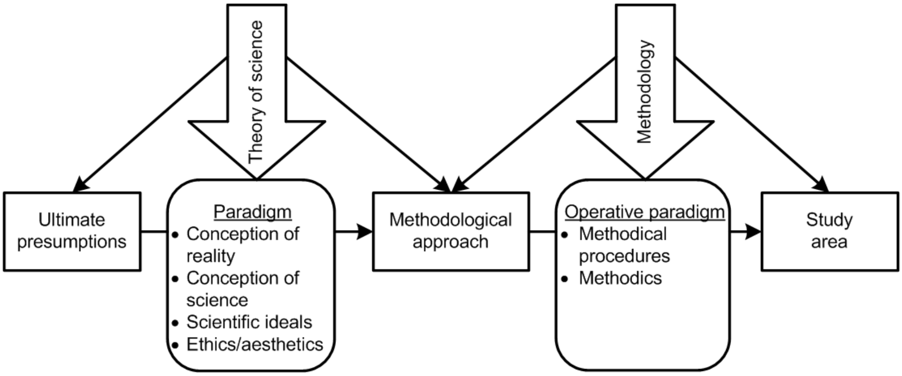


*Figure 2-1 Methodological framework*

### 2.1.1. ULTIMATE PRESUMPTIONS AND SCIENTIFIC PARADIGM

Researchers may have certain presumptions about their surroundings, which influences how a researcher approaches and addresses a problem. A paradigm is constituted by a set of such presumptions as it is defined by Kuhn (1962): A paradigm is a set of presumptions, values, and ideals, typically within a certain scientific area. Various classifications of paradigms have been proposed. Coughlan & Coghlan (2002) and Gummesson (2000) advocate for two views, i.e. positivistic and hermeneutic. Four classes are promoted by Guba (1990): positivism, post positivism, critical theory, and constructivism. Likewise, Creswell et al. (2003) promote four classes: post positivism, constructivism, advocacy/participatory, and pragmatism. Arbnor and Bjerke (2008) classified the social science paradigms into six categories, in-between the two extremes: objectivist-rationalistic and subjectivist-relativistic.

Another scientific paradigm is critical rationalism, which was introduced by Popper (1959). As it will be elaborated, critical rationalism is considered relevant to this project. One of the main elements of critical rationalism is the theory of falsification, introduced by Popper (1935). Schroeder-Heister (2001) describes the principles of falsification by stating that a general acknowledged theory can be falsified by a single observation that proves it wrong. Similarly, Popper (1959) argues that researchers should try to falsify theories in order to prove their validity. The concept of critical rationalism developed by Popper (1959) is defined in following way by Schroeder-Heister (2001): "Theoretical progress is made by successive critique and revision of existing theories, which is governed by the idea of objective truth". Thus, falsification can be applied to improve existing theories by revising them to encompass what originally falsified them, and not to reject them (Schroeder-Heister, 2001). According to the principles of critical rationalism a scientific theory should never be perceived as final, because new knowledge or observations may lead to falsification, which is the reasoning behind stating that theory does not necessarily describe the truth with absolute certainty. Hence, in cases of falsification and subsequently revision of theory, Schroeder-Heister (2004) argues that the new theory is closer to the truth. By positioning critical rationalism between the two extremes framing the different paradigms presented by Arbnor and Bjerke (1997), critical rationalism will be positioned close to the one extreme (i.e. objectivist-rationalistic), since it is the objective truth that is sought, and critical rationalism attempt to explain reality.

Critical rationalism is in line with the approach applied throughout this project and critical rationalism is therefore found particularly relevant to this project. A main purpose of this project has been to identify theories and methods from reconfigurable manufacturing and determine whether they can be applied to the uncovered field of low volume industry. Thus, in relation to critical rationalism, theory and methods related to RMSs are attempted falsified in this project in order to revise existing theory to expand the knowledge base on this specific research area. The following of this chapter elaborates on how principles of critical rationalism are applied.

### 2.1.2. METHODOLOGICAL APPROACH

As presented above, the scientific paradigms and thereby the underlying ultimate presumptions have a decisive influence on the derivation of the methodological approach that should be applied. Arbnor & Bjerke (2008) presents the following three main methodological approaches:

- The Analytical approach: The analytical approach is characterised by its summative character, which can be summarised in the statement “The whole is the sum of its parts” (Arbnor & Bjerke, 2008). Hence, the analytical approach strives to create theory within a delimited research area and does not focus attention on the relation to other areas.
- The Systems approach: In the systems approach a research area is addressed as a whole based on a number of problems, considering their relations and implications, and can be summarized in the statement “The whole differs from the sum of its parts” (Arbnor & Bjerke, 2008). Therefore, it is also assumed in the systems approach that knowledge about a delimited area is dependent on the system in which the particular area is a part of.
- The Actors approach: The actors approach is mainly relevant in relation to social research, and is differentiating from the remaining two in the fact that knowledge is obtained subjectively dependent on actors (Arbnor & Bjerke, 2008).

By referring the analytical approach to this project, it would imply that research solutions are carried out on reconfigurable manufacturing without relating it to the system (i.e. the case company) in which the research solutions are applied. In the systems approach, research solutions are created with the conviction that no single approach to reconfigurable manufacturing provides optimal solutions in all systems (i.e. companies). In relation to this project, the actors approach would involve analysing the social structures related to reconfigurable manufacturing addressing the organisational issues of developing and implementing reconfigurable manufacturing systems. The latter is relevant, but this project has its focus on the design of systems, and organisational issues is thus not addressed explicitly. However, in order to create knowledge about the system, the meanings and perceptions of actors are interpreted through both case study research and action research why actors from the industrial partner has been included in the project.

One of the main intentions of this project is to investigate the applicability of theories and methods from RMS literature within the particular area of low volume industry. Much literature within the field of RMS is either targeted a rather specific research area or it concern quite universal solutions. Thus, it is unknown if theories and methods from RMS literature are applicable in all contexts. Therefore, the dominant methodological approach, which is chosen for this project, is the systems approach. The systems approach allows for an evaluation of whether theories and methods are directly applicable or if they should be modified in order for them to fit the context of low volume industry.

As it is suggested by Arbnor & Bjerke (2008) the operative paradigm should be derived from the methodological approach, since different methods are required depending on the how the research is approached. Arbnor & Bjerke (2008) argues that case study and the “trial and error” technique is appropriate methods to apply within the systems approach. The latter will be described in relation to action research. Both the case study research and action research is considered suitable for this project, since such approaches aid detailed studies of single cases, which can reveal complex relation within a system.

### 2.1.3. CASE STUDY RESEARCH

Case study research is often applied for generating theory within operations management (Voss, Tsikriktsis, & Frohlich, 2002), which is the general research area this project operates within. Case study research is appropriate for describing and analyzing contemporary phenomena in a single case (Yin, 2003). Applying case study research implies that the researcher has no control or influence over behavioral events, since it may influence validity of conclusions (Yin, 2003). Case studies depend upon empirical data of a high number of variables, which is collected in one or a few case studies, and consist of observations and subsequently analysis of observations (Yin, 2003). Case study research is according to Voss et al. (2002) adapted from (Handfield & Melnyk, 1998) appropriate to conduct in relation to exploration, theory building, theory testing, and theory extension / refinement.

Case study research has been criticized for different reasons. The critique is primarily questioning if the findings of a single case can be generalized (Flyvbjerg, 2006). Additionally, (Flyvbjerg, 2006) argues that case study research primarily is relevant for explorative analysis in the initial stages of an investigation, and that it should be complemented with both larger quantitative investigations and a larger sample to accomplish results of scientific value. However, it is argued by Flyvbjerg (2006) that case study research is a strong method for falsification of general theories, described by Popper (1959). Hence, findings of a case study can be of great interest if they complement existing theory or if they do not fit established theory, since this will add to the knowledge base of a research area.

A number of papers in this dissertation apply the case study method to identify in which areas the existing theory is not directly applicable to the industrial partner. Applying case study research the researcher does not have any influence on the behavioral events of the case. Therefore, case study research was found more suitable in the beginning of the project, where the role of the author had an observational character. Due to the project being an Industrial PhD project the number of cases is limited to one dominant case. However, this case is considered suitable for falsification of current theory on reconfigurable manufacturing system design in relation to low volume industry.

### 2.1.4. ACTION RESEARCH

Action research may seem similar to case study research but in action research the researcher is not an observer but rather an actor who actively interacts with the case. Coughlan & Coghlan (2002) outlines the main points of action research to be research in action, participative, concurrent with action, a sequence of events, and an approach to problem solving. A number of authors have characterized action research as a cyclic process, and various cycles with similar content, have been proposed (Checkland, 1991; Susman, 1983) referred from (Baglin, 2007; Baskerville & Wood-Harper, 1996; Coughlan & Coghlan, 2002). Generally, these cycles consist of an identification of a problem, acting to find a solution to the problem, evaluation and thus identification of a new problem.

Choosing action research as a research method it is important to bear in mind that in action research knowledge is created through action and the knowledge created will therefore in many cases be specific the particular case (Coughlan & Coghlan, 2002). However, it may be possible to generalize knowledge afterwards. Additionally, Gummesson (2000) highlights another limitation of action research, namely the fact that it is necessary to acquire some degree of knowledge about the researched area before action research can be initiated. This is primarily because action research is concerned with a change process and subsequent evaluation of the effects. However, if contextual knowledge within the research area has not been acquired it will be difficult to determine which changes would be appropriate. Therefore, action research is supplemented by case study research in this dissertation.

Due to the nature of an Industrial PhD project, the intentions of this project is to deliver practically applicable results to the industrial partner of the project. By actively designing reconfigurable manufacturing system architectures applying the industrial partner as a case methods created through this project could be validated, and can therefore be characterized as action research. Introductory to the research project the case study method was applied to gather knowledge, but this knowledge was later applied in action research.

## 2.2. RESEARCH DESIGN

The research design builds upon a commonly cited methodological procedure for research projects that was presented by Jørgensen (2000). The methodological procedure is illustrated in Figure 2-2. It is based on basic principles of systems theory, which makes it consistent with this project; this project uses the systems approach in accordance to the definition of Arbnor and Bjerke (2008), which implies that research problems are not addressed isolated, but a research area is considered as a number of research problems which need to be addressed as a whole. Based on that observation the methodological procedures by Joergensen (2000) seems suitable for this application, since it starts by analyzing the existing, surrounding system, and thus the research area is addressed as a whole. It takes outset in analysis and synthesis, which are two elementary system concepts, defined as follows, by Jørgensen (2000).

- 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 (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.

Analysis and synthesis is complementary and can be carried out in various sequences. Jørgensen (2000) identifies two sequences, which are commonly used, namely the problem-solving sequence and the design sequence. The problem-solving sequence involves analysing an identified problem and then synthesise an attempted solution to the original problem. In the design sequence, it is in the reverse order, starting with a synthesis activity creating innovation, which is subsequently analysed, leading to a specified innovation. As it is argued by Jørgensen (2000) these sequences may be embedded in each other, which is the case to this particular research project. This is illustrated in Figure 2-3, which is based on the commonly used structure for research projects proposed by Jørgensen (2000). Hence, the methodological procedure applied in this project takes outset in an analysis, which leads to the formulation of a diagnosis, i.e. research objective and related research questions regarding the lack of a design methodology for RMS. Thus, the purpose of the first analysis has been to identify problems within this area of research and to identify if this particular research field have already been addressed or not. Subsequently, to the diagnosis follows a synthesis, which again consists of a sequence of synthesis followed by an analysis.

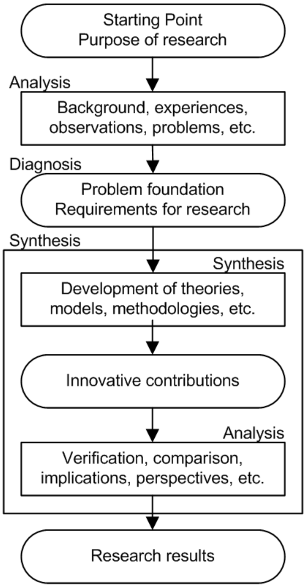


*Figure 2-2 Methodological procedure for research projects (Jørgensen, 2000)*

Based on the diagnosis this second sequence includes the development of the theory and methods, which addresses the initially stated diagnosis, followed by a verification and assessment of these new contributions, leading to new research results. The way this method is applied in this particular project is sketched in figure Figure 2-3 below. In this figure, it is also illustrated how the different activities relate to the included papers (P) and research questions (RQ). As it is apparent from Figure 2-3, the contributions of this dissertation lie within the second sequence, which is divided in two parallel set of design activities, each consisting of synthesis and analysis. Thereby, first, each single design activity (i.e. 1-5) needs to be identified within the two system levels (i.e. machine level and system level), and then the synthesis and analysis of each design activity can be carried out. Though the overall methodological procedure, identical to the two most common sequences, has been an underlying structure for the project, the different design activities and their content has been continuously formed during the project. Thus, each research question and each paper have contributed to this structure. I.e., Paper 1 and Paper 2 deals with the entire sequence of activities on each of their respective system levels, whereas the rest of the papers are focused on specific details within one or more design activities on either both or one of the two system level.

## 2.1. RESEARCH QUESTIONS

Based on current, available literature and numerous industrial visits it is evident that neither academia nor industry provides directly applicable approaches to design reconfigurable manufacturing systems. The transition towards a reconfigurable system is rather unexplored, especially in regard to low volume companies that traditionally represent systems with excess flexibility. Thus, the overall research objective is formulated as follows.

**Research objective:**
Provide a methodology that enables low volume manufacturers to design reconfigurable manufacturing system architectures.

The research objective forms the basis for formulating the research questions. On this basis, additional research questions are posed in order to provide such a methodology, fill in gaps, and improve existing approaches. The outcome has been a number of contributions, which are related and framed in the methodological procedure (Figure 2-3). Below, it is argued why each research question has been asked followed by a short description of how they are answered by summarising each related paper. As it is apparent from the methodological procedure illustrated in Figure 2-3 contributions differentiate in scope. However, all included contribution is concentrated within the framework that can be derived from Figure 2-3 . As it will appear from the following descriptions of the included papers they can all be related to design phases apparent from Figure 2-3. This framework implicitly implies some key delimitations, which are subsequently presented.

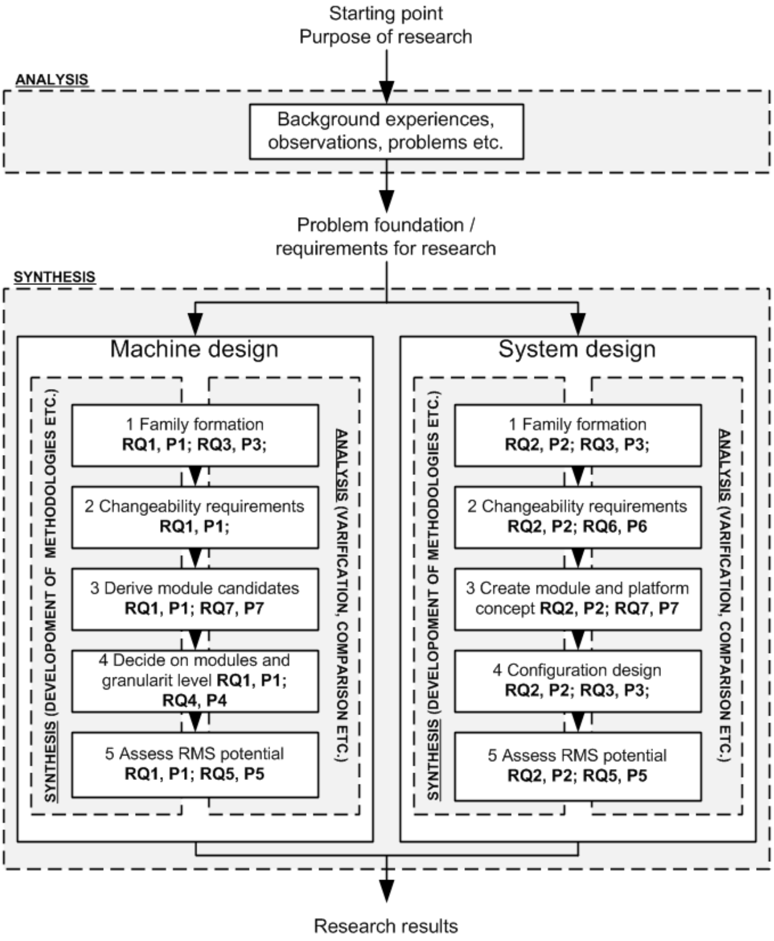


*Figure 2-3 Methodological framework for the dissertation*

Paper 1 deals with the lack of a design methodology on machine level. Reconfigurable fixture architecture design is not addressed in existing literature, nor is a methodology for design of reconfigurable machines in general. However, reconfigurable fixtures is a very important enabler to cope with increasing product variety and shorter lifecycles. Reconfigurable fixtures aids to enable change between variants as well as they allows for far less time and resource-intensive introductions of new product variants. A very little number of reconfigurable fixtures have been developed previously and nor documented in literature, and most of them are prototyping systems that are designed intuitively (Paper 1). Therefore the following research question is asked.

*Table 2-1 Research question and content of paper 1*

| **Paper 1:** Methodology for Reconfigurable Fixture Architecture Design |
|---|
| **Research question:** How can a methodology for fixture architecture design be derived and adapted from a generic framework methodology for reconfigurable manufacturing system design?<br>**Content:** An architecture design methodology for the design of reconfigurable fixtures is proposed in this paper. First a literature review is conducted to determine the need for a methodology for reconfigurable fixture design on machine level, which revealed that no such existed. For this purpose, a generic method for reconfigurable manufacturing systems design has been adapted for fixture design. This has required an additional, extensive literature search on current practises within each stage suggested in the adapted method in order to propose applicable tools for reconfigurable fixture architecture design. The methodology is validated by applying it on a practical example in industry, which revealed a potential for higher production efficiency and reduced costs for new product introductions on a welding task. |

RMS is often associated with high volume industry but RMS should not be reserved companies with such characteristics. The consequence is that RMSs in low volume industry is rather unexplored, which therefore also includes design of RMS in companies with such characteristics. Though the reconfigurations most often are carried out on machine level in low volume industry, the system level design is also important, since decisions on system level influences design specifications on machine level. Nevertheless, generally there is still uncertainty associated with decisions related to reconfiguration level and type of reconfigurability in companies with different characteristics. The following two research questions are asked, which will help to understand the benefits of RMS in low volume industry on system level.

*Table 2-2 Research question and content of paper 2*

| **Paper 2:** Reconfigurable Manufacturing System Architecture Redesign in Low Volume Industry |
|---|
| **Research question:** How can a methodology for RMS architecture design for low volume industry be created and how will it take shape? Is such a methodology applicable and valuable to low volume industry?<br>**Content:** A methodology for reconfigurable manufacturing system design in low volume industry is presented in this paper. The methodology synthesises existing literature on RMS design with outset in a generic method for RMS design. The methodology is validated by applying it on an industrial case. Thus, the transition towards a reconfigurable line for a family of product components from a more flexible system is demonstrated. Furthermore, the paper elaborates on some of the benefits of implementing RMS in low volume industry. |

One of the important design phases on system level is regarding configuration of the system, and thus how the layout is configured when it is transformed from a more flexible system. Therefore, this design phase becomes quite important to low volume manufacturers. Consequently, the following research question was formulated.

*Table 2-3 Research question and content of paper 3*

**Paper 3:** Machine-Part Formation Enabling Reconfigurable Manufacturing Systems Configuration Design: Line Balancing Problem for Low Volume and High Variety

**Research question:** How can low volume manufacturers change their layout from a flexible process layout towards a layout focused around families of parts or products?

**Content:** This paper presents how to configure a layout going from general flexibility towards a system focused around families of parts and products. Transforming the layout of low volume manufacturing systems towards increased reconfigurability focused around families of parts or products, which presumable on beforehand had a more flexible systems requires two steps. First of all parts or products are grouped in families, as it is known from group technology. Secondly, part or product families are being balanced on their independent systems to configure the layout. This is demonstrated for a product component family on an industrial example. This helped to evaluate the line balancing problem of the relative high variety introduced on one line implied by such a transformation.

Modularity is an important characteristics of the reconfigurable manufacturing system, which enables the rapid response to market changes, both related to functionality and capacity. Thus, it is important to become aware which modular drivers are most important when the modular manufacturing equipment is being designed. Basic concepts of modularity and platform architectures known from product development literature can often be applied in a production context (Brunoe, Bossen, & Nielsen, 2015b). This does however not mean that generic methods for development of modular products can be adopted directly for design of modular manufacturing systems like the RMS (Brunoe et al., 2015b). However, this is an important design issue, but still rather unexplored in relation to applying modular drivers to decide upon the modular structure of a manufacturing system. This led to the following research question, which is highly relevant to the design phase concerned by the derivation of modules Figure 2-3.

*Table 2-4 Research question and content of paper 4*

**Paper 4:** Application of Module Drivers Creating Modular Manufacturing Equipment Enabling Changeability

**Research question:** How can module drivers be applied to design modular manufacturing equipment?

**Content**: In this paper a method from product development literature is adopted for the purpose of modularizing manufacturing equipment seeking the optimal modular structure. Based on an industrial case a generic functional structure was derived from six somewhat similar welding fixtures. The means to carry out these functions was then further integrated based on the importance of different module drivers to each of the derived means. This is carried out by combining the Module Indication Matrix from Ericsson et al. (1999) with the module drivers for production system development suggested by Brunoe et al. (2015b). It should be noted that this approach is not a substitute to the Design Structuring Matrix and the Cladistics analysis previously applied in this context but rather a complementary decision tool.

The implementation of reconfigurability affects performance on different parameters depending on the level, type, and degree of reconfigurability implemented, which is again is determined on the basis of company characteristics. Different approaches has been suggested to evaluate the potential of RMS on different systems levels on different stages of the system's lifecycle, i.e. from early justification of choosing RMS to suggestions of performance metrics after the systems implementation. However, there is a lack of literature regarding investigation and quantification of the potential in reconfigurable manufacturing for low volume industry.

*Table 2-5 Research question and content of paper 5*

| **Paper 5:** Reconfigurable Manufacturing Potential in Small and Medium Enterprises with Low Volume and High Variety: Pre-design Evaluation of RMS |
|---|
| **Research question:** How can reconfigurable manufacturing systems address today's challenges of SMEs with low volume and high variety and how can the potential be identified and measured?<br>**Content**: In this paper it is suggested that low volume manufacturers can modularize manufacturing equipment as a means to cope with today's challenges of a global market. Based on a conceptual modularization of manufacturing equipment carried out on an industrial case, measures on the potential of RMS in low volume industry conducted. It is illustrated how reconfigurability (i.e. the modular equipment) influences 1) changeover time and the time spent on retrieving equipment, 2) storing capacity, 3) and time and resources spent on new product introductions, including design, manufacturing, and installation of equipment. |

The line balancing problems related to layout configuration was addressed in paper 3. However, when new products are introduce new problems will arise. Among others one problem is related to the maturity of the production processes. This includes unforeseen bottlenecks as a consequence of inaccurate prediction of process time before production ramp-up. Thus, for a line with high frequency of NPIs it is important that the expected process time is somewhat accurate and that not too much time is spent in this process. This motivated the following research question.

*Table 2-6 Research question and content of paper 6*

| **Paper 6:** Prediction of Process Time for Early Production Planning Purposes |
|---|
| **Research question:** How can process time for new products be predicted more rapidly and more accurate compared to conventional approaches?<br>**Content**: In order to rapidly predict reliable process times a statistical model is presented in this paper. This model is based on historical product-data and can be applied in the production planning part of the ramp-up process to predict the process time for new products that is to be introduced on the existing manufacturing equipment. The linear regression analysis is applied to analyse the relations between product related data and the process time. Applying the model to a case company revealed that historically the case company was able to predict process time with an average deviation from the actual process time of 25 % while by applying the model this number was only 7.5 %. |

As it has been stated previously, modularity is an important enabler for reconfigurability. However, it can be argued that in low volume environments you would often find that commonality should be identified across equipment that handles much higher degree of product variety (Brunoe et al., 2017). Nonetheless, it is important to low volume industry to find ways to modular and platform based production architectures. Therefore, models that support the coordinated development between product and production systems is of great importance. However, not much attention has been paid to this research area, and it lacks attention to production platforms (Bossen, Brunoe, Bejlegaard, & Nielsen, 2017).

*Table 2-7 Research question and content of paper 7*

| **Paper 7:** Conceptual Model for Developing Platform-Centric Production Architectures |
|---|
| **Research question:** How can a conceptual model be described for expressing the context of production platforms? How can the conceptual model be applied and instantiated to create a platform architecture model?<br>**Content**: This paper presents a conceptual model, which defines the concepts involved in defining a platform architecture for production development, which is framed as one of two aspects in platform-based co-development and co-evolution of product and production systems. Additionally, recommendations for applying the model are presented in order to assist practitioners in developing a domain-specific platform architecture model. |

Another four papers have been co-authored, but these are excluded, as these contributions does not explicitly address the design issues related to reconfigurable manufacturing system architecture design. These papers are listed below:

- Javadi, Siavash, et al. “The Introduction Process of Low-Volume Products: Challenges and Potentials of Information Management.” IFIP International Conference on Advances in Production Management Systems. Springer, Cham, 2016.
- Andersen, Ann-Louise, et al. “Investigating the impact of product volume and variety on production ramp-up.” Managing Complexity. Springer International Publishing, 2017. 421-434.
- Andersen, Ann-Louise, et al. ”Evaluating the investment feasibility and industrial implementation of changeable and reconfigurable manufacturing concepts” Flexible Services and Manufacturing Journal (In review)
- Sørensen, Daniel G.H. et al. “Production Platform Development through the Four Loops of Concerns” Proceedings of the 9th World Conference on Mass Customization, Personalization, and Co-Creation. Springer, 2017. (In review)

## 2.2. RESEARCH DELIMINATION

A number of delimitations is presented below. The delimitations serve the purpose of focusing the project on research which both contributes to science and creates value to the industrial partner.

- Architecture design refers to the first of three design issues of a reconfigurable system (i.e. architecture design, configuration design, and control design). These design issues refer to different stages of a reconfigurable system's lifecycle (i.e. system design, system application, system operation). Thus, this project is not concerned by system application and operation. Elaborating definitions can be found in Bi et al. (2008).
- Since it is the actual architecture of the system that is of interest, this project is concerned by the conceptual design and not the more detailed embodiment design nor the actual detailed design (phases known from engineering design). However, a detailed design of a fixture have been designed and a simulation have been carried out to validate the methodology suggested for reconfigurable fixture architecture design.
- The factory structuring levels besides system/cell level (referred to as system level) and station level (referred to as machine level) is not included. This is simply to include the levels which is most important to low volume industry. These levels are described by Wiendahl et al. (2007) and Westkämper (2006)
- Co-development of product and production systems is equally important systems to capitalise on commonality. However, this project takes a production viewpoint and thus product platforming and modularization is not considered.

# CHAPTER 3. RMS ARCHITECTURE DESIGN ON MACHINE LEVEL

In general, there is a lack of consensus regarding the actual definition of a reconfigurable fixture across the little number of prototypes identified in literature. Furthermore, fixtures that are claimed to be reconfigurable are intuitively developed and a systematic design methodology is lacking. Figure 3-1 illustrates an IDEF diagram of a novel methodology for architecture design of reconfigurable fixtures, which is presented in this chapter. This methodology is also expected to be applicable to design of Reconfigurable Machine architectures in general. The phases of the methodology relates the design issues addressed in literature, and it thus builds on a generic understanding of how to design a reconfigurable system in general presented in XX. This has been related to fixture design which has led to the concrete activities to conduct in each phase and the tools, techniques, and procedures relevant to each phase. Besides suggesting which activities to conduct in each phase of the methodology, practical examples from an industrial case is presented as well along with each phase. Hence, the methodology is verified on a family of product components in a welding facility characterised by high mix and small batches. Applying the methodology allows combining the capabilities of six former dedicated fixtures (illustrated in Figure 1-3) into one single reconfigurable fixture, which provides noticeable benefits.

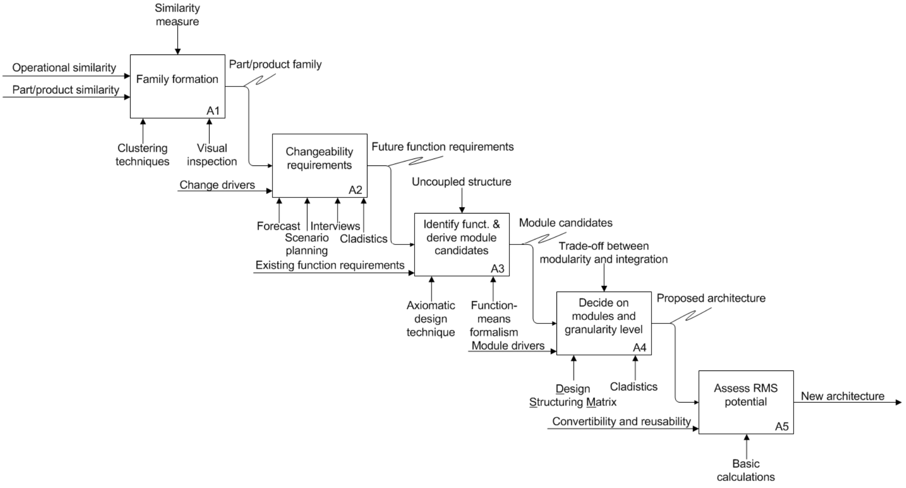
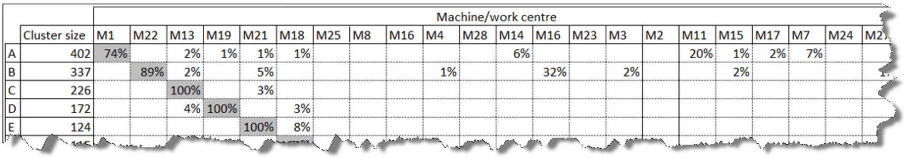


*Figure 3-1 Reconfigurable fixture architecture design (Source: Paper 1)*

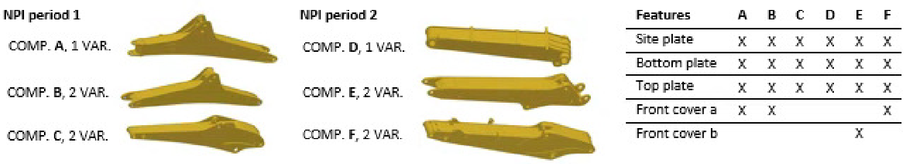
## 3.1. FAMILY FORMATION

Logically, the first step in designing a reconfigurable manufacturing system is to identify the part or product variety, which the equipment should be capable to reconfigure across. Thus, it is desired to identify adequate process and/or product commonality or similarity in order to enable manufacturing systems to cope with as high product variety as possible considering the trade-off between parts or product variety and manufacturing efficiency. Thus, this becomes an important design issue to low volume manufactures, who can expect more frequent reconfiguration compared to high volume industry with presumably less part or product variety to be handled by the same equipment. To identify groups of parts or products that could potentially be manufactured by applying the same manufacturing equipment and obtain economy of scale, different techniques can be applied. Generally, for literature published within the field of RMS there is a tendency to apply a hierarchical clustering technique, based on operational sequences alone or together with market requirements (Paper 1). However, the actual approach depends on the level and type of diversity between products or parts. A transformation towards reconfigurability for low volume companies can often be associated with a transition from a more flexible system with high part or product variety. Therefore, an approach capable of handling high variety is suggested, namely hierarchical clustering based on operational sequences (i.e. a machine-part formation). With the high variety represented in the case study, further deviation of product components is necessary in order to end up with families across which manufacturing equipment can be standardized and modularized as an enabler for reconfigurability. Figure 3-3 illustrates one out of three families that could be derived from one of the clusters illustrated in Figure 3-2. The five product component features illustrated in Figure 3-3 illustrates that this family may have adequate commonality to share manufacturing equipment. This is sought verified in the following.



| | | Machine/work centre | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Cluster size | M1 | M22 | M13 | M19 | M21 | M18 | M25 | M8 | M16 | M4 | M28 | M14 | M16 | M23 | M3 | M2 | M11 | M15 | M17 | M7 | M24 | M2 |
| A | 402 | 74% | | 2% | 1% | 1% | 1% | | | | | | 6% | | | | | 20% | 1% | 2% | 7% | | |
| B | 337 | | 89% | 2% | | 5% | | | | | 1% | | | 32% | | 2% | | | 2% | | | | 1 |
| C | 226 | | | 100% | | 3% | | | | | | | | | | | | | | | | | |
| D | 172 | | | 4% | 100% | | 3% | | | | | | | | | | | | | | | | |
| E | 124 | | | | | 100% | 8% | | | | | | | | | | | | | | | | |

*Figure 3-2 Machine-part formation (Source: Paper 1)*



| Features | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| Site plate | X | X | X | X | X | X |
| Bottom plate | X | X | X | X | X | X |
| Top plate | X | X | X | X | X | X |
| Front cover a | X | X | | | | X |
| Front cover b | | | | | X | |

*Figure 3-3Product component family with shared variant parts (Source: Paper 1)*

## 3.2. CHANGEABILITY REQUIREMENTS

The reconfigurable fixture is characterised by the capabilities to change between variants within the same family and the capabilities to adapt functionality to cope with new product introductions. Thus, it is also of high importance to somehow predict future scenarios in order to increase the reuse of fixtures. Therefore this phase becomes crucial in order to extend the lifetime of fixtures. Thus, changeability requirements should be identified, which is related to capacity change (i.e. scalability) and to functionality change (i.e. convertibility). In literature different approaches to identify changeability requirements is presented. Rösiö (2012b) and Bruch & Bellgran (2014) presented approaches, which can be applied to predict future changes on different system levels. AlGeddawy & ElMaraghy (2011) presented a co-evolution model to track the mutual evolution between products design and manufacturing system capabilities, which however is not directly applicable to this particular application area in its current form. Changeability requirements can also be described through change drivers (Wiendahl et al., 2007) and can be differentiated between product, volume, and technology-related (Schuh et al., 2009), despite the fact that they can be difficult to generalize. Such change drivers are commonly used and are seen as an appropriate approach to identify changeability requirements. As it is elaborated in paper 1, only product related change is expected to have influence on future changeability requirements in this particular industrial example. Therefore internal interviews was conducted to acquire expert knowledge in order to explain expected future market requirements to products. This was supplemented by an analysis of the general historical evolution tendency across product components within the concerned family. Figure 3-4 illustrates a generic product component, which was applied to explain the general geometric future requirements. These requirements could then be translated into future functional needs, which was transferred to the next phase.

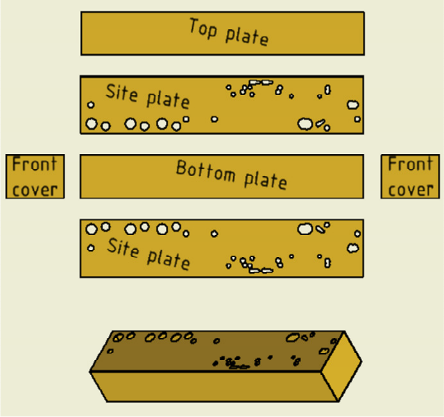


*Figure 3-4 Generic product representation (Source: Paper 1)*

## 3.3. DERIVE MODULE CANDIDATES

In this phase the existing functional requirements are derived from the existing fixtures to be replaced in favour of a new reconfigurable fixture. Then, these functional requirements and the future functional requirements derived from previous phase is mapped toward the physical domain in order to derive provisional modules. As a starting point these provisional modules should be as decoupled as possible from the functional requirements. This gives the best possible starting point to design an architecture to which a minimum of change is required when the fixture is reconfigured or when new product components are introduced. Literature related to this phase is supplementary; they all focus on the mapping between the functional domain and the physical domain with more or less focus on co-development of products and manufacturing systems. Bi et al. (2010) apply axiomatic design theory to design the architecture of a robot, though without considering the product. Conversely, Michaelis et al. (2014) integrate both the product and the production system using function-means formalism. However, both contributions are practical examples in which relations between the functional domain and the physical domain are being mapped. Like these two examples, relation between the functional domain and the physical domain are mapped in the industrial example applied in this project. However, as illustrated in Figure 3-5, in-between the function requirements to the left (i.e. functional domain) and the means to the right generic function requirements are mapped. These led to the generic provisional modules illustrated on the generic fixture reference model in Figure 3-6 (means in Figure 3-5).

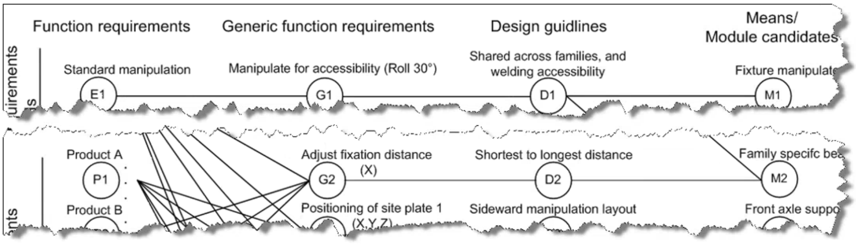


*Figure 3-5 Mapping between functional and physical domain (Source: Paper 1)*

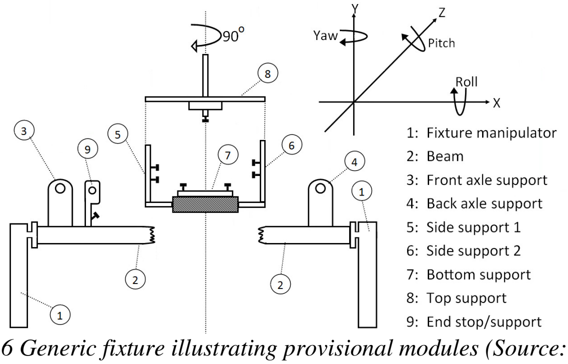


*Figure 3-6 Generic fixture illustrating provisional modules (Source: Paper 1)*

## 3.4. DECIDE ON MODULES AND GRANULARITY LEVEL

It is in this phase assessed if the provisional modules derived in previous phase should be further integrated or maintain the highest number of modules possible derived in previous stage based on identified functional requirements. After deciding the optimal number of modules, the relations between modules are decided and the modules that needs to be exchanged when a reconfigurations occur is identified. The latter is referred to as the optimal granularity level. Thus, this becomes a trade-off between rapid reconfigurations off few integrated modules and having modules representing each necessary function, which can easily be exchanged for new functionality. The finer the granularity the more room for variety, however the variety is limited to a family and only modules serving the functions that are different between part or product variety should be exchanged. Approaches from product development literature (Ericsson & Erixon, 1999; Lange & Imsdahl, 2014; Ulrich & Steven, 2008) is adopted to derive production platform drivers (Brunoe, Bossen, & Nielsen, 2015a) and to cluster system elements in order to derive modules (Bejlegaard, Brunoe, & Nielsen, 2016). However, these approaches do not allow to determine a hierarchical structure with modules interconnections. Consequently, ElMaraghy et al. (2015) applied cladistics and a cladogram representation to decide modules' interconnections and the optimal granularity level. As it is apparent from paper 1, the industrial example illustrated in this project applies the Design Structuring Matrix known from product development literature (Eppinger & Browning, 2012) combined with three important module drivers to derive modules (see Figure 3-7). Secondly, a cladistics analysis is conducted to decide on a hierarchical structure and identify the optimal granularity level for reconfigurations (see Figure 3-8).

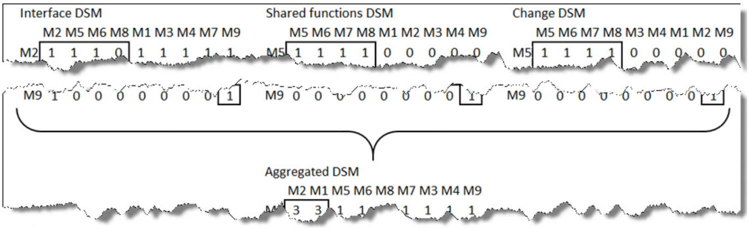


*Figure 3-7Aggregated DSM based on three modules drivers (Source: Paper 1)*

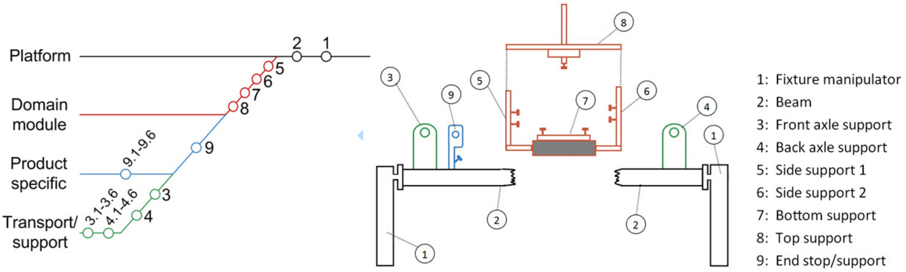


*Figure 3-8 Proposed architecture of a reconfigurable fixture (Source: Paper 1)*

## 3.5. FINANCIAL ASSESSMENT OF RMS POTENTIAL

Before the embodiment design can be initiated it should be assessed if the potential financial benefits from implementing the reconfigurable fixture is too small or involves too much risk to proceed. As it has been emphasized, the financial benefits of reconfigurability in fixtures (or in Reconfigurable Machines in general) is in particularly realized through two capabilities. Firstly, the convertibility that allows to change between part or product variants within a family without changing the entire fixture. Secondly, the reusability that allows for introduction of new parts or products on the reconfigurable fixture by only developing a few new modules instead of an entire new fixture. Thus, the most of the fixture remain unchanged and can be reused across product generations. Different literature on the financial potential of reconfigurable manufacturing systems have been published. Some are concerned by early assessment of the feasibility of different system alternatives (Kuzgunkaya & ElMaraghy, 2007; Singh, Khilwani, & Tiwari, 2007), which is quite extensive for a rather simple assessment. Other practically applicable approaches have been provided, though for capacity savings across lines in high volume environments (Andersen et al., 2015a). However, more applicable approaches for machine level is also provided. Maler-Speredelozzi & Koren (2003) proposed metrics for convertibility, Ko et al. (2005) proposed metrics for reusability, and both convertibility and reusability is considered in paper 1 and paper 5 in this dissertation. The product component family subject to this case constitute a main part of the different machines and thus frequent introductions of new product components is expected. Hence, the reusability of the reconfigurable fixture will imply a drastic decrease in investments in fixtures. However, the initial investment (including design, manufacturing, and installation) is expected to be twice as much as the investment in conventional dedicated fixtures. Yet, it only takes approximately two new product introductions before the investment is payed off. The modular architecture of the reconfigurable fixture also implies that only a few modules are exchanged during a changeover whereas the current approach implies a complete exchange of the entire fixture. As it is apparent from Table 3-2 the convertibility therefore also has a major influence on the time spent on changeovers (i.e. approximately 130 hours a year).

*Table 3-1 Reusability (Source: Paper 1)*

| | **NPI equipment need** | **Initial Investment** | **Investment for future product introductions** |
|---|---|---|---|
| Current (dedicated) | 1 new fixture | 20,000 € | 20,000 € |
| Reconfigurable | 1-3 new modules | 40,000 € | 4,000 € |

*Table 3-2 Convertibility (Source: Paper 1)*

| | **Equipment change between variants** | **Changeover time / reconfiguration time** |
|---|---|---|
| Current (dedicated) | Change of the entire fixture | 45 minutes |
| Reconfigurable | Change of 1-3 modules | 10 minutes |

# CHAPTER 4. RMS ARCHITECTURE DESIGN ON SYSTEM LEVEL

So far, research on reconfigurable manufacturing systems have had a predominant focus on high volume industry. Thus, there is a dominant trend in literature to be concerned about the transition from more rigid, typically dedicated systems towards reconfigurability (Brunoe et al., 2017). Previous chapter clearly emphasises the potential of reconfigurability on machine level in a low volume environment manufacturing products with a relatively high variance, whereas this chapter will focus on the advantages of RMS architecture design on system level. As described in (Andersen et al., 2015a) reconfigurability on system level in high volume industry gives the opportunity to share capacity across lines. However, that is not the case in low volume industry as described initially. This chapter emphasise on the fact that reconfigurability considerations on system level influences decisions on machine level which leads to avoidance of sub optimisation. As the methodology described in previous chapter, this one builds on a generic understanding of how to design a reconfigurable system. This has been related to low volume industry, which led to suggestions of concrete tools, techniques, and procedures to apply in each phase. Like in previous chapter, practical examples from an industrial case is presented as well, along with each design phase.

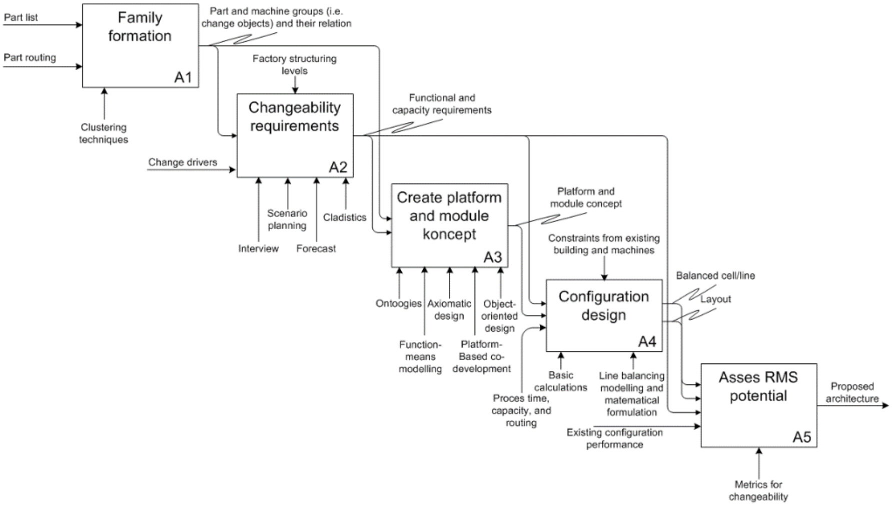
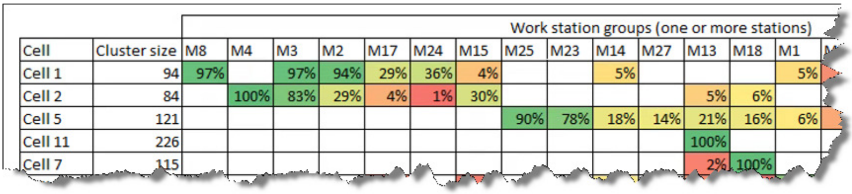


*Figure 4-1 RMS architecture design on system level (Source: Paper 2)*

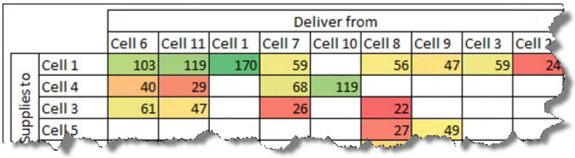
## 4.1. FAMILY FORMATION

This design issue is important in order to succeed in the implementation of reconfigurable manufacturing systems since the efficiency of a reconfigurable system is very dependent on how well parts or products are divided into families. Deciding on a set of part or product families is based on the expectation that it contains the adequate similarity or commonality for increased reuse of resources across a family. This is not unique to implementation of reconfigurable manufacturing systems; family formations has its origin in Group Technology. However, it is a subject that have advances ever since, and family formations is the starting point and a prerequisite to implement reconfigurable manufacturing systems. Different contributions has been provided relating family formation to reconfigurable manufacturing using different criteria for these formations. Galan et al. (2007) uses product requirements to select families, whereas Goyal et al. (2013) and Abdi & Labib (2004) uses operational sequence similarities to derive families. These contributions do all apply hierarchical clustering, which is also applied in particular industrial example. Since the transformation takes offset in an overall more flexible system with a very high number of product components a machine-part formation is applied to cluster similar operation sequences. In this way families of product components with similar operational sequence is clustered. The results from the machine-part formation carried out to cluster product components in the industrial example is summarised in Figure 4-2. Each row in Figure 4-2 illustrates which machines that are suggested to form a potentially new cell or line. It appears from the analysis that independent cells or lines could be derived. Thus, a layout focused around part or product component families is possible instead of the existing process layout divided in departments (i.e. cutting, welding, machining etc.). The financial potential of such initiatives is elaborated in section 0. As it is illustrated in Figure 4-3 an additional analysis can be conducted to decide how the potentially new cells or lines should be placed relative to each other in order to reduce transport of material and the like. Cell 1 illustrated in Figure 4-2 represent the product component family which is subject to this industrial example.



| | | Work station groups (one or more stations) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cell | Cluster size | M8 | M4 | M3 | M2 | M17 | M24 | M15 | M25 | M23 | M14 | M27 | M13 | M18 | M1 |
| Cell 1 | 94 | 97% | | 97% | 94% | 29% | 36% | 4% | | | 5% | | | | 5% |
| Cell 2 | 84 | | 100% | 83% | 29% | 4% | 1% | 30% | | | | | 5% | 6% | |
| Cell 5 | 121 | | | | | | | | 90% | 78% | 18% | 14% | 21% | 16% | 6% |
| Cell 11 | 226 | | | | | | | | | | | | 100% | | |
| Cell 7 | 115 | | | | | | | | | | | | 2% | 100% | |

*Figure 4-2 Machine-part formation (Source: Paper 2)*

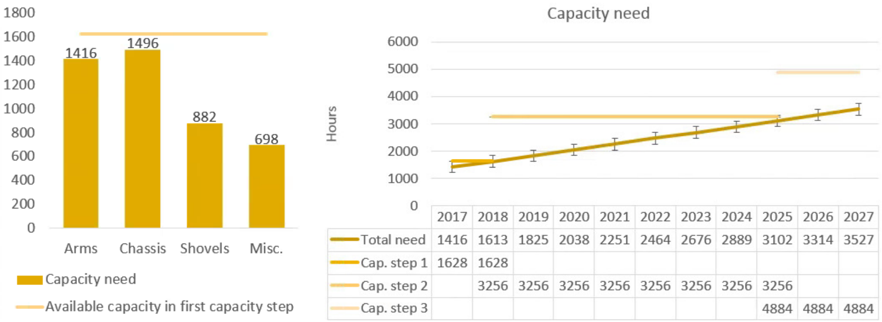


| | | Deliver from | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Cell 6 | Cell 11 | Cell 1 | Cell 7 | Cell 10 | Cell 8 | Cell 9 | Cell 3 | Cell |
| Supplies to | Cell 1 | 103 | 119 | 170 | 59 | | 56 | 47 | 59 | 24 |
| | Cell 4 | 40 | 29 | | 68 | 119 | | | | |
| | Cell 3 | 61 | 47 | | 26 | | 22 | | | |
| | Cell 5 | | | | | | 27 | 49 | | |

*Figure 4-3 Customer/supplier relation between cells (Source: Paper 2)*

## 4.2. CHANGEABILITY REQUIREMENTS

This design phase is rather important since it may help to avoid sub optimisation on machine level when reconfigurable machines (e.g. fixtures) are designed. As it is argued in previous chapter, it is important to identify change drivers and how they influences change objects. Schuh et al. (2009) describe how change is triggered through three change drivers (i.e. volume volatility, product variety, and change in strategy or technology). These change drivers influences change objects, which are often categorised within product, process, production system, and organisation (Bruch & Bellgran, 2014; Rösiö, 2012b; Tolio et al., 2010; Wiendahl et al., 2007). Furthermore literature describes how the evolution of change objects should be coordinated (i.e. co-evolution) throughout the systems' lifetime (AlGeddawy & ElMaraghy, 2011; Bryan, Ko, Hu, & Koren, 2007; Tolio et al., 2010). One approach, which is applicable on system level is to bring forward the expected future changeability requirements by generating probable scenarios, as described by Rössiö (2012b). Similar approach have been applied for this particular industrial example; identifying change drivers influence on change objects. However, only some of the most important observations that should receive particular attention are highlighted in the following. It is on one hand desired to embrace many variants in a family in order increase the volume within a family, but on the other hand the family should not embrace too much variety since the manufacturing equipment should be able to reconfigure efficiently between variants. This trade-off between volume and variety is made in order to achieve economy of scale without losing efficiency. The bar graph in Figure 4-4(A) illustrates how available capacity on each of the four workstations is allocated groups of similar product components. The reconfigurable fixture architecture designed in previous chapter supports an expectation that equipment on the other workstations can be standardised as well, and still cope with NPIs. Based on the group of product components named arms, the graph in Figure 4-4(B) exemplifies how increases in sales expectedly will cause a capacity expansion in 2018. This suggests that a new layout should have room for workstations to be duplicated. However, as it is illustrated in the following section, a common equipment platform across arms, chassis, and shovels will allow for capacity sharing across workstations.



| | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Total need | 1416 | 1613 | 1825 | 2038 | 2251 | 2464 | 2676 | 2889 | 3102 | 3314 | 3527 |
| Cap. step 1 | 1628 | 1628 | | | | | | | | | |
| Cap. step 2 | | 3256 | 3256 | 3256 | 3256 | 3256 | 3256 | 3256 | 3256 | | |
| Cap. step 3 | | | | | | | | | 4884 | 4884 | 4884 |

A B

*Figure 4-4 Current cap. need (A), and expected cap. need (B) (Source Paper 2)*

## 4.3. CREATE MODULE AND PLATFORM CONCEPT

As indicated above, change drivers have a strong influence on how systems should be designed. Therefore, the changeability requirements derived from previous design phase is applied to define the functionality and capacity needed on the different levels of a system to meet existing and future needs to the system. In this phase, a conceptual model is outlined, which should embrace the scalability and functionality needed to meet the market demand striving to find the optimum trade-off between reuse and efficiency. Key enablers for this is modularity and integrability. In line with this, Schuh et al. (2009) separate system objects in complicated and complex system elements to enable easy transformation to new capabilities and emphasises the importance narrowing variance in product structures and production processes by optimizing on commonality. Both Schuh et al. (2009) and Michaelis et al. (2011) furthermore emphasise on the joint development between products and manufacturing systems based on a platform approach. The conceptual model to create production platform architectures presented in paper 7, is the model applied to arrive on the production architecture model presented Figure 4-5 (elaborated in paper 2). The model is presented from a production development viewpoint and the blurred red box represents the area which were in focus when the fixture presented in previous chapter were designed. Different system levels illustrate how platforms and modules are reused across product components and the granularity for different types of changes.

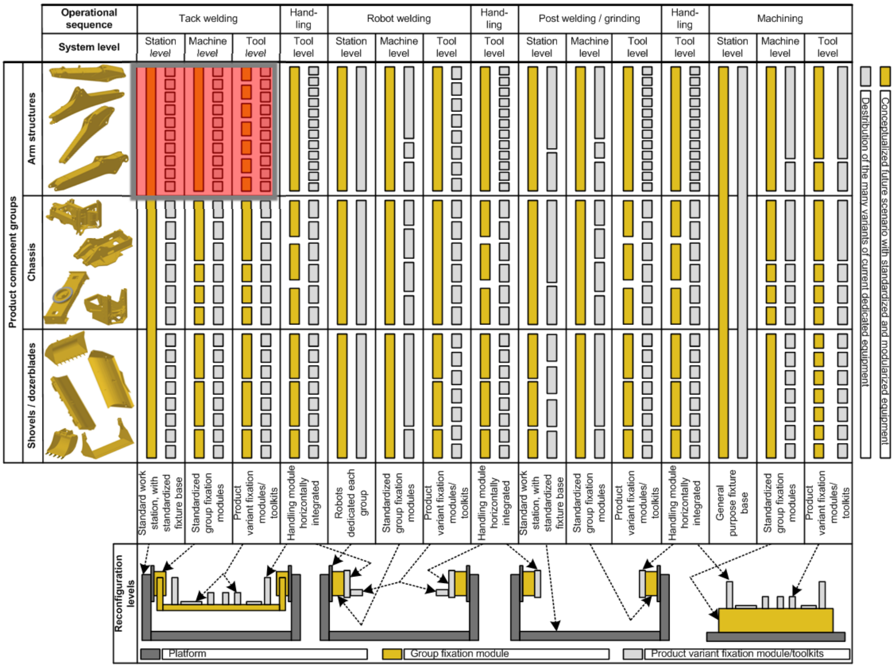


*Figure 4-5Production platform architecture model (Source: Paper 2)*

## 4.4. CONFIGURATION DESIGN

By focusing the manufacturing system around families in low volume industry imply that it should be designed for high variety in order to utilize the full capacity of the system. However, an asynchronous configuration allows for differentiating process times on functional stages and is not constrained by a unique sequence (Hu et al., 2011). Configuration design should not be confused with configuration selection and configuration measurement, which are design issues considered later in a system's life cycle. Configuration design on system level is concerned by the arrangement of physical components (i.e. layout configuratins) and the line balancing problem (Hu et al., 2011; Koren & Shpitalni, 2010; Xiaobo, Wang, & Luo, 2000). ElMaraghy et al. (2006) addresses different layout configuration characteristics and Boysen et al. (2007) classifies different line balancing problems. Koren et al. (2010; 2013) illustrates the advantages of an RMS configuration and how to achieve one. This approach is suitable for low volume industry and is adopted for the industrial example. The concerned machines are distributed into a sequence of functional stages based on the most frequent occurring sequence. The number of machines in each stage correspond to the average process time spent in each functional stage (see Figure 4-1) Though the conceptual layout presented in Figure 4-6 is divided into functional stages the variety of product components and the cost of changeovers justifies work stations on some of the functional states do not perform the same jobs. These work stations are therefore dedicated to families of product components corresponding to the platform architecture model presented above. However, the modular structure of manufacturing equipment allows for workstations to share capacity if necessary.

*Table 4-1 Minimum number of machines (Source: Paper 2)*

| | Stage 1 | Stage 2 | Stage 3 | Stage 4 | Stage 5 | Stage 6 |
|---|---|---|---|---|---|---|
| **Operational sequence** | Tack welding | Robot welding | Grinding | Machining | Manual welding | Cleaning |
| **% time** | 28 % | 17 % | 29 % | 25 % | 1 % | < 1 % |
| **Machines** | 2.8 ≈ 3 | 1.7 ≈ 2 | 2.9 ≈ 3 | 2.5 ≈ 3 | 0.1 ≈ 1 | - |
| **Machine numbers** | M2 (I,II,III,IV) | M8 (I,II) | M3 (I,II,III) | M17 (I), M24 (I) | M1 (I), ~~M14~~ | ~~M11~~ |

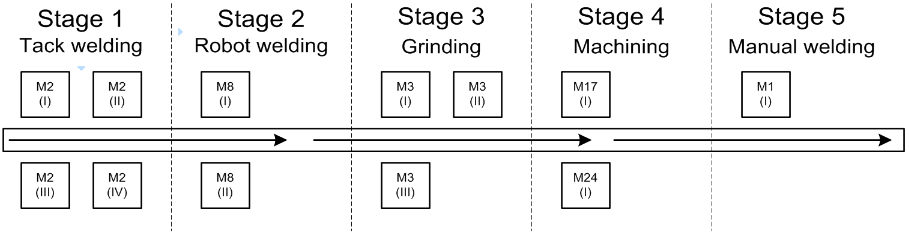


*Figure 4-6 RMS configuration with balanced stages (Source: Paper 2)*

## 4.1. ASSESS RMS POTENTIAL

The first design phase of the suggested design methodology is concerned by family formation. In itself, the first phase provides the opportunity to capitalise on the benefits of focused factories (Wemmerlov & Johnson, 1997). However, the subsequent phases of the methodology for RMS design on system level in low volume industry serves the purpose of achieving reconfigurability on system level and structure the effort on machine level from which additional benefits follow. Numerous metrics is presented in literature with different approaches to measure the possible advantages of reconfigurability. Farid et al. (2014) presented metrics to measure integrability, convertibility, and customization. Koren et al. (1998) applies metrics to measure reliability and productivity, product quality, capacity scalability, and cost for different system configurations. Youssef et al. (2006) applies metrics to measure time, cost, and effort related to conversion between configurations on different system levels. Maler-Speredelozzi et al. (2003) presented metrics to measure convertibility. Ko et al. (2005) applied a metric to measure reusability. Lafou et al. (2015) presents different configuration flexibility metrics and relates them to NPI. Andersen et al. (2015a) quantifies a capacity sharing potential in a high volume environment. In paper 5 the convertibility and reusability of modular manufacturing equipment is assessed in a low volume environment focusing on machine level. Common to all these contributions is that reconfigurability measures is related to the six RMS characteristics presented above. It also appears that reconfigurability is measured differently depending on the related system level. The research by Brunoe et al. (2017) supports that observation by suggesting that volume has influence on the level to which reconfigurability has the greatest impact. It is evident from previous chapter that convertibility and reusability measures can describe to advantage related to reconfigurability on machine level. It is often seen that scalability and capacity sharing across lines constitute the greatest advantages of reconfigurability at system level for high volume industry (Andersen et al., 2015a). However, low volume industry differs from high volume industry in terms of where reconfigurability has its greatest advantages, since there isn’t adequate volume to share capacity across lines, but just enough volume for one line. However, capacity can be shared within functional stages on one because a common platform can implemented (e.g. within stage 1 presented in previous section). The reuse of platforms makes it possible to share capacity on workstations but to scale capacity by sharing workstations requires duplication of some product specific modules. However, that is significantly less costly than duplicating the entire workstation. Then there is of cause also the benefits of focused factories in general, which is not directly influenced by reconfigurability. The suggested layout will imply some additional benefits as described in paper 2. The average travel distance for product components will be reduced by approximately 60 % and a pull strategy will imply that the number of times that product components needs be handled is reduced by approximately 70 % because they are moved directly to the customer process. Therefore, it is also expected that WIP inventories between the functional stages can be reduced by approximately 50 %.

# CHAPTER 5. CONCLUSION AND PERSPECTIVES

*This chapter briefly summarises the contributions and results of the project, and further gives some perspectives on contributions and results. More detailed conclusions on specific topics are furthermore available in the papers enclosed.*

## 5.1. DESIGN METHODOLOGIES

As indicated in chapter 1, the transition towards a reconfigurable system in low volume industry is largely unexplored. Therefore, an overall objective of providing a methodology that enables low volume manufacturers to design reconfigurable manufacturing system architectures was set. Consequently, two methodologies for RMS architecture design in low volume industry have been synthesised for machine level and system level, respectively. Each of the design phases correspond to design issues, which in one way or the other are addressed in literature. However in this literature, the relation between methods, procedures, tools etc. to address design issues is vaguely described. Additionally, the methods, procedures, tools etc. are often limited to a certain application area, which is rarely a low volume context. Thus, the suggested methodologies deal with the fact that RMS design has not been addressed in relation to low volume industry by synthesising methods, procedures, tools etc. relevant to low volume industry. Additionally, different design issues related to different design phases have also been addressed individually in paper 3 to 7, which has supported the emergence of the methodologies presented in paper 1 and 2. By applying the two methodologies to the case company, the two methodologies have proven to be practically applicable in a specific low volume environment. However, this is expected to also be the case to low volume industry in general. Thus, this dissertation does not only close unexplored gaps in literature, it also provides practitioners in low volume industry with methodologies that have proven to bring great value.

## 5.1. FURTHER RESEARCH

The research in this dissertation contributes to the theory related to design of RMS by presenting new methodologies to design RMS architectures in low volume industry. It is the author's belief that the overall objective has been met, and it is confirmed that RMS can bring value to low volume industry. However, applying RMS theory on low volume industry confirms the expectations that company characteristics has a strong influence on the level to which reconfigurability has the strongest impact and thus to the type of reconfigurability that should be implemented. Therefore, the research conducted reinforces the reason to further investigate the relation between company characteristics and the type and level of reconfigurability, which can contribute to facilitate a focused transformation effort.

## 5.2. APPLICABILITY AND GENERALISABILITY

Since the focus of this dissertation has been focused on low volume companies, the applicability of much of the research is limited to this type of companies. Hence, companies with different characteristics are less likely to be able to apply the resulting methodologies proposed in this dissertation. However, the design phases of the methodologies originate from overall generic design issues described in literature. Therefore, it is expected that the five phased design methodologies for architecture design can be adopted for RMS architecture design in companies with different characteristics. However, this will imply that the choice of methods, techniques, procedures, tools etc. is adapted to the specific application area.

Though industrial visits at companies similar to the industrial partner gives an overall insight into this particular industry, the empirical work of this project is based on the industrial partner, Hydrema. This could give reason to question the applicability of the results to other low volume companies. It is however the author's clear impression that other low volume companies are facing the same challenges related to high mix in small batches, which can be met by increased reconfigurability. Exchange of experience within the industry has confirmed that they encounter similar challenges, which is believed can be met by applying the two methodologies. Hence, this strengthens the expectation that the methodologies can bring value to some of the companies represented in this industry, if not all. The nature of the project as an industrial PhD project, is likely to increase the applicability because the project is thus carried out together with application specialists in industry. Furthermore, SMEs characterised by low volume and high variety constitute a considerable part of the industrial companies in Denmark, and in high wage countries in general. This suggest that the contributions of this dissertation is even more important than methodologies for high volume companies, which has received the most attention previously.

## 5.3. VERIFICATION AND VALIDATION

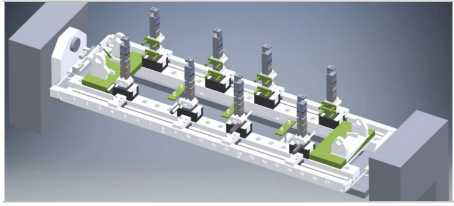
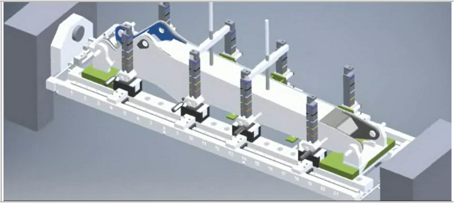
In collaboration with the industrial partner tests of the methodologies have been conducted as it is apparent from paper 1 and 2. These tests helped to evaluate the implications of applying the proposed methodologies and the applicability in industry. Thus, it was verified that the proposed methodologies were applicable to the industrial partner, and thus reconfigurable architectures were designed.

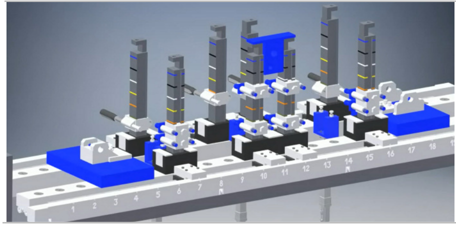
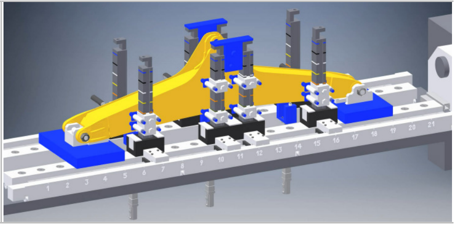
In order to validate the results of applying the methodology for machine level detailed design of a fixture and subsequently simulations of reconfigurations have been conducted. Thereby, it was validated that the proposed architecture for a reconfigurable fixture could in fact be applied to make an architecture that could be adopted for detailed design of a fixture, which is capable of reconfiguring across considerable product component variery. From Table 5-1 an example of a reconfiguration is visualized. The example shows a reconfiguration from one configuration to another. Modules that are unique to the product components (green and blue) are exchanged whereas the standard modules simply change position. The two product components illustrated in Table 5-1 are considerably different, though similar. This indicates that some of the challenges that follow high mix and small batches, and thus some of the challenges faced by low volume manufacturers, are likely to be met by reconfigurable production equipment, in general.

## 5.1. ALTERNATIVE SOLUTION

High wages in the labor market have contributed to an automation tendency in Danish industry, while robots at the same time are getting cheaper. This may suggest that labor intensive processes such as tack welding should be replaced by flexible robots and not just assisted with reconfigurable manufacturing equipment. Hence, the jig-less welding cell illustrated in Figure 5-1 was developed in collaboration with the Danish Technological Institute. The cell was developed for tack welding of the same component family as the one subject to the case concerned by fixture design. However, the longer the project got into the design process the design revealed some weaknesses. Though it is somehow positive current solution has 60 % excess capacity, which implies that the investment is divided on relatively few product components.

*Table 5-1 Fixture reconfiguration*

| Arm structure 1 | |
|---|---|
| Reconfiguration | Set-up and tack welding |
|  |  |

| Arm structure 2 | |
|---|---|
| Reconfiguration | Set-up and tack welding |
|  |  |

Another weakness is the cost of introducing existing product components (app. 100) and the cost of introducing new product components is relatively high due to time consuming programming of the welding jobs. For now, the industrial partner wish to invest in reconfigurable manufacturing systems, since it has considerable, positive perspectives to the industrial partner. However, when obsolete welding robots needs to be replaced in future the jig-less welding concept may be relevant as a substitute if it can combine both tack welding and the full welding job. That however doesn't imply that reconfigurable equipment is not useful to the industrial partner. The general-purpose machines which make up the majority of the machines at the industrial partner are all supported by dedicated auxiliary equipment, e.g. fixtures. Development, manufacturing and installation of dedicated equipment is associated with some very high costs, and it is expected that increased reconfigurability can reduced these costs significantly. Anyway, the jig-less concept partly consist of a reconfigurable floor, which can be reconfigured for different product components by adding, removing or changing the position of dowels in the floor.

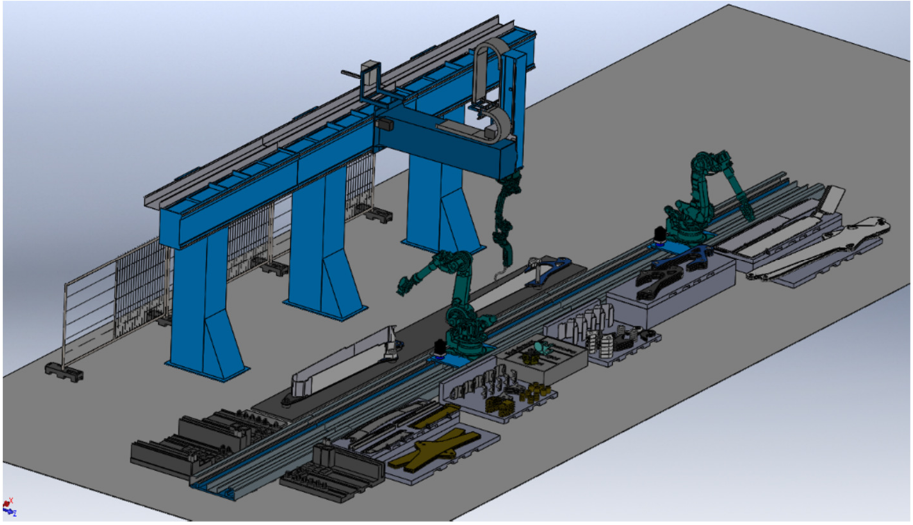


*Figure 5-1 Jigless welding*

# CHAPTER 6. BIBLIOGRAPHY

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# APPENDIX

## Paper 1

Methodology for Reconfigurable Fixture Architecture Design
*Bejlegaard, Mads; ElMaraghy, Waguih; Brunoe, Thomas Ditlev; Andersen, Ann-Louise; Nielsen, Kjeld.* Submitted to Journal of Manufacturing Science and Technology

## Paper 2

Reconfigurable Manufacturing System Architecture Redesign in Low Volume Industry
*Bejlegaard, Mads; Brunoe, Thomas Ditlev; Nielsen, Kjeld.* Submitted to Journal of Manufacturing Systems

## Paper 3

Machine-Part Formation Enabling Reconfigurable Manufacturing Systems Configuration Design: Line Balancing Problem for Low Volume and High Variety.
*Bejlegaard, Mads; Brunø, Thomas Ditlev; Nielsen, Kjeld; Bossen, Jacob.* Managing Complexity. Springer International Publishing, 2017. 139-146.

## Paper 4

Application of Module Drivers Creating Modular Manufacturing Equipment Enabling Changeability.
*Bejlegaard, Mads; Brunoe, Thomas Ditlev; Nielsen, Kjeld.* Procedia CIRP 52 (2016): 134-138.

## Paper 5

Reconfigurable Manufacturing Potential in Small and Medium Enterprises with Low Volume and High Variety : Pre-design Evaluation of RMS.
*Bejlegaard, Mads; Brunoe, Thomas D.; Bossen, Jacob; Andersen, Ann Louise; Nielsen, Kjeld.* Procedia CIRP 51 (2016): 32-37.

## Paper 6

Prediction of process time for early production planning purposes.
*Bejlegaard, Mads; Brunoe, Thomas Ditlev; Nielsen, Kjeld.* IFIP International Conference on Advances in Production Management Systems. Springer, Cham, 2015.

## Paper 7

Conceptual Model for Developing Platform-Centric Production Architectures.
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