Development of Changeable and Reconfigurable Manufacturing Systems

Supporting Context-specific Design of Changeability

Andersen, Ann-Louise

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DEVELOPMENT OF CHANGEABLE AND RECONFIGURABLE MANUFACTURING SYSTEMS

SUPPORTING CONTEXT-SPECIFIC DESIGN OF CHANGEABILITY

BY
ANN-LOUISE ANDERSEN

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AALBORG UNIVERSITY
DENMARK

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by

Ann-Louise Andersen

AALBORG UNIVERSITY
DENMARK

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PhD supervisor: Associate Professor Kjeld Nielsen
Aalborg University

Assistant PhD supervisor: Associate Professor Thomas Ditlev Brunø
Aalborg University

PhD committee: Charles Møller (chairman)
Aalborg University

Kristina Säfsten
Jönköping Univeristy

Associate Professor Arne Bilberg
University of Southern Denmark

PhD Series: Faculty of Engineering and Science, Aalborg University

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Ann-Louise Andersen was born in Kongerslev in Nordjylland, Denmark. She studied at Aalborg University, where she completed a BSc degree in Global Business Engineering in 2012, followed by a MSc degree in Operations and Supply Chain Management in 2014. Since then, she has been a PhD fellow at the Department of Materials and Production at Aalborg University, where her research on changeable and reconfigurable manufacturing is part of the Manufacturing Academy Denmark (MADE) project, funded by the Innovation Fund Denmark.

ENGLISH SUMMARY

In today's global manufacturing environment, change is inevitable, whether it is in markets, consumer preferences, technologies, materials, or legislation. These types of changes have generally resulted in increased heterogeneity and fragmentation of demand, increasing uncertainty and turbulence of markets, as well as growing international competition from low-wage countries that causes higher pressure for cost-reduction and productivity. For high-wage countries such as Denmark, these requirements that encompass not only low cost, but also high quality, high variety, and rapid responsiveness, represent dichotomies that should be resolved and reduced in order to sustain competitiveness. This is referred to as the poly-lemma of production. On one hand, high economies of scope in terms of one piece flow, flexibility, and low planning effort promote adaptability to global market conditions. On the other hand, unit cost must be reduced and resources optimally utilized, which require high economies of scale and a high planning orientation in production. Neither traditional mass production nor highly flexible production for niche markets resolve this poly-lemma of production, however, changeable and reconfigurable manufacturing systems that are dynamically responsive to change in functionality and capacity appear promising.

A changeable manufacturing system has appropriate change enablers to accomplish proactive, timely, and economically feasible adjustments of structures and processes on all levels in response to external and internal requirements, in order to continuously and efficiently match changing functionality and capacity requirements. In this respect, flexibility is utilized to adjust manufacturing quickly and with limited effort within a predefined flexibility range, while reconfigurability is utilized to expand this range, thereby changing the system to suit new requirement emerging from e.g. new product features, materials, or technologies. Most often, manufacturing systems will contain a context-specific combination of flexibility and reconfigurability in order to be changeable, where flexibility ranges are pre-selected to a specific situation, by mixing the options of either reconfiguring the system or using built-in flexibility.

In order to support an industrial transition towards changeable manufacturing systems, traditional design methodologies and trial-and-error approaches are insufficient. Primarily, this is due to changeability being a non-functional property that is usually manifested after the system has been put to its initial use. Thus, considering changeability complicates the design process significantly. In particular, complexity results from difficulties in terms of anticipating and understanding change requirements, as well as comprehending and evaluating the vast amount of design choices, e.g. regarding the specific combination of flexibility and reconfigurability, the appropriate change enablers, and the system level or constituents that should be able to change.

Therefore, the objective of this thesis is to create a design methodology for changeable and reconfigurable manufacturing systems that can be applied in practice in various manufacturing settings to support context-specific design of changeability. The overall research approach is interactive and collaborative with two case companies that have polar-like product and production characteristics. This interactive research approach is driven by problems originated in both research and practise, based on both previous research and practical experience, and conducted through both data collection and analysis, as well as some kind of organisational action, in order to ensure both practical relevance and novelty of results. As a consequence, various research methods are embraced, in order to address specific research questions that arise throughout the long-term emerging collaboration with the case companies. The research methods applied cover systematic literature reviews for defining theoretical requirements for the design methodology, as well as in-depth case studies, multiple comparative case studies, and quantitative surveys for defining industry-related requirements for the design methodology.

The research presented in the thesis progresses in three overall parts that collectively cover a total of eleven appended research papers. Initially, the theoretical requirements for the design methodology are established through systematic literature analysis and synthesis, followed by empirical research related to practical requirements for the design methodology. Together, these requirements reflect both the need for supporting and planning the process of designing changeability and the need for supporting the actual design task. Based on these requirements, a design methodology for changeable and reconfigurable manufacturing systems is proposed, covering system requirement analysis, concept design, and embodiment design. The methodology builds on the premise that differences in changeability implementation level, type, and extent are contingent on the type of manufacturing context. The strength of the design methodology is that it supports fundamental decisions related to changeability, while offering a systematic rationalization of the design process. This is demonstrated through the application of the design methodology in the two collaborating case companies. In addition, an evaluation method is proposed, which can be applied in initial stages of design for evaluating the investment feasibility of changeable and reconfigurable manufacturing concepts based on future demand predictions and their uncertainties. In combination, the design methodology and the supportive evaluation method constitute valuable support for design and development of changeable and reconfigurable manufacturing systems. Conclusively, practical implications of the design methodology are investigated in terms of critical design preconditions, thereby creating a solid foundation for conducting the actual design process and identifying essential aspects that impact its success.

DANSK RESUME

I vor tids globale produktionsmiljø er forandring uundgåelig, hvad enten det er i markeder, forbrugerpræferencer, teknologier, materialer eller lovgivning. Disse typer ændringer har overordnet set resulteret i øget forskellighed og fragmentering af efterspørgsel, stigende markedsusikkerhed og turbulens, samt øget international konkurrence fra lavtlønslande, der resulterer i højere pres for omkostningsreduktion og produktivitet. For at opretholde konkurrenceevnen i højtlønslande som Danmark omfatter kravene ikke kun lave omkostninger, men også høj kvalitet, høj varians og hurtig respons, hvilket repræsenter dikotomier der skal løses og reduceres. Dette er det såkaldte produktions poly-lemma. På den ene side fremmes tilpasningsevne til globale markedsforhold af synergifordele i form af et-styks flow og fleksibilitet med lav planlægningsindsats. På den anden side må enhedsomkostninger reduceres og ressourcer udnyttes optimalt, hvilket kræver stordriftsfordele og en høj planlægningsorientering i produktionen. Hverken traditionel masseproduktion eller ekstremt fleksibel produktion til niche-markeder løser dette såkaldte produktions poly-lemma, derimod forekommer omstillingsparate og rekonfigurerbare produktionssystemer lovende, idet de reagerer dynamisk på ændringer i funktionalitet og kapacitet.

Et omstillingsparat produktionssystem har nødvendige egenskaber til at opnå proaktive, rettidige og økonomisk kvalificerede tilpasninger af strukturer og processer på alle niveauer som reaktion på eksterne og interne krav omkring kontinuerlig og effektiv tilpasning til skiftende funktionalitet- og kapacitetsbehov. I denne henseende benyttes fleksibilitet til at justere produktionen hurtigt og med begrænset indsats indenfor et foruddefineret spillerum, mens rekonfigurerbarhed anvendes til at udvide dette spillerum, hvorved systemet ændres i forhold til nye krav, der fremkommer af f.eks. nye produktegenskaber, materialer eller teknologier. Produktionssystemer indeholder oftest en kontekstspecifik kombination af fleksibilitet og rekonfigurerbarhed for at være omstillingsparat, hvor fleksibilitet er foruddefineret til en bestemt situation ved at blande mulighederne for enten at rekonfigurere systemet eller bruge indbygget fleksibilitet.

For at understøtte en industriel overgang til omstillingsparate produktionssystemer er traditionelle systemdesignmetoder og trial-and-error tilgange utilstrækkelige. Dette skyldes primært at omstillingsparathed er en ikke-funktionel systemegenskab, der normalt manifesteres efter at systemet er sat i dets første anvendelse. Når man betragter omstillingsparathed i produktion, kompliceres designprocessen betydeligt. Dette er især ift. definering og forståelse af ændringsbehov, samt forståelse og evaluering af det store antal designvalg, f.eks. den specifikke kombination af fleksibilitet og rekonfigurerbarhed, de nødvendige ændringsegenskaber, og systemniveauet eller elementer i produktionen der skal kunne ændres.

Formålet med denne afhandling er derfor at udvikle en designmetode for omstillingsparate og rekonfigurerbare produktionssystemer, som i praksis kan anvendes i forskellige produktionssituationer for at understøtte kontekstspecifik design af omstillingsparathed. Overordnet er forskningsmetoden interaktiv med to case virksomheder, der repræsenterer modsatte produkt- og produktionskarakteristika. Denne interaktive tilgang er drevet af problemer, der stammer fra både forskning og praksis, baseret på både tidligere forskning og praktisk erfaring, og gennemføres både gennem dataindsamling og analyse, samt gennem en organisatorisk indsats for at sikre både praktisk relevans og nyhedsværdi af resultaterne. Som følge heraf er forskellige forskningsmetoder anvendt for at løse specifikke forskningsspørgsmål, der opstår i det længerevarende samarbejde med case virksomhederne. De anvendte forskningsmetoder omfatter systematiske litteraturstudier for at definere teoretiske krav til designmetoden, samt dybdegående casestudier, multiple komparative casestudier og kvantitative spørgeskemaundersøgelser for at definere industri relaterede krav til designmetoden.

Denne afhandling er inddelt i tre overordnede dele, der samlet dækker i alt elleve vedhæftede forskningsartikler. Indledningsvist etableres de teoretiske krav til designmetoden gennem systematisk litteraturanalyse og syntese, efterfulgt af empiriske undersøgelser relateret til praktiske krav til designmetoden. Tilsammen afspejler disse krav både behovet for at understøtte planlægning af designprocessen for omstillingsparat produktion og behovet for at understøtte den aktuelle designopgave. På baggrund af disse krav, præsenteres en designmetode for omstillingsparate og rekonfigurerbare produktionssystemer, der dækker systemkravsanalyse, konceptdesign, og mere detaljeret design. Metoden bygger på forudsætningen om at forskelle i implementeringsniveau, type og omfang af omstillingsparathed er afhængig af produktionskonteksten. Designmetodens styrke er at den understøtter beslutninger relateret til alle fundamentale aspekter af omstillingsparathed, samtidig med at den skaber en systematisk rationalisering af designprocessen. Dette demonstreres gennem anvendelse af designmetoden i de to case virksomheder. Derudover præsenteres en evalueringsmetode i afhandlingen, som kan anvendes i indledende faser af system design til evaluering af investeringsfordelagtighed af omstillingsparate og rekonfigurerbare produktionskoncepter, baseret på fremtidige efterspørgselsforudsigelser og usikkerheder. Tilsammen udgør designmetoden og den tilhørende evalueringsmetode et værdifuldt fundament for design og udvikling af omstillingsparate og rekonfigurerbare produktionssystemer. Slutteligt undersøges konsekvenserne af den praktiske anvendelse af designmetoden med hensyn til kritiske designforudsætninger, for derved at skabe et solidt fundament for at udføre den egentlige designproces og identificere væsentlige aspekter, der påvirker succesen af designeprocessen og dens udfald.

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CHAPTER 1. INTRODUCTION

During the last decades, manufacturing has undergone significant changes and continues to witness major shifts that have led to edge of entering the fourth industrial revolution. Centuries ago, manufacturing consisted solely of craftsmanship providing high customization of products on demand. This paradigm remained until the first industrial revolution, driven by mechanization on the basis of water and steam, resulting in major productivity gains and an industrialized society with factories and growth (Drath and Horch 2014, Schwab 2017). At the end of the twentieth century, mass production started to flourish with the spread of electrical power and labour division, widely symbolised by Henry Ford's conveyer belts introduced for production of affordable standard automobiles (Drath and Horch 2014). However, as societies and markets grew wealthier, demand for product variety emerged together with the use of electronics and computers for factory automation (Koren 2010). As manufacturing went digital with e.g. computer-numerically-controlled machines, customization of products at lower cost became the new manufacturing vision (Hu 2013). At present, the fourth stage of manufacturing has arrived based on the internet-of-things and smart, adaptable, and reconfigurable manufacturing systems (Jeschke *et al.* 2016). This fourth industrial revolution builds on the visions and enablers of previous manufacturing paradigms, spanning from low cost and dedicated machines to high variety and flexible machines, however, promising new levels of responsiveness, flexibility, and productivity (Koren 2010).

1.1. IMPORTANCE OF MANUFACTURING

The first two industrial revolutions played major roles in creating wealth and economic growth, however, in recent years, high-wage countries have lost significant market share of mass production, resulting in major reductions of manufacturing jobs (McKinsey 2012). During the last decade, employment in manufacturing as a share of total employment decreased from more than 19% to less than 13% in Denmark (Iris Group 2015), with similar developments occurring in other high-wage countries (McKinsey 2012). Automation, extensive outsourcing and offshoring, and emergence of new global competitors from low-wage countries are among the main reasons for this (Brecher *et al.* 2012). As such, the global structure of manufacturing has changed and the manufacturing share of countries' gross domestic product has fallen significantly in high-income and advanced economies, such as in most European countries, while being notably higher in middle income countries, such as China, India, Thailand, and Russia (McKinsey 2012). With this de-industrialization trend in advanced economies, a shift in global demand towards developing countries followed (McKinsey 2012). Generally, this shift results in increased fragmentation of customer demand, increased number of market segments with diverse needs, and increased turbulence and uncertainty of markets (Westkämper 2006).

With the fourth industrial revolution, manufacturing is once again placed at a central role in advanced economies, however, not as a traditional large-scale employment contributor, but rather as a source of innovation, productivity, and higher value jobs (Brecher *et al.* 2012, McKinsey 2012). Alternative sources of competitiveness to low-wage production are emphasised in this new manufacturing paradigm, e.g. individualized production; technology leadership, environmental sustainability, premium quality, and innovation (Brecher *et al.* 2012, Jeschke *et al.* 2017). These goals of the fourth industrial stage create competitive advantage for high-wage countries, with potentials of counteracting the de-industrialization process and exploiting global market trends of increased heterogeneity and volatility of demand. With these promising potentials of the fourth industrial revolution, major national research initiatives have been initiated worldwide for its realization, e.g. the German "Industrie 4.0". Likewise, in Denmark, the MADE (Manufacturing Academy Denmark) initiative has been initiated for advancing Danish manufacturing through collaboration between research and industry, which this PhD thesis is a result of.

Compared to requirements met by previous manufacturing paradigms, the present requirements imposed on manufacturing encompass both low cost, high quality, high variety, and rapid responsiveness (Koren 2010). Balancing economies of scale and economies of scope has become a key challenge (Brecher *et al.* 2012, ElMaraghy *et al.* 2009). On one hand, high economies of scope, in terms of one piece flow and flexibility, and low planning effort promote adaptability to global market conditions. On the other hand, unit costs must be reduced and resources optimally utilized, which requires high economies of scale and a high planning orientation in production (Schuh *et al.* 2009). Resolving and more importantly reducing these dichotomies between scale and scope and value-orientation and planning-orientation, referred to as the production poly-lemma, are widely regarded as the key to competitive advantage in high-wage countries (Brecher *et al.* 2012). In other words, focusing solely on mass production or sophisticated production for premium niche market have proved not to be viable directions for future manufacturing in advanced economies, instead individualized, flexible, and high quality production at mass efficiency appears promising.

Product-related strategies, such as modularization of the product architecture and reuse of a product platform across variants in a product family have been widely and successfully applied for managing variety in an efficient way (Ericsson and Erixon 1999, Ulrich and Tung 1991). One of the most well-known and popular examples of this is the "Modulare Querbaukasten" (MQB) concept invented by Volkswagen, which ensures high variety in cars, reduction in unit cost, and less engineered hours per vehicle, through standardization of design and commonality of parts and subassemblies. The newest generation of the MQB platform is combined with a modular production concept estimated to create savings around 1,000 Euros per produced car (Schuh & Co. 2015). A plethora of additional successful implementations of product modularization exist, however, the Volkswagen example emphasises that meeting requirements of today's global manufacturing environment requires not only well-design products, but also well-designed production systems. In itself, the presence of modularization and a platform approach to product development does not ensure effective use of production resources, nor responsiveness in terms of rapid production development and ramp-up (Michaelis and Johannesson 2011). In particular, reusing production equipment across product variants, product families, and product generations is becoming ever more critical with the decrease of product lifecycles and the importance of time-to-market. In recent studies, it has been indicated that the mean time for new products to get adopted by the market has decreased significantly (Chandrasekaran and Tellis 2008), product variety has been more than doubled in average between 1997 and 2012, whereas product lifecycles have been shortened dramatically (Roland Berger Strategy Consultants GmbH 2012). In contrary, the technical life of manufacturing system components such as robotics, conveying systems, controls, etc. is in general much longer (Järvenpää 2012). Thus, introduction of product modularity will not on its own respond to this challenge, however, in combination with an appropriate changeable production setup, affordable product variety and rapid responsiveness can be achieved.

1.2. CHANGEABLE MANUFACTURING

Different types of variety-oriented manufacturing concepts have in recent years been proposed to deal with the challenges of increased demand for product variety and volatility of markets, widely being referred to as changeable manufacturing concepts. Changeability can be defined as the ability to accomplish early and foresighted adjustments in an economically feasible way on all factory levels spanning from the workstation to the production network (ElMaraghy and Wiendahl 2009). Thus, changeability is an umbrella term encompassing various levels and constituents of the manufacturing company, e.g. logical and physical elements (Wiendahl *et al.* 2007). Consequently, a fundamental element of changeability is a systems perspective of manufacturing, considering functional, structural, and hierarchical dimensions.

Compared to mass production, changeable manufacturing concepts enable both physical and logical responses to changes in product variety and volume (ElMaraghy *et al.* 2012a). The first changeable manufacturing concept introduced is the Flexible Manufacturing System (FMS), which was popularized with the third industrial revolution in the 70's and 80's (Koren 2010, Zhang *et al.* 2006). The FMS is an integrated system of general-purpose computerized-numerically controlled machine tools and computer-controlled handling equipment, which can be adjusted with almost no effort between job types. Compared to dedicated transfer lines and systems used previously for mass production, the FMS brought new levels of product variety, however, with limited production rates and high investments (Koren 2006, Mehrabi *et al.* 2002). Various industrial examples of unsuccessful implementations of highly flexible manufacturing systems have been set forward, covering disadvantages regarding excess functionality, over-capacity, high maintenance cost, and large initial capital investments (Koren 2010). In fact, a survey conducted during 2001 indicated that around 20% of the FMSs installed in the 90's had been discontinued, due to the former mentioned reasons (Koren 2010). Therefore, the concept of the Reconfigurable Manufacturing System (RMS) was introduced in the late 90's, as an extension of the FMS combining high throughput known from traditional dedicated manufacturing lines and the flexibility of the FMS (Koren *et al.* 1999). The main difference between the two concepts is the RMS's ability to be continuously changed, in order to have the exact functionality, and capacity needed to produce product and part families, as well as new products or parts (Mehrabi *et al.* 2002). This feature is key to reducing the traditional trade-off between flexibility and productivity, being enabled by six core characteristics: customization, convertibility, scalability, modularity, integrability, and diagnosability (Koren and Shpitalni 2010). Customization refers to system and machine flexibility being limited to meet requirements of product and part families, convertibility refers to being able to easily change and transform functionality of the system to new requirements, and scalability refers to easy modification of production capacity. These are so-called necessary RMS characteristics (Koren 2006). Modularity and integrability refer to the system and machine functionalities being grouped in smaller units with standard interfaces that can be easily combined, while diagnosability refers to the ability to easily detect and diagnose errors during reconfiguration and ramp-up. The three latter characteristics are so-called supportive RMS characteristics, meaning that they enable the necessary RMS characteristics. Additionally, the ability to change the degree of automation of the system, denoted as automatibility, and the ability to change location of modules and station, denoted as mobility, are related characteristics of reconfigurability (ElMaraghy and Wiendahl 2009). In the RMS, these characteristics are embedded in both physical and logical aspects of the system and within its sublevels (Koren 2006). On system level, reconfigurability is achieved by adding, removing, or changing the modules of the system, thereby changing the functionality or the capacity (Koren 2010). On lower levels, reconfigurable machines are utilized, covering tools, fixtures, inspection machines, and material handling systems (Bi *et al.* 2008b). These reconfigurable machines have modular structures, which enable quick conversion between different parts within a part family, as well as in working speed or volumes (Katz 2007).

Both the FMS and the RMS are changeable manufacturing concepts, however, with significant differences in terms of how changeability is achieved and what the dimension and object of change is. Generally, the notion of flexibility has been widely discussed and various dimensions and types of flexibility have been proposed, e.g. machine flexibility, operation flexibility, product flexibility, routing flexibility, expansion flexibility, etc. (ElMaraghy 2005b). However, a main logic behind different types of flexibility is that they often relate to a specific change goal, e.g. the product, the mix, or the volume, a specific level of the company, e.g. the system, the cell of the machines, or a feature of the manufacturing system, e.g. the process, the routing, the machine, etc. (De Toni and Tonchia 1998, ElMaraghy 2005b). However, two goals of changeability appear universal and particularly prominent; being able to change functionality of the system e.g. to suit a whole range of products or new products, and being able to change capacity (Koren 2006, Terkaj *et al.* 2009b). Generally, the FMS is regarded as a system that has limited capacity and ability to be expanded, as well as high pre-planned functionality to suit various processing requirements (Koren 2006). In contrary, the RMS is designed at the outset for change and is expandable in both capacity and functionality to suit dynamic functionality and capacity requirements (Koren 2010).

Thus, flexibility and reconfigurability can in a broader sense be viewed as different types of changeability, where flexibility covers built-in and pre-planned ability to change and reconfigurability covers the ability to acquire ability to change as needed (Terkaj *et al.* 2009a). In other words, flexible manufacturing systems are generally regarded as manufacturing systems that can produce a wide variety of products without physically altering the structure of the system, as they have built-in general purpose flexibility within predefined boundaries (Koren and Shpitalni 2010). The reconfigurable manufacturing system is able to expand these flexibility boundaries, in order to have the exact functionality and capacity needed exactly when needed (ElMaraghy 2005b). Thus, in the short-term or for each configuration, the reconfigurable manufacturing system is likely to have limited flexibility compared to the flexible manufacturing system, which is often depicted as in Figure 1. However, in the long-term, the reconfigurable system can be extended in functionality and capacity, thereby potentially exceeding the scope of the flexible manufacturing system, not only in capacity but also in functionality.

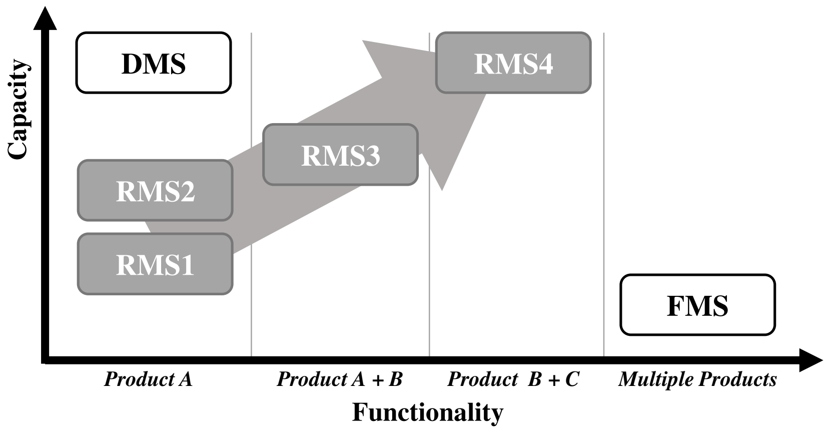

Figure 1. Comparison of dedicated manufacturing (DMS), flexible manufacturing (FMS), and reconfigurable manufacturing (RMS) (Koren and Shpitalni 2010).

Most often, manufacturing systems will contain a combination of flexibility and reconfigurability in order to be changeable, where flexibility ranges are pre-selected or customized to a specific situation, by mixing the options of either reconfiguring the system or using built-in flexibility (Terkaj *et al.* 2009a, Terkaj *et al.* 2009b). Thus, flexibility will be utilized to adjust manufacturing quickly and with limited effort within a predefined flexibility range, while reconfigurability will be utilized to expand this range of functionality, thereby changing the system to suit new processing requirement emerging from e.g. new product features, materials, or technologies (Azab *et al.* 2013). In Figure 2, the distinction between flexibility and reconfigurability is depicted in terms of functionality, showing difference in their timing of realization. Flexibility represents a system's existing capabilities to change, while reconfigurability involves utilizing enablers such as modularity for acquiring an ability to change either capacity of functionality (Terkaj *et al.* 2009b). The specific combination of the two is believed to be context dependent and a matter of deciding whether to invest in a larger range of flexibility than needed by the present situation and prior to its long-term utilization or investing in a more limited range of flexibility with enablers of reconfigurability for rapid and efficient change of the system (Benkamoun 2016, Terkaj *et al.* 2009a). Thus, reconfigurability is a dynamic and fundamental manufacturing principle for meeting requirements of high product variety, individualized production, small lot sizes, fluctuating market demand, and rapid introduction of new features, materials, and technologies.

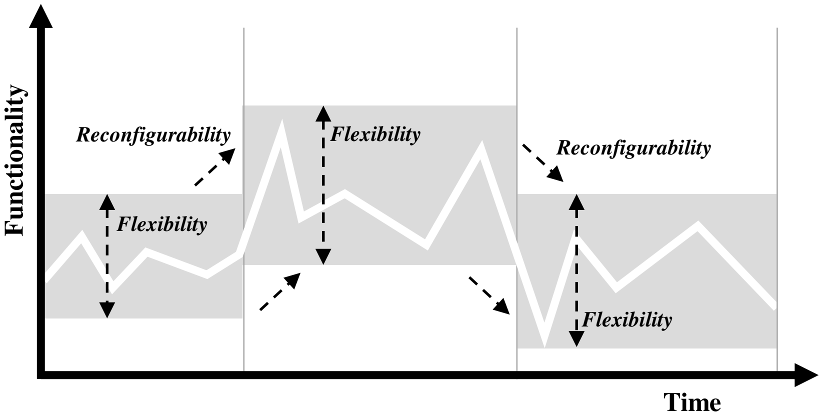

Figure 2. Changeability as a combination of flexibility and reconfigurability. Adapted from Azab et al. (2013).

A prominent and widely successful example of the development and implementation of changeable manufacturing is the aforementioned "Modulare Produktionsbaukasten Prinzip" (MPB) from Volkswagen, which involves standardisation of production processes, resources, and organisational elements across global production locations (Waltl and Wildemann 2014b). Simultaneously to the introduction of the well-known "MQB" modular product platform, Volkswagen initiated a production modularisation strategy with the aim of segmenting the entire factory into smaller modules to realise flexibility and cost efficiency at the same time. The platform covers both various hierarchical levels of the company, e.g. factory, the site, the line, or the station, as well as different structuring elements, e.g. logistics and assembly (Waltl and Wildemann 2014a, Waltl and Wildemann 2014c). For instance, the chassis of various cars is produced by using a collection of common production modules that has the exact flexibility needed (Waltl and Wildemann 2014a). Significant improvements are estimated as a consequences of this modular production initiative, e.g. reductions in equipment investments of around 30%, reduction in planning costs of around 20%, and significant productivity improvements (Waltl and Wildemann 2014a).

The MPB example from Volkswagen demonstrates the use of modularity as an enabler of realizing needed flexibility corridors and expanding these through reconfiguration when needed, as depicted in Figure 2. Yet, such examples of successful implementations of changeability and reconfigurability are not yet widely available, nor described widely in research. However, glancing into the future, the fourth industrial revolution envisions manufacturing systems that are built on the fundamental principles of changeability combined with advanced digitalization and automation. This further extension of the reconfigurable manufacturing concept is a network of physical and digital objects that allows for extensive interaction and integration (Jeschke *et al.* 2017). The industrial internet-of-things enables such cyber-physical manufacturing systems that are highly reconfigurable, autonomous, and intelligent, creating new levels of adaptability, productivity, and individualisation of production (Oks *et al.* 2017). Technological aspects of these systems are advancing quickly, thus, well-designed manufacturing systems that have fundamental features of changeability and reconfigurability, e.g. modularity in both physical and logical design features, standard interfaces, and reliable flexibility for a range of anticipated functional requirements, are likely to evolve into these smart and networked manufacturing systems that capture the essence of the fourth industrial revolution (ElMaraghy *et al.* 2012b, Wang *et al.* 2016).

1.1. DESIGN FOR CHANGEABILITY AND RECONFIGURABILITY

Traditional manufacturing systems that are dedicated for mass production are not able to respond dynamically to change, as they have static, pre-planned, and built-in functionalities. Therefore, from a design and development perspective, these systems are designed purely for their initial purpose and are less complex design problems than in the case of changeable and reconfigurable systems, which have dynamic abilities to change. In other words, changeability and reconfigurability are lifecycle properties of manufacturing systems, which are emergent and usually demonstrated after the system has been put into initial use (de Weck *et al.* 2011, Farid 2016). Thus, when designing changeability and reconfigurability, the immediate and initial use of the system is not the sole focus, but rather seen in combination with properties that have more long-term exposure, however still being designed at the outset (Benkamoun 2016, de Weck *et al.* 2011).

Changeability and reconfigurability foster a systems perspective on manufacturing and the design problem, as all levels and constituents of the system must be considered and prepared for change (ElMaraghy and Wiendahl 2009). Applying a systems perspective to a manufacturing system implies that it is a collection of interrelated elements working together to reach a common goal (Bellgran and Säfsten 2009). Furthermore, in the systems perspective, required consideration of the complete problem and not only technical sub-problems suggests a holistic view comprising people, machines, equipment, technology, facilities, etc. (Bellgran 2003, Bellgran and Säfsten 2009). In systems engineering and engineering design, the creation and management of systems that fulfil required needs is central, while at the same time considering the complete problem (Farid 2016). Often this is supported by formal, structured, and systematic approaches that include fundamental activities of requirements specification, analysis, synthesis, verification, and validation (Farid 2016). Well-known approaches to engineering design are among others axiomatic design (Farid and Suh 2016), quality function deployment (Govers 1996), problem-solving cycles for design (Roozenburg and Eekels 1995), or phased design models (Pahl and Beitz 2013). Systematic design methodologies for manufacturing systems should support both the planning and execution of the design process, as well as the actual design; the so-called double task of design (Bellgran and Säfsten 2009). With this double-task of design, focus is not only on the actual design task, but also on the understanding and dynamics of the design process. However, in practise it is widely recognised that design of manufacturing systems is usually not carefully planned and executed as prescribed by systems engineering design methodologies, but rather conducted iteratively and in an ad-hoc manner (Bellgran and Säfsten 2009). Such trial-and-error approaches seldom implies careful discovery and specification of system requirements and solutions, but rather involve guesses regarding a suitable system solutions and evaluation of its adherence to performance requirements (Bellgran and Säfsten 2009). Evidently, such trial-and-error approaches will likely lead to dedicated systems that realise immediately present requirements, rather than dynamic and changing requirements in the long-term. Thus, the necessity of systematic design approaches intensifies in the presence of changeability and reconfigurability.

The nature of changeability and reconfigurability as non-functional lifecycle manufacturing system requirements, challenges both the application of ad-hoc trial-and-error approaches, as well as traditional systems design methodologies. As systems design generally can be regarded as the task of specifying requirements in the functional domain and mapping these into a solution in the physical domain that meet specified constraints (Farid 2016), several concerns regarding the consideration of changeability are evident. First of all, as changeability and reconfigurability are non-functional system requirements relating to the behaviour of the system in the long-term, traditional approaches that solely considers immediate system requirements, such as the specification of the initial product and its required production volume, will not lead to dynamically changeable systems. Secondly, compared to the direct mapping from functional requirements to physical system parameters, the design of a physical solution to non-functional design requirements is challenged, as numerous options for its realization are available, e.g. in terms of the context-dependent combination of flexibility and reconfigurability. Lastly, the evaluation of the designed system and its adherence to initial requirements creates difficulties, as some of the designed changeability properties are first realised after the system has been put into use. In other words, the traditional approach to manufacturing system design, which often initiates after a specific product has been designed and has a primary focus on the product specification and the required tact time (Bellgran and Säfsten 2009), does not meet changeability and reconfigurability objectives, but rather leads to a situation where the system becomes obsolete quickly due to turbulent global market conditions. Thus, in order to enable an paradigm shift in industry towards changeable and reconfigurable manufacturing systems rather than traditional dedicated systems, new design methodologies are needed that support the realization of systems with dynamic ability to change through explicit inclusion of essential changeability and reconfigurability parameters. Nevertheless, this issue has only received limited attention in research on changeability and reconfigurability, which rather tends to focus on design sub-problems of largely technical nature, e.g. selecting an appropriate configuration of the modular system (Wang and Koren 2012, Xiaobo *et al.* 2000, Youssef and ElMaraghy 2006, Youssef and ElMaraghy 2007), developing reconfigurable machines and tooling (Bi *et al.* 2008a, Hollstein *et al.* 2012, Katz 2007), grouping and selecting product families (Abdi and Labib 2004b, Galan *et al.* 2007, Yigit *et al.* 2002), capacity management (Deif and ElMaraghy 2007a, Deif and ElMaraghy 2007b), or production and process planning (Azab and ElMaraghy 2007a, Azab and ElMaraghy 2007b). These research issues are largely related to detailed levels of design or the management of the changeable system. However, the main challenges regarding design for changeability as a lifetime system property, covering anticipating need for changeability, deriving an appropriate context-dependent changeable system solution, and evaluating it, precede these detailed design issues and are at the same time subject to greater uncertainty and criticality (Benkamoun 2016, Terkaj *et al.* 2009b). Only few general design methodologies for changeability and reconfigurability exist (Azab *et al.* 2013, Benkamoun *et al.* 2014, Deif and ElMaraghy 2006, Francalanza *et al.* 2014, Rösiö 2012a, Schuh *et al.* 2009, Tracht and Hogreve 2012). However, their applicability in different industrial settings have not yet been widely demonstrated, only to a limited extent in the automotive industry (Abdi and Labib 2004a, Al-Zaher *et al.* 2013, Benkamoun 2016, ElMaraghy and Abbas 2015, Rösiö and Säfsten 2013) or in the electronic industry (Deif and ElMaraghy 2006). Thus, the context-dependency of an appropriate changeable system solution is not explicitly addressed in current research, nor are current methodologies for design of changeability and reconfigurability sufficient for supporting the double task of design as being both the actual design task, as well as an organisational process that should be planned and executed.

1.2. THESIS OBJECTIVE

The development of manufacturing systems that are changeable and reconfigurable is a key feature of realizing the fourth industrial revolution and reducing the poly-lemma of production, in order to create competitive manufacturing in advanced economies and respond to global challenges of increased market heterogeneity, volatility, and uncertainty. Accordingly, in a Danish manufacturing context and in the aforementioned MADE research initiative, which this PhD project has been part of, the need for developing and realising manufacturing changeability has been set forward as a major competitive concern. However, in order to support an industrial transition towards changeable manufacturing concepts, traditional systems design methodologies and trial-and-errors approaches are insufficient, thus, a new design methodology is needed, which captures essential decisions and considerations regarding changeability and reconfigurability as dynamic lifetime properties of the manufacturing system. Therefore, the objective of this thesis is as follows:

Establish a systematic design methodology for changeable and reconfigurable manufacturing systems that can be applied in various types of manufacturing contexts for supporting the transition towards variety-oriented, responsive, and high quality production at mass production efficiency.

Both design for changeability and reconfigurability are considered, despite the former being an umbrella term that subsumes the latter. Particularly, reconfigurability is emphasised, as present manufacturing systems must have dynamic rather than static ability to change. However, changeability in terms of a combination of flexibility and reconfigurability is considered as well, in order to adequately cover options for changeability implementation in different manufacturing contexts. Thus, the context-dependency of a suitable combination of reconfigurability and flexibility is a central element considered in the creation of the methodology for design of changeability, in order to ensure an industrial paradigm shift, not only being limited to specific industrial settings or company types. Likewise, as this PhD project has been part of research conducted within the MADE initiative, the creation of a design methodology for changeable manufacturing that has practical relevance in different industrial contexts, represented by the project's case companies, is a central issue.

The research presented in the thesis is delimited to primarily covering the manufacturing system level, where reconfigurability is defined as a changeability enabler, and not higher levels of changeability including e.g. agile factories or the manufacturing network. Thus, the design of the entire manufacturing system comprising technology, machines, humans, etc. is considered, rather than focusing on detailed technical aspects of design, meaning that emphasis is particularly on the critical initial stages of design that precedes detailed and separate issues regarding design of hardware and software solutions. Furthermore, particular emphasis is placed on manufacturing system design and development being not only the actual task of design, in terms of establishing requirements and making a suitable solution, but also being a process that should be planned and executed properly. Thus, the complexity introduced by designing changeable and reconfigurable systems in terms of design prerequisites and barriers are considered as well, in order to enhance its industrial applicability and an actual industrial paradigm shift towards changeable system concepts.

1.3. CONTENT

This thesis builds upon a collection of papers each addressing research questions derived from the overall thesis objective. In Table 1, an outline of the thesis is presented, covering its chapters, the papers they build on, and summaries of all papers.

Table 1. Overview of papers covered in thesis chapters.

Thesis Chapter 3: Theoretical Foundation
Paper 1: Reconfigurable Manufacturing on Multiple Levels: Literature Review and Research Directions. **Research method:** Systematic literature review and classification. **Summary:** The purpose of this paper is to review state-of-the-art literature on reconfigurable manufacturing and classify each contribution based on the structuring level of the factory being addressed. Accordingly, prominent research issues at each level are identified. Based on a systematic literature retrieval and exclusion process, 152 publications are included in the review. The findings suggest that research on reconfigurable manufacturing is related primarily to the system and workstation levels. System issues are mainly related to logical of soft types of reconfigurations, such as optimal reconfiguration selection or process planning, whereas work-station issues heavily address physical and hard types of reconfigurations, e.g. in terms of designing reconfigurable machines. The paper emphasises the vast amount of variety in previous research regarding level of reconfigurability implementation and corresponding design issues.
Paper 2: Towards a Generic Design Method for Reconfigurable Manufacturing Systems – Analysis and Synthesis of Current Design Methods and Evaluation of Supportive Tools. **Research method:** Systematic literature review, classification, and synthesis. **Summary:** The paper provides a thorough review of design methods and methodologies for reconfigurable manufacturing systems. After systematic literature retrieval, exclusion, and an additional snowball approach, 21 design methods or frameworks were identified and analysed in terms their structure, steps, sequence of decisions, coverage, and applied procedures. The findings suggest that current design methods can be divided into either

Table 1. Overview of papers covered in thesis chapters.

being predominately of problem solving character or phase character, which represent two different perspectives on design that supplement each other. Based on this, a generic design process for reconfigurable manufacturing is proposed and practical implications are discussed in terms of available supportive tools.
Thesis Chapter 4: Empirical Foundation
Paper 3: Investigating the Impact of Product Volume and Variety on Production Ramp-up. **Research method:** Comparative multiple case study. **Summary:** In this paper, production start-up and ramp-up challenges are investigated and compared in two industrial cases, in order to identify fundamental differences derived from different product volume and variety characteristics. In the two cases, a large enterprise producing high-volume standard electronic products and a SME producing low-volume customized excavators, data on production ramp-up challenges were collected through semi-structured interviews based on generic problem categories identified in an initial literature review. Cross-case comparison of challenges and problems experienced for each category highlight important differences in start-up and ramp-up challenges, which further emphasises differences in application and potential of reconfigurability.
Paper 4: Investigating the Potential in Reconfigurable Manufacturing: A Case Study from Danish Industry. **Research method:** Single case study. **Summary:** This paper proposes and applies a practical approach for assessing the potential of reconfigurability in high-volume manufacturing companies, which can be used in initial design phases. In this approach, historical production data is analysed, focusing explicitly on potential capacity savings due to reuse of modular production lines rather than replacement of dedicated production lines. The investigated case indicates potential capacity savings of 50% as a result reconfigurability, as well as important aspects of reconfigurability potential in high-volume production contexts.
Paper 5: Reconfigurable Manufacturing Systems in Small and Medium Enterprises. **Research method:** Single case study. **Summary:** The research presented in this paper explores how small and medium sized companies (SMEs), which are often characterised by low production volume and high product variety or customization, can benefit from implementing principles of reconfigurability compared to large enterprises with higher production volumes. By

Table 1. Overview of papers covered in thesis chapters.

conducting a case study of a Danish SME that is currently in a transition towards reconfigurability, it is concluded that the implementation of reconfigurability and the challenges in its development differ significantly in small medium sized companies with high variety and low volume compared to larger enterprises with different volume and variety characteristics. This leads to the conclusion, that decisions on reconfigurability in terms of its level, type, and extent should be supported in design methodologies in order to suit various types of companies and industrial contexts.
Paper 6: Critical Enablers of Changeable and Reconfigurable Manufacturing Systems and Their Industrial Implementation. **Research method:** Industrial questionnaire survey. **Summary:** The aim of this paper is to investigate the criticality and degree of implementation of various enablers of changeable and reconfigurable manufacturing, as well as their contingency on the manufacturing setting, characterised by the firm size, country, production type, and the product type. Responses from 60 manufacturing companies were collected through a questionnaire survey and subsequently analysed using non-parametric statistics due to non-normality of data. The findings indicate that the level of implementation of the changeability and reconfigurability enablers is rudimentary, while their criticality is perceived higher than the current level of implementation. Significant differences regarding implementation and criticality of mobility, scalability, and convertibility were found for companies with varying degrees of manual work, make-to-stock production, and varying production volume, industry type and organisation size.
Thesis Chapter 5: Design Methodology and Practical Implications
Paper 7: A Participatory Systems Design Methodology for Changeable Manufacturing Systems. **Research method:** Conceptual research and comparative multiple case study. **Summary:** In this paper, a participatory and systematic design methodology for the design and development of changeable and reconfigurable manufacturing systems is proposed and applied in two industrial cases. The methodology supports companies in transitioning towards changeable manufacturing systems, based on knowledge of products, production, technologies, and facilities, and is applicable to both new and existing manufacturing systems. The methodology covers fundamental phases of design; requirement specification, conceptual design, and embodiment design. The comparative case application of the design methodology highlights essential differences in suitable design of changeability, as a result of differences in manufacturing characteristics, change requirements, and suitable enablers.

Table 1. Overview of papers covered in thesis chapters.

Paper 8: Evaluating the Investment Feasibility and Industrial Implementation of Changeable and Reconfigurable Manufacturing Concepts. **Research method:** Empirical quantitative modelling and comparative multiple case study. **Summary:** The objective of this paper is to present an investment evaluation model for changeability and reconfigurability that can be applied in initial stages of design, where critical decisions regarding type, extent, and level of changeability must be made, regardless of high degrees of uncertainty about future demand scenarios. For this purpose, a quantitative model is developed based on both theoretical and practical requirements, by conducting model conceptualization, validation, and implementation in two Danish manufacturing companies. The proposed model evaluates the discounted value of capital and operating costs of changeable manufacturing concepts, based on essential characteristics regarding their type and extent of changeability. In both of the investigated cases, the model implementation suggests that a reconfigurable manufacturing setup is feasible, however, the model also captures differences in changeability drivers, e.g. capacity changes, introduction of new variants, or introduction of more long-term changes to the functionality of the system, and differences in changeability implementation, e.g. ability to expand functionality, expand capacity, or change rapidly between variants.
Paper 9: Reconfigurable Manufacturing – An Enabler for a Production System Portfolio Approach. **Research method:** Comparative multiple case study. **Summary:** The objective of this paper is to address how the development of a strategically integrated product and production system portfolio can be enabled by the concept of reconfigurable manufacturing. The process of developing reconfigurable manufacturing systems requires high interrelatedness between product and production, therefore, implementing reconfigurability is likely to lead to greater alignment between product and production portfolios on a strategic level. Numerous challenges in regard to establishing strategic portfolio development are initially identified in previous research, and subsequently investigated in two industrial cases that are developing reconfigurable manufacturing concepts. The findings indicate various enabling factors and actions that will lead to strategic portfolio development.
Paper 10: Prerequisites and Barriers for the Development of Reconfigurable Manufacturing Systems for High Speed Ramp-up. **Research method:** Single case study.

Table 1. Overview of papers covered in thesis chapters.

Summary: The aim of this paper is to address design prerequisites for the development and design of changeable and reconfigurable manufacturing systems. A literature review is conducted in order to identify challenges related to design for changeability and related prerequisites. A long-term in-depth case study is conducted in a large enterprises working on development of reconfigurable manufacturing concepts, in order to explore the presence of the prerequisites, barriers towards these, and potential actions conducted to facilitate their development. The findings indicate that development of changeability requires a paradigm shift in industry, and that multiple barriers exist, however, some suggestions of how to manage these are proposed as well.
Paper 11: Exploring Barriers Towards the Development of Changeable and Reconfigurable Manufacturing Systems for Mass Customized Products: an Industrial Survey. **Research method:** Industrial questionnaire survey. **Summary:** This paper extends research in the previous paper, by exploring prerequisites for development of changeable and reconfigurable manufacturing in a broader empirical context. A questionnaire survey is conducted, in order to provide more generalizable evidence across industries and production types, with the aim of exploring the presence of the prerequisites and significant differences across industrial settings. The findings indicate that the prerequisites are only rudimentarily developed, and that knowledge and skills regarding reconfigurable system design are limited. In addition, having a long-term view on investments in production capacity and a strong relation between production and product development were identified as prerequisites being contingent on the industrial setting.

The research presented in the papers progresses sequentially in three parts towards the overall objective of establishing a design methodology for changeable and reconfigurable manufacturing systems. Initial papers cover the theoretical requirements for the methodology through systematic literature analysis and synthesis. Fundamental knowledge regarding changeability, reconfigurability, and its design and development is established in these initial papers. Subsequent papers cover the empirical foundation related to design and development of changeability and reconfigurability, acquired through case studies and an industrial survey. Important differences in the applicability of changeability and reconfigurability are identified across different industrial contexts, which provide important input to the design methodology. Papers covered in the final part of the thesis present the proposed design methodology and the supportive tool for initial stages of design evaluation. In addition, practical implications and design preconditions related to the actual development of changeability and reconfigurability in industry are presented from case studies and an industrial survey.

CHAPTER 2. RESEARCH DESIGN

The creation of knowledge on development of changeable and reconfigurable manufacturing systems that has both practical relevance and a strong theoretical contribution is central in this thesis. The limited ability of current systems design methodologies to support design of dynamically changeable manufacturing systems indicate a need for creating new theoretical concepts and models that contribute to advancing state-of-the-art research, however, at the same time being applicable in industry for actually conducting design of systems having the right combination of reconfigurability and flexibility. This two-fold intended contribution promotes a research approach that is collaborative with industry, as the knowledge created should be of both high novelty and industrial relevance, making traditional and merely detached observation and archival studies inadequate for understanding and addressing the complexity of the research problem.

2.1. INTERACTIVE RESEARCH APPROACH

Interactive research is an approach to research, which is driven by problems originated in both research and practise, based on both previous research and practical experience, and conducted through both data collection and analysis, as well as some kind of organisational action (Svensson *et al.* 2007). In Figure 3, the fundamental model of knowledge creation in this type of research is depicted, where the central element is a common conceptualization and interpretation of the research object, which leads to further cycles in both the research and practise system (Ellström 2008).

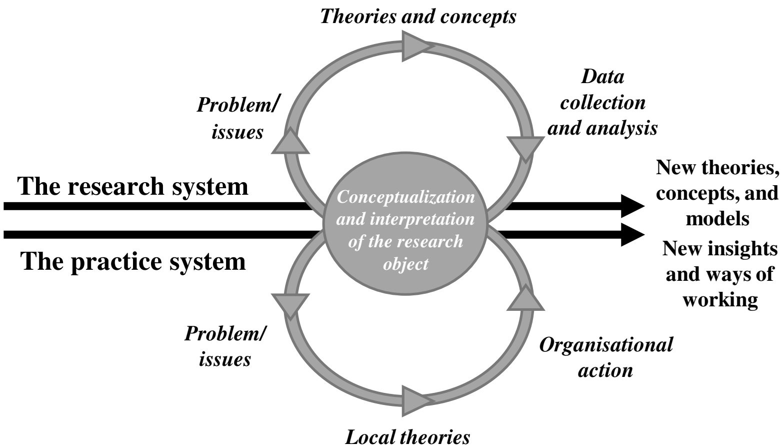

Figure 3. The interactive research approach. Adapted from Svensson et al. (2007) and Ellström (2008).

In the interactive research approach, the research system and the practise system collaborate on carrying out research regarding a specific topic, in to order not only produce academic contributions, but also industrial and managerial insight and action. This is accomplished through interaction between reflection and sense-making in the research system and experience and action in the practise system (Heron and Reason 2006). The joint learning throughout the entire research process is essential within the interactive research approach, meaning that research is carried out “with” rather than “on” practitioners and industry (Heron and Reason 2006).

An interactive research process usually initiates with a joint agreement of research goals and obligations, followed by a joint analysis of the selected research object. On one hand, researchers investigate practitioners’ methods and insights in order to determine how local theories, e.g. experience, methods, mind-sets, etc., can be further developed. On the other hand, practitioners also aim at finding a deeper understanding of the problem (Svensson *et al.* 2007). Thus, in this joint analysis, thought and action are embedded in each other, as both researchers and practitioners seek explanations and understanding of the problem at hand, through e.g. interviews, focus groups, questionnaires, seminars, etc. (Svensson *et al.* 2007). In final phases of the interactive research process, new knowledge, theories, methods, and models are created, which practitioners can apply to reach successful change (Svensson *et al.* 2007).

Despite the strong collaboration between research and practise in the interactive research approach, practitioners, and not the researchers, have responsibility for the organisational change process in the practise system (Svensson *et al.* 2007). The role of the researcher is not to be a change agent in the collaborating organisation, but rather to contribute to the shared conceptualization and interpretation of the practical change process, by giving feedback, discussing, and exploring the ongoing research and change process (Ellström 2008). In this sense, interactive research differs from action research, where the active involvement of the researcher in the organisational change process is emphasised, explicitly avoiding a distinction between theory and action (Coughlan and Coghlan 2002). Therefore, interactive research can be seen as an extension of action research, focusing less on the responsibility of the researcher in taking action in practise, and more on the researcher’s role in conducting analysis based on theory, thereby creating knowledge that is practically relevant (Svensson *et al.* 2007). Thus, the role of the researcher is a main difference between interactive research and action research, where the ambition of interactive research is to maintain the traditional role of the researcher, primarily being a creator of knowledge, rather than a change agent that has a strong role in an organisational change process (Ellström 2008). Consequently, interactive research seeks to reduce the drawbacks of action research in terms of proximity risks regarding the researcher’s personal involvement in the company and prominence on local understanding and practical knowledge (Svensson *et al.* 2007). Therefore, in interactive research, the collaborative relations between researchers and practitioners are merely based on mutual willingness and urge to find deeper understanding and solutions to problems where the practitioners also contribute to the theoretical work, whereas in action research, mutual relations are primarily relying on the researcher's contribution to practical development (Svensson *et al.* 2007).

2.1.1. PHILOSOPHICAL RESEARCH POSITION

A fundamental notion in interactive research is that real life problems are complex and have to be analysed and redefined through an interactive process of problem finding and diagnosis, before possible solutions can be developed and applied (Ellström 2008). In other words, solely applying detached observation or retrospective case studies is considered inadequate to fully understand and address the problems or research objects that are suitable for an interactive research approach (Coughlan and Coghlan 2002). This underlying notion is opposing compared to traditional and more linear approaches to research, where real-life problems are considered to be both well-defined and understood, waiting to be solved by new methods or results provided and disseminated by researchers (Ellström 2008). Thus, collaborative research methods including both interactive research and action research, have philosophically different standpoints than traditional research with a more positivistic or rational standpoint, where knowledge is considered universal, data considered context free, and where the researcher is detached from the research setting (Coughlan and Coghlan 2002, Heron and Reason 1997, Heron and Reason 2006).

Various classifications of research paradigms exist, however, an important dichotomy is between the worldviews of positivism and constructivism (Croom 2009, Guba and Lincoln 1994). In positivism, knowledge is believed to be universal and the world is believed to be external to the researcher (Croom 2009). Research taking this standpoint usually emphasises observable facts that are context-free and produces conclusions that are verifiable and generalizable (Guba and Lincoln 1994). In other words, the truth is viewed as a result of pure reasoning and reality is believed to exist as truth, whereas in the contrasting constructivist worldview, observations, analyses, and results are believed to be socially constructed and reality is seen as dependent on the individual (Croom 2009). Positivistic research is merely the process of finding facts or explanatory results that are general, whereas the constructivist research process is more about seeking understanding or interpretation of a specific phenomenon (Arbnor and Bjerke 2008, Croom 2009). Arbnor and Bjerke (2008) distinguish between three methodological approaches to research based on different philosophical standpoints between the objectivist-rationalistic paradigm, which aims at explanatory knowledge, and the subjectivist-relativistic paradigm, which aims at understanding knowledge; the analytical approach, the systems approach, and the actors approach. In the analytical approach, which is rather positivistic, reality is considered concrete and the knowledge created is independent to the researcher. In the systems approach, emphasis is on mutually considering the whole and its parts, where both explanation and understanding are sought (Arbnor and Bjerke 2008). Compared to the analytical approach where research problems are widely seen as separate, the systems approach considers a research problem in relation to for instance other research problems. In the actors approach, reality is largely considered as a social construction, which needs to be understood (Arbnor and Bjerke 2008). Thus, the knowledge created is dependent on the actor or the researcher, which makes this approach highly similar to the basic assumptions behind collaborative research approaches. However, in collaborative research approaches, the complexity of research problems is also recognized, which calls for a holistic understanding including all relevant system elements (Coughlan and Coghlan 2002). As this understanding is likely to evolve over time, as cycles between the research system and the action system progress, a systems approach also appears to be fundamental in interactive research.

Collaborative research approaches, including action research and interactive research, are generally considered direct opposites of the traditional positivistic worldview. However, collaborative research has been argued as being grounded in various philosophical standpoints (Coghlan 2011). Similarities with constructivism have been highlighted, e.g. in terms of the mutual emphasis on including the voice of the stakeholders, focusing equally on the tangible reality and the researcher's or participant's constructed reality, such as the constructed sense-making and understanding (Creswell 2013, Lincoln 2001). However, differences to constructivists approaches have also been indicated, primarily in relation to the level, intensity, and duration of the researcher's commitment in the researched field, as well as the heavy reliance on qualitative methods in constructivism (Creswell 2013, Lincoln 2001). A participatory worldview has also been advocated in relation to collaborative research, particularly emphasizing the action-orientation that is not largely encouraged in constructivism (Creswell 2013, Heron and Reason 1997, Heron and Reason 2006). Likewise, a pragmatic worldview has also been related to collaborative research, being grounded on the notion that research problems can be adequately addressed by various types of methods that are typically acknowledged within contrasting philosophical positions (Creswell 2013). Thus, pragmatic researchers tend to apply both quantitative methods, e.g. surveys that are typically applied in positivistic science for hypothesis testing or theory verification, as well as qualitative methods, e.g. case studies or observation typically being applied in constructivist science for creating understanding and meaning of a research object (Creswell 2013, Johnson and Onwuegbuzie 2004). In this sense, a clear similarity between the pragmatic worldview and the interactive research approach exists, as both do not prescribe particular types of research methods to apply, but rather comprise several methods that can be applied for joint learning in the practise system and the research system (Svensson *et al.* 2007).

Taking a pragmatic worldview, the clear distinction between traditional positivistic knowledge creation and collaborative knowledge creation appears as an indication of both their compatibility for adequately addressing a research problem, as well as their applicability for addressing different types of research problems (Creswell 2013, Karlsson 2010). Thus, the pragmatic worldview acknowledges overlaps between research approaches and the fact that research problems are often not perfectly settled within just one philosophical paradigm (Arbnor and Bjerke 2008, Croom 2009). As the research topic of this thesis, development of knowledge regarding design of changeable and reconfigurable manufacturing systems, is a real-life complex problem, which there is neither predefined solutions to nor adequate understanding of requirements for a potential solution, a combination of research methods rooted in traditionally opposing research paradigms appears suitable. Thus, the research presented in this thesis has largely been conducted with a pragmatic approach to knowledge creation, considering different research methods as a means to strengthening knowledge creation and sufficiently covering the problem of developing changeable manufacturing systems.

The ambition of the research presented in this thesis has been to conduct research with industrial collaborators throughout the entire process of understanding the research problem, creating a solution, and validating it. In this sense, this research is generally interactive, where industry is not seen only as a place for collecting data and applying research, but also as a place for conducting e.g. empirical studies or pilot projects in order to understand and define the problem to be solved, as well as generating ideas for how to best solve the research object being common to both researchers and practitioners (Svensson *et al.* 2007). Within the conducted interactive research approach, various research methods are embraced, e.g. quantitative modelling or surveys, in order to address specific research questions that arise throughout the long-term emerging collaboration process with the industrial companies, where the situation and the understanding of the research object change over time. Consequently, this thesis is a result of a mixed-method research approach, where combinations of qualitative and quantitative data and a combination of research methods to gathering, analysing, and interpreting data are used.

2.1.2. INTERACTIVE RESEARCH PROCESS

With the emergent nature of interactive research, the research presented in this thesis has emerged over time too, representing different levels of knowledge regarding the overall research problem, through the combination of complementary research methods and increasing contextual understanding. Thus, through evolving interactions between practise and theory, the research problem has been increasingly understood, redefined, assessed and resolved, symbolised by successive cycles as outlined in the interactive research model in Figure 3. Initially, research cycles focused on analysis, refinement, and diagnosis within the problem area, whereas later research cycles focused on addressing the problem, solving it by developing new methods and theories, and analysing the use of these in practise.

This emergent nature of the conducted research is largely a consequence of applying a systems perspective throughout the entire research process, where various related research problems are considered both separately and interactively in terms of their mutual relations, in order to adequately address the complexity of the research topic. In a systems approach to research, two approaches or sequences to research and development are usually distinguished; 1) analysis of an existing problem, situation, or system followed by diagnosis and synthesis of a possible solution, or 2) synthesis of new methods and models based on theory, followed by an analysis of consistency and validity (Joergensen 1992). Both approaches potentially ends up with new research insight, however, the former is largely of problem-solving character, whereas the latter initiates without explicit focus on solving a practical problem, but instead initiates with some kind of innovation that is subsequently analysed (Joergensen 1992). A widely applied methodological approach for research design is a combination of the two approaches, including initial analysis and diagnosis of the existing situation and problem, as well as synthesis of new theories and methods to solve the problem, including a final verification of the solution (Joergensen 1992). As a result of this combination, research starts by addressing a certain problem from both a practical and theoretical point of view, which results in the problem specification. Synthesis follows this initial analysis, where new theory is developed as an innovative result, followed by a second analysis in order to verify the usefulness and consistency.

By combining the systems approach to research and the fundamental cycle for interactive research, an adequate representation of the research presented in this thesis results. The interactive research cycle emphasises interaction between the research system and the practise system in order to reach increasing knowledge of the problem and its solution. Various stages of the cycles can be distinguished in accordance with the systems approach, where different sequences of analysis and synthesis are combined in an iterative manner, taking outset in both a theoretical base and an existing practical problem. In Figure 4, a combination of the systems approach to research covering three phases of analysis, synthesis, and analysis and the interactive research cycle is proposed. In the figure, the three phases roughly correspond to the sequence of chapters presented in this thesis, as well as the sequence of appended papers. In Chapter 3, the theoretical requirements and foundation for creating a design methodology for changeable manufacturing systems is established, whereas Chapter 4 presents the corresponding practical requirements and foundation. In combination, these two chapters and the initial six appended papers address the first research phase of analysing the theoretical and practical problem of designing changeable manufacturing systems. With this as the foundation, Chapter 5 presents both a new design methodology for changeability, as well as a decision support tool for design concept evaluation. This chapter largely covers the second phase of the research model, however, practical implications are addressed as well, through application of the methodology in industrial cases and analyses regarding prerequisites for the application. Thus, Chapter 4 and the remaining seven appended papers cover the last two phases of the model.

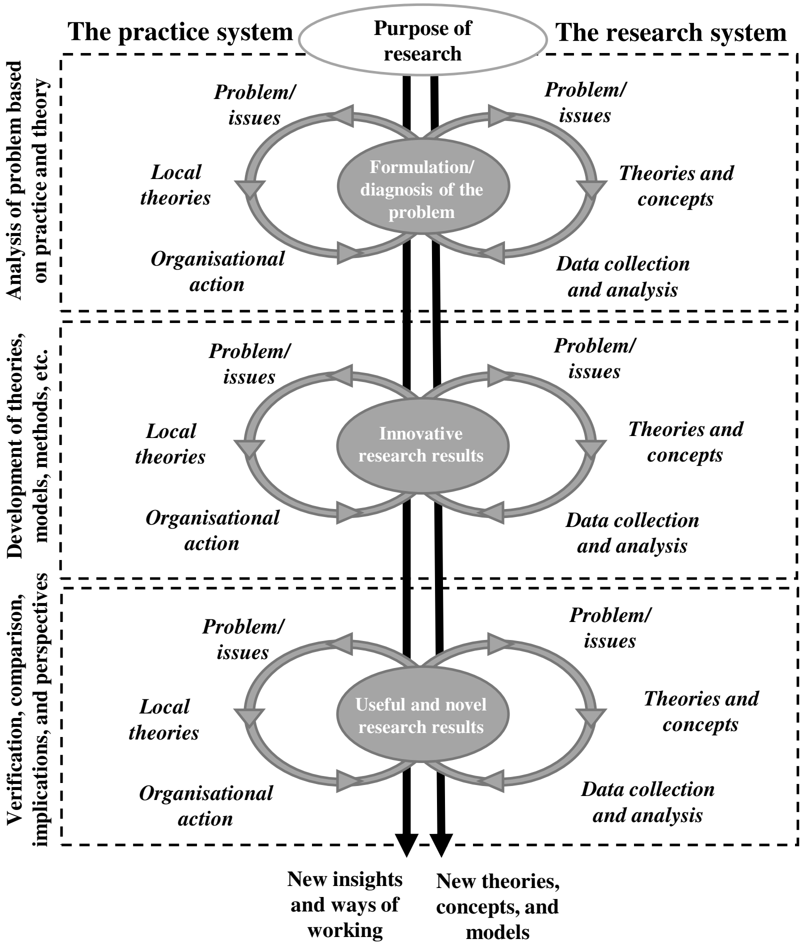

Figure 4. Proposed combination of the interactive research approach and the problem solving and synthesis sequence. Adapted from Svensson et al. (2007), Ellström (2008), and Jørgensen (1992).

2.2. APPLIED RESEARCH METHODS

The overall objective of this thesis is to establish a design methodology for changeable and reconfigurable manufacturing systems that has industrial applicability. As seen in Figure 4, the interactive research approach in terms of a long-term industry collaboration has acted as the foundation for all research conducted in relation to this overall objective. However, as a result of interactive findings in practise and theory and increased understanding of the research topic, more specific research questions have emerged throughout the research process, which based on their nature of inquiry, were suited for different types of research methods.

2.2.1. MIXED-METHOD RESEARCH

As the interactive research is founded on both theoretical and practical knowledge, research questions in both domains have evolved, contributing to the theoretically and practically combined understanding, refinement, and solving of the overall research problem. In Table 2, an overview of the specific research questions addressed in the thesis is presented, as well as the selected research methods.

Table 2. Outline of research phases, research questions, and research methods.

Purpose of research	
Overall thesis objective: Establish a systematic design methodology for changeable and reconfigurable manufacturing systems that can be applied in various manufacturing contexts for supporting the transition towards variety-oriented, responsive, and high quality production at mass production efficiency.	
Research Phase 1: Analysis of problem based on theory and practise	
Research question 1: What are theoretical and practical requirements for the design and development of changeable and reconfigurable manufacturing systems in various manufacturing settings, and how are these supported by existing design methodologies for changeability and reconfigurability?	
Research question 1.1: Which structuring levels of manufacturing are dealt with in research on reconfigurable manufacturing and its development, what are dominant research issues at each level, and which issues remain rather unexplored? (Paper 1)	**Research method:** Systematic literature review and classification.
Research question 1.2: Which steps and phases make up the structure of the design process for reconfigurable manufacturing? Are current design methodologies opposing or supplementary, and can a generic design method be recognized? Which supportive tools and procedures could be applied in order to support practitioners in carrying out the design? (Paper 2)	**Research method:** Systematic literature review, including classification, analysis, and synthesis.
Research question 1.3: What are critical challenges during new production development and ramp-up in relation to new product introductions, and which differences exist across companies with varying product volume and variety characteristics? (Paper 3)	**Research method:** Multiple comparative case study in case company A and case company B.

Table 2. Outline of research phases, research questions, and research methods.

Research question 1.4: How can the potential in reconfigurable manufacturing be determined for manufacturing companies being characterised by high production volume? (Paper 4)	**Research method:** Single case study in case company A.
Research question 1.5: What is the potential in reconfigurability in small and medium sized companies characterised by low volume and high product variety, and what are major challenges in relation to its development and implementation? (Paper 5)	**Research method:** Single case study in case company B.
Research question 1.6: Which enablers of changeable and reconfigurable manufacturing are critical and what are their current state of implementation in industry? Are there significant differences across production contexts regarding the criticality and degree of implementation of the enablers? (Paper 6)	**Research method:** Industrial survey with non-parametric data analysis of relative importance and significance.
Research Phase 2: Synthesis of new theories, models, and concepts	
Research question 2: How can a design methodology for changeable and reconfigurable manufacturing systems be established and implemented in industry to support various types of manufacturing contexts in the transition towards changeability and reconfigurability?	
Research question 2.1: How can a design methodology for changeable and reconfigurable manufacturing be established, which supports various types of manufacturing contexts in designing manufacturing systems with internally and externally consistent fit between required and applied manufacturing paradigm and in identifying the corresponding additional required enablers? (Paper 7)	**Research method:** Conceptual research and comparative multiple case study in case company A and case company B.
Research question 2.2: How can a decision support tool be created, which can be applied in initial stages of design for evaluating the investment feasibility of changeable and reconfigurable manufacturing concepts, based on future demand predictions and their uncertainties? (Paper 8)	**Research method:** Quantitative empirical modelling and simulation, including comparative multiple case study in case company A and case company B.
Research Phase 3: Analysis, verification, comparison, perspectives, etc.	

Table 2. Outline of research phases, research questions, and research methods.

Research question 3: Which practical implications and design preconditions exist in regard to implementing the proposed design methodology and for the development of changeability and reconfigurability in industry, and how can these be resolved?	
Research question 3.1: How can a strategic alignment between production and product portfolios be enabled by the development of manufacturing reconfigurability, and what are main challenges in regard to this? (Paper 9)	**Research method:** Comparative multiple case study in case company A and case company C.
Research question 3.2: What are prerequisites for developing reconfigurable manufacturing compared to traditional manufacturing, which industrial barriers exist in relation to these, and how can these be addressed? (Paper 10)	**Research method:** Single case study in case company A.
Research question 3.3: What are critical barriers in industry towards the development and realization of changeable and reconfigurable manufacturing systems, and are their significant differences regarding their presence in different manufacturing contexts? (Paper 11)	**Research method:** Industrial survey with non-parametric data analysis of relative importance and significance.

As seen in Table 2, each of the three main research phases are characterised by an overall research question derived from the thesis objective. Additionally, more detailed sub research questions are addressed in each phase, which are the basis for selecting specific research methods complimentary to the overall interactive research approach. Industrial questionnaire surveys, single case studies, comparative multiple case studies, and quantitative modelling and simulation have been applied to address these specific research questions. All research questions that are addressed by methods involving empirical data are based on the long-term collaboration and interaction with case company A and case company B. Additionally, investigations in case company C have been applied in the final phase of the research, in order to increase generalizability beyond the context of the two primary collaborating companies.

Generally, case studies have been considered appropriate for addressing research questions that require the research object to be investigated in-depth and in its natural setting, which is one of the main strength of case research (Voss *et al.* 2002). Moreover, one of the benefits of case research is that it leads to a relatively full understanding of the complexity of the research problem that is not yet fully understood (Voss *et al.* 2002). This is indeed the situation in early phases of this research project, where the phenomena being researched is not yet completely understood, e.g. in relation to varying requirements and potentials for changeability and reconfigurability in different industrial settings. Thus, case studies in the first phase of the conducted research lean towards a purpose of theory generation, aiming at identifying important variables and their relations, as well as understanding why these relations exist (Voss *et al.* 2002). The premise for these types of case studies is that existing theory does not explain or address the phenomena being researched, and that new theory can be developed through empirical analysis (Ketokivi and Choi 2014). In particular, multiple case studies are relevant, in order to identify both similarities and differences across cases that can lead to theoretical generalizations (Ketokivi and Choi 2014). Therefore, two in-depth single case studies have been conducted regarding the potential and benefits of reconfigurability in cases with opposite volume and variety characteristics, as well as a multiple comparative case study regarding differences and challenges during production development and ramp-up, which is potentially aided by reconfigurability.

In the second phase of the research, where a design methodology for changeability is created, case study research has primarily been used to examine its application and implementation in industry to support development of dynamically changeable systems. Thus, the comparative multiple case studies conducted in this phase can be categorised as having the purpose of theory testing, where proposed theory is tested through contextual considerations and empirical data (Ketokivi and Choi 2014, Voss *et al.* 2002). However, some elements of theory creation are present in this phase as well, in relation to the creation of a quantitative model for concept evaluation during design, where knowledge gathered in the two cases is used for the actual model development. Thus, the selected quantitative modelling approach is largely empirical and prescriptive (Will M. Bertrand and Fransoo 2002). Finally, in the last phase of the research process, the purpose of the conducted case studies is largely of theory refinement character, as the design for changeability is examined more deeply in terms of how it enables strategic product and production alignment and in terms of the related design prerequisites. In this sense, these case studies do not aim at testing already created knowledge, but rather at reaching more general insight (Ketokivi and Choi 2014).

For all case studies, long-term collaboration with the two primary industrial case companies serves as the foundation. Generally, collaborative research is conducted in real-time and represents a live case study that can be written as it unfolds. However, collaborative research can also be written in retrospect as a traditional case study, which then act as interventions in the collaborating organisations to promote reflection and learning (Coughlan and Coghlan 2002). Therefore, the case studies presented in Table 2 are all written in retrospect, merely as learning histories, however, being based particularly on the evolving contextual understanding of the cases gained through interaction, but also on quantitative and qualitative data collected specifically for the purpose.

In addition to the case studies and the collaborative research, survey research has been applied as a complimentary research method. The appropriateness of quantitative surveys to compliment e.g. long-term case studies or action research is widely acknowledged as a way of strengthening generalizability and understanding in a research area (Creswell *et al.* 2003, Creswell 2013, Karlsson 2010). In general, survey research involves collection of larger amount of data through e.g. questionnaires, thereby gathering information that is usually analysed quantitatively in order to create knowledge through generalization of the sample information (Malhotra and Grover 1998). The two research questions in Table 2 that are addressed by survey research are of rather descriptive and explanatory nature (Forza 2002). In other words, these questions are descriptive as they seek facts and generalizable evidence regarding the presence of both enablers and prerequisites for changeability and reconfigurability, and explanatory in terms of finding significant relations between enablers or prerequisites and characteristics of the sample companies.

2.2.2. DATA COLLECTION

The mixed-method approach applied throughout this thesis involves quantitative and qualitative methods to data collection, analysis, and interpretation, which is usually characterised as a sequential exploratory mixed method strategy (Creswell *et al.* 2003). Quantitative methods, such as surveys, are primarily used to support qualitative findings from the collaborative research project gained through participation in workshops, seminars, etc. Thus, the foundation for addressing the various research questions indicated in Table 2 is primarily qualitative data gained through the long-term interaction with the case companies, e.g. participation and observation in seminars, project meetings, project workshops, factory tours, as well as meetings and joint discussions with the company managers and employees being responsible for the company change project and the research collaboration. In these interactions, the researcher primarily had the role of challenging local theories in terms of company understanding, norms, and mind-sets, thereby bringing new knowledge into the company for shaping the combined understanding of the research problem. Moreover facilitating roles were also taken, in particular in final research phases, where new theories, knowledge, and models were created and thus had to be applied and implemented in practise. Regardless of the type of interaction, thorough field notes were always taken involving facts, observations, practitioner statements, own reflections, and subjective interpretations, which were supplemented with data from interviews and archival records. In addition to this primary type of qualitative data gained through the joint learning in the collaborative research project, complimentary qualitative and quantitative data collected through surveys, interviews, and various types of archival records were used as well. In Table 3, an overview of the long-term collaborative research project in the two primary case companies is presented. Additionally, the timing of complimentary data collection for specific research questions is indicated.

Table 3. Overview of long-term collaborative research project in case companies.

	2014	**2015**	**2016**	**2017**
Participation in project-related activities e.g. workshops, seminars, or factory tours.	Case company A: 2 Case company B: 1	Case company A: 18	Case company A: 7 Case company B: 9	Case company B: 2
Research project team meetings with primary practitioners responsible for research collaboration.	Combined A and B: 1 Case company A: 12	Combined A and B: 2 Case company A: 18 Case company B: 1	Case company A: 8 Case company B: 1	Case company A: 4 Case company B: 2
Collection of complementary data through archival records and interviews.	Collection of archival production records in case A for research question 1.4.	Collection of data from 7 interviews in case A and 3 in case B, as well as archival data on production ramp-up for research question 1.3.	Collection of archival production and demand records in case A and case B for research question 2.2. Collection of data through questionnaire survey in additional manufacturing companies for research question 1.6 and 3.3. Collection of data/information from additional case, company C, for research question 3.1.	

In Table 3 it is evident that the timing of collecting the various types of qualitative and quantitative empirical data, as well as the interaction with the case companies have alternated in intensity throughout project. Moreover, the timing of data collection for the various research questions does not entirely match the sequence of research questions and papers presented in this thesis. This is primarily due to the emergent nature of the collaborative research project, where research questions have developed in accordance with the increased understanding of the research problem.

2.3. INDUSTRIAL CASES

In interactive research and in case research, the choice of cases to either collaborate with or do research on plays an essential role in terms of both the success of the research process and eventually the novelty and practical relevance of the created knowledge. Various strategies for choosing a suitable number and type of cases have been emphasised in case-based research methodologies. However, in practise, researchers are often not able to choose cases freely having these strategies in mind, rather cases may be pre-selected for various reasons. Being a part of a larger research project, the MADE initiative, two primary industrial cases to collaborate with were selected prior to initiating the research process. In this sense, the term case refers to a manufacturing firm including various cases of production contexts that can be studied. However, in both case companies, the production context in focus was also pre-selected. Therefore, the strategies for selecting appropriate cases is merely discussed here as an evaluation of the pre-selected case companies and production contexts for the long-term research collaboration, emphasizing their relevance in terms of creating knowledge regarding changeable and reconfigurable manufacturing.

In case research, the number of cases is usually stressed as an important choice, where single case-studies foster greater in-depth understanding, however, multiple comparative cases increase generalizability of conclusions (Voss *et al.* 2002). A mixture of the two approaches has been exploited in this research, where long-term collaborating research projects were conducted in the two primary cases simultaneously. However, as seen in Table 3, the interaction with the companies alternated throughout the process as a result of the focus of the specific research questions, which sometimes required a sole focus on only one of the industrial cases. Moreover, cases should ideally be selected based on either literal replication, meaning that the case is suitable for replicating or extending theory, or theoretical replication, meaning that the case is able to produce contrasting results for some predictable reasons (Voss *et al.* 2002). Thus, using so-called polar cases with evidently contrasting characteristics is a highly suitable strategy in case-based research. In interactive research approaches, a suitable participating case has been emphasised as being a case that has already done some work on the specific research topic, thereby bringing complimentary assets to the joint research collaboration (Ahlström *et al.* 2007). In this research, both of the collaborating industrial cases have prior to initiating the research project done some groundwork within the research area, thereby developing local theories, experience, and a specific mind-set, that nurtured the co-learning in the interactive research project. However, as elaborated in the following, the two cases represent notable differences, which can be widely regarded as polar characteristics.

2.3.1. CASE COMPANY A

The first case company being a primary collaborator in this research, denoted as case company A, is a global manufacturer of mechatronic products for domestic and industrial use. The company is founded in Denmark where headquarters, development, and a large part of production facilities remain located, however, additional production facilities and sales offices cover more than 80 different countries. At present, the company employs 18,000 people worldwide and produces more than 16 million units a year. The company offers a broad product range for multiple customer segments and types of applications; from fully engineered-to-order or customized industrial products to mass production of more standard products. The company is largely horizontally integrated, as final product assembly as well as most production of sub components and parts remains internal to the company.

The company is currently facing high demand for rapid new product introductions, decreased time-to-market and profit, increased product variety, and pressure for productivity improvements and cost reductions. Therefore, prior to engaging in this research project, the company formed a production development initiative aiming at defining strategic production technologies in each main production domain, in order to increase standardization and reuse of technologies across global production sites to reduce the time for introducing new products in production. Thus, the company aimed at introducing efficient ability to adapt to change in terms of new product introduction, through developing a common technology platforms. Having recognized the need and importance of this initiative, the company engaged in the MADE research project in 2014, and devoted additional resources for exploring manufacturing modularity and changeability in collaboration with researchers from Aalborg University. During the collaboration and interaction with research, the company's ambitions and efforts developed accordingly. In 2015 the company initiated its first large co-development project covering both production and product development, aiming at having corporate agreement between product and production architectures and platforms in order to enable effective and efficient development and introduction of new products, as well as ability to scale capacity in accordance with demand. Thus, focus was devoted to both development of a production architecture that could be reused over time for e.g. new product generations or variants, as well as across various plants as a type of generic and common production concept. The project is thus considered as a complete green-field project not tied specifically to a particular new product. A specific production context was selected as focus for this project, covering assembly of an electronic subassembly for the company's high-end circulation product. This initial project focused largely on discovering actual benefits and potentials in developing manufacturing platforms and reconfigurability and creating a method for joint development between product and production. Based on the outcomes of this project, an extension with the same production focus was initiated in spring 2016 in order to establish actual changeable assembly concepts, as well as additional similar projects covering other production contexts within the company.

As seen in Table 3, the long-term collaboration with case company A started in 2014 prior to the company's formal development projects tied to a specific production context. In this initial phase, the research collaboration focused largely on understanding the research problem and investigating the potential and means for solving it. Moreover, interaction between researcher and practitioners was primarily based on knowledge dissemination and joint discussions in research project meetings. However, as more formal project with more than 20 participating employees were initiated in the company, the collaboration was to higher extent based on participation in project workshops, seminars, and meetings, where the role of the researcher was to observe, contribute with reflections and theoretical knowledge, suggest approaches and focus areas for workshops, and challenge local theories and mind-sets of practitioners.

2.3.2. CASE COMPANY B

The other primary case company for this research, denoted as case company B, is a medium sized manufacturer of capital goods that are customized to specific customer needs. The company has headquarter, development, and production in Denmark, as well as production of some product families in Germany. In total, less than 200 employees are employed in the company. Both final assembly of products and production of large welded components are conducted internally, whereas other main modules of the products are sourced externally. Prior to engaging in the MADE research project, the company worked extensively on modularizing their product architectures to enable more efficient creation of product variety. Therefore, at present the offered products are configured based on customer orders from a modular product architecture, thereafter being assembled in a job-shop environment. The production of large welded components is also conducted in a job-shop environment. However, with increasing demand for rapid new product generations and fast market launch, as well as pressure for cost reduction and increased efficiency, the company seeks to exploit principles of changeability in production to accommodate the large product variety.

During 2014, the company initiated a project aiming at increasing changeability in the production of large welded components in order to increase efficiency of handling the large product variety. This development project was driven by a few employees, as a specific production development department is not existing. This company project involved collaboration with Aalborg University, and is thus the basis for the research presented in this thesis. However, the interaction with the company intensified particularly during the last phases of the research project, where actual system concepts where being designed, and the researcher contributed with theoretical knowledge regarding changeable system design and evaluation, thereby aiding the transition process towards changeable and reconfigurable production in the company.

2.3.3. CASE COMPARISON

In Table 4, a comparative overview of the two industrial case companies is presented, which indicates their polar characteristics. In addition to these, a third case was included for addressing research question 3.1. This case company is a large Swedish manufacturer of construction equipment aiming at developing a multi-product assembly concept to be exploited in global assembly plants. This case is further elaborated in the appended paper 9.

Table 4. Overview of collaborative case companies.

	Case Company A	**Case Company B**
Company type	Large Enterprise with > 4000 employees in Denmark.	Medium enterprise with < 200 employees in Denmark.
Development	Large technology, product, and production development departments.	Product development department with 2-3 production developers.
Industry	Mechatronic products.	Capital goods.
Production context in focus for research	Electronic subassembly for high-runner product.	Large welded components for excavators and loaders.
Volume	> 100,000 units/month.	< 200 units/year.
Variety	Less than 25 active variants for each generation of the product family.	Fully customized end-products, with high variety of large welded components within four part families.
Frequency of new products	Approximately every second year.	Approximately every 7-10 years.
Production set-up	Fully-automatic and dedicated assembly setup.	Mostly manual setup with dedicated tooling.
Cycle-time	Approximately 10 seconds.	Approximately 15 hours.
Planning Policy	Make-to-stock of final products.	Make-to-order of final products.

2.4. RESEARCH QUALITY

The strength of applying an interactive and mixed method research approach for increasing research quality has been widely elaborated in this chapter. Generally, research quality is evaluated by validity and reliability, which can be further differentiated by a number of dimensions. However, depending on the applied research method and related philosophical position, different criteria for research quality and interpretations of validity and reliability exist, as well as different strategies for ensuring these (Dellinger and Leech 2007). For instance, in traditional positivistic research, e.g. survey research, research quality is mostly considered in relation to construct validity and the extent to which research is measuring what it is supposed to, as well as external validity being ensured through statistical generalization and sampling (Dellinger and Leech 2007, Forza 2002). In case based research, construct validity is ensured through applying multiple sources of evidence and triangulation, whereas external validity is ensured through theoretical abstraction and literal or theoretical replication logic (Voss *et al.* 2002). Collaborative and action-oriented research approaches have fundamentally different quality criteria, aiming at ensuring a valid and non-biased representation and understanding of the conducted research, despite a well-established relationship between researchers and the research object, through continuous testing of assumptions, dialogue with participants and society, and systematic cycles of reflection and action (Coughlan and Coghlan 2002, Svensson *et al.* 2007). Moreover, in collaborative research, quality should also be assessed by the value created for practitioners, as well as the implications beyond the research setting (Coghlan 2011). The latter is related to the duality criterion, meaning that research is situationally grounded, however, at the same time having broader theoretical understanding (Ketokivi and Choi 2014).

As the research presented in this thesis builds on the fundamental pragmatic assumptions that different research methods from potentially opposing philosophical positions have different characteristics making them suitable for different types of research questions, various criteria for research quality must be applied too. In regard to this, criticism of mixed method research has been set forward, due to the considerable distance between criteria for validity in quantitative and qualitative research, and the limited rigour compared to single-method approaches (Karlsson 2010). Moreover, the issue of being able to understand and practise various different research methods and in particular mix them appropriately has been emphasised as a main challenge of mixed-method research approaches (Johnson and Onwuegbuzie 2004). In mixed method research, various combinations of quantitative and qualitative research methods can be selected and applied, guided by the nature and sequence of research questions (Johnson and Onwuegbuzie 2004). Consequently, problems of legitimation and integration emerge, referring to difficulties in making credible, trustworthy, dependable, transferable, and confirmable theories (Onwuegbuzie and Johnson 2006). Accordingly, different types of legitimation criteria have been proposed for assessing the quality of mixed method research, concentrating on how well the research combines research methods (Onwuegbuzie and Johnson 2006). Some legitimation types include sample integration, referring to the extent to which relationships between quantitative and qualitative sample demonstrate quality meta-inferences, and weakness minimization legitimation, referring to the extent to which methods compensate each other (Onwuegbuzie and Johnson 2006).

2.4.1. LEGITIMATION EVALUATION

Thus, in mixed method research it is not sufficient to purely evaluate research quality by separately applying research quality criteria from traditionally opposing research approaches, rather quality criteria related to issues arising from the actual mixing of methods should be included as well (Dellinger and Leech 2007, Johnson and Onwuegbuzie 2004). In a unifying framework for validity in mixed method research, Dellinger and Leech (2010) suggest that mixed method research should be assessed by quantitative and qualitative criteria in the specific steps of the research where they are applied, and that their mixing and legitimation should be assessed accordingly. In line with these suggestions, separate quality criteria have been applied for the research presented in this thesis, in accordance with each type of applied research method. In Table 5, an overview is presented, covering the most important quality criteria in quantitative and qualitative research respectively, and the related strengths and weaknesses of the research presented in this thesis. Furthermore, important types of legitimation as suggested by Johnson and Onwuegbuzie (2006) are indicated as an assessment of the quality of the mixed research approach and the meta-inferences resulting from the combinatory use of research methods. In this sense, meta-inference are the overall conclusions derived from integrating inferences resulting from different research methods (Tashakkori and Teddlie 2008). In this thesis, meta-inferences are present in all three main parts of the thesis as indicated in Table 2, however, primarily the mixing of survey research and more qualitative interactive or case based research has resulted in central meta-inferences regarding practical requirements for the design of changeability and reconfigurability, as well as meta-inferences about the prerequisites and barriers for the industrial implementation of the proposed design methodology.

The common foundation for all legitimation types indicated in Table 5, is the so-called weakness minimization or combinatory strength, which generally is believed to increase research quality (Onwuegbuzie and Johnson 2006). Generalization limitations resulting from qualitative inferences from the two primary cases are counteracted by the use of a larger pool of quantitative survey data. Likewise, potential validity issues resulting from high interaction and collaboration with case companies is reduced by including quantitative data that are context-free and objective to higher extent. Thus, the pragmatic foundation and mixed-method research approach applied here is believed to be well-suited for producing both novel and practical knowledge of high quality regarding design of changeable and reconfigurable manufacturing systems.

Table 5. Overview of research quality of qualitative and quantitative approaches and legitimation of their mixing.

Qualitative element (interactive research and case research)	**Mixing element**	**Quantitative element** (surveys)
External validity: + theoretical replication logic in selection of multiple polar cases. + Inclusion of additional relevant case for research question 3.1. - High situationally grounding of research in collaborative cases. *Construct validity:* + use of multiple sources of evidence collected in the case companies. + /- Data generation from interaction with case companies. *Internal validity:* + dialogue and discussion with practitioners about inferences. - interaction of research in research environment and the risk of "going native" or presenting biased results. *Reliability:* + writing systematic field notes. - research interaction conducted "live", thereby being non-repeatable.	*Sample integration legitimation:* + Inferences based on qualitative data from small group of cases integrated with inferences from large sample of quantitative data. *Inside-outside legitimation:* + Integration of quantitative data representing "outsider" view and qualitative data from case interaction representing "insider" view. *Sequential legitimation:* - sequence of qualitative inference followed by quantitative inferences may have impacted interpretations. *Multiple validities legitimation:* + mixed quality and validity criteria applied throughout research (as outlined in this table).	*External validity:* + Various industries, product types, and production types being represented. - Non-random sampling and relatively low sample size, being limited to primarily one country. *Construct validity:* + pre-test and discussions with experts on measured variables (convergence validity). + Some use of multi-item measurements. *Statistical inference validity:* + Monte-Carlo simulation applied in addition to sample analysis. *Reliability:* + adequate Cronbach alpha values of measurements.

CHAPTER 3. THEORETICAL FOUNDATION

In order to identify theoretical requirements for designing changeable and reconfigurable manufacturing systems, two systematic literature reviews have been conducted. The findings of these reviews are presented in the appended paper 1 and 2, however, the present chapter briefly summarises their main findings as a foundation for specifying theoretical requirements for the design methodology for changeable and reconfigurable manufacturing systems. In this respects, a theoretical requirement is regarded as a necessary element, feature, concept, or notion derived from theory that is fundamental to designing dynamically changeable manufacturing systems, rather than traditional static systems, which therefore should be considered in a design methodology for changeability.

3.1. FUNDAMENTALS OF CHANGEABILITY

A changeable manufacturing system is a manufacturing system that has appropriate change enablers to accomplish proactive, timely, and economically feasible adjustments of structures and processes on all levels in response to external and internal requirements, in order to continuously and efficiently match changing functionality and capacity requirements (Azab *et al.* 2013, Schuh *et al.* 2009, Wiendahl *et al.* 2007). Thus, a fundamental concept related to changeability is change drivers, which prompt continuous and profound changes in specific change objects that are eventually facilitated by different types of enablers being embedded in the manufacturing system constituents (ElMaraghy and Wiendahl 2009, Wiendahl *et al.* 2007). In the seminal works by Wiendahl et al. (2007) and ElMaraghy and Wiendahl (2009), a model for deriving the objects of changeability is proposed, which explains the fundamental theory and constructs of changeability. A modification of this changeability model is presented in Figure 5.

Every change is triggered by change drivers, which can be defined as reasons behind requests for change (De Toni and Tonchia 1998, Schuh *et al.* 2009). Numerous types of change drivers exist, e.g. variability of demand, shorter lifecycles of products and technologies, wider scope of products, increased customization, shorter delivery times, etc. (De Toni and Tonchia 1998). However, change drivers are usually categorized as being product-related, volume-related, technology-related, or strategy-related (Rösiö 2012b, Schuh *et al.* 2009) and as being either internal or external to the manufacturing company (Wiendahl *et al.* 2007). In dedicated and non-changeable manufacturing systems, a change driver usually prompts changes to numerous constituents of the manufacturing system, which makes it a rather extensive task to accomplish the required changes (Rösiö 2012b, Schuh *et al.* 2009). In contrary, in a changeable manufacturing system, change drivers have less impact on the system, as it is built for accomplishing change e.g. through modularity, where dependencies between change drivers and manufacturing system constituents are determined and limited to a few modules (Schuh *et al.* 2009).

The change drivers prompt changes in change objects. The change objects are mainly associated with the output of production and changes connected to customer requirements, covering products, products mix, and production volumes (Hallgren and Olhager 2009, Upton 1994). However, as changeability is not only limited to changes in system outputs, the technical systems and the organisation should also be considered (Wiendahl et al. 2007). These internal object are not directly related to what the customers perceive as being changeable, rather they are related to dimensions of competition other than those customers see (Upton 1994). Thus, the internal change objects cover the organisation, processes, and equipment, which may be required to change in terms of performance, e.g. increased productivity, incorporation of new processing technologies, etc. (ElMaraghy and Wiendahl 2009). In combination, the internal and external change objects determine the changeability performance and success. For instance, in the thesis introduction in Chapter 1, the Volkswagen example of combining a modular product platform and a changeable production setup enabled by modularity highlights the need for considering both types of change objects simultaneously.

The change strategy represents a company's decisions and plans for responding to the change drivers and the need for accomplishing change in the different change objects, e.g. if responding to changes is solely for survival or for securing a competitive advantage (ElMaraghy and Wiendahl 2009). The change strategy also determines the utilization and extent of changes to be accomplished in terms of which level of the factory that should be changeable, the frequency of changes, and the effort related to changes (ElMaraghy and Wiendahl 2009). The change extent is largely determined by the selected combination of flexibility and reconfigurability, which requires balancing investments of pre-planned and in-built ranges of flexibility, which may be larger than required initially, and investments in reconfigurability enablers, e.g. modularity, to accommodate changes on demand (Benkamoun 2016, Terkaj *et al.* 2009b).

Finally, the change needed to be accomplished in the change objects are enabled by certain change enablers. These change enablers are usually differentiated based on being either physical or logical, based on the factory level on which they are implemented, e.g. the factory, system, or equipment level, as well as based on their type, e.g. modularity, scalability, etc. For instance, reconfigurability characteristics such as modularity, convertibility, integrability, scalability, convertibility, and diagnosability are enablers of change on system and workstation level (ElMaraghy 2005a, Koren 2006), whereas the ability to change the level of automation, and the ability to change location of systems are additional enablers (ElMaraghy 2005a).

These different change enablers can be designed and implemented in the constituents of the manufacturing system, e.g. material handling, machines, software, etc. depending on the specific manufacturing context and the required changes to accomplish.

In regard to designing changeable manufacturing systems, the main related constructs of the changeability model are change drivers, change objects, change enablers, and the change extent. Obviously, the change drivers need to be identified and understood in order to design a system that is able to meet these at the outset in a dynamic and efficient way (ElMaraghy and Wiendahl 2009). In other words, the identification and understanding of change drivers lead to a specification of lifetime changeability requirements for the design of the manufacturing system. Likewise, the change objects which have to be changeable as requested by the change drivers must be determined and designed with the right enablers of change and the right extent of change (ElMaraghy 2005a). In Table 6, an overview of the fundamental changeability constructs and the related essential design decisions is presented.

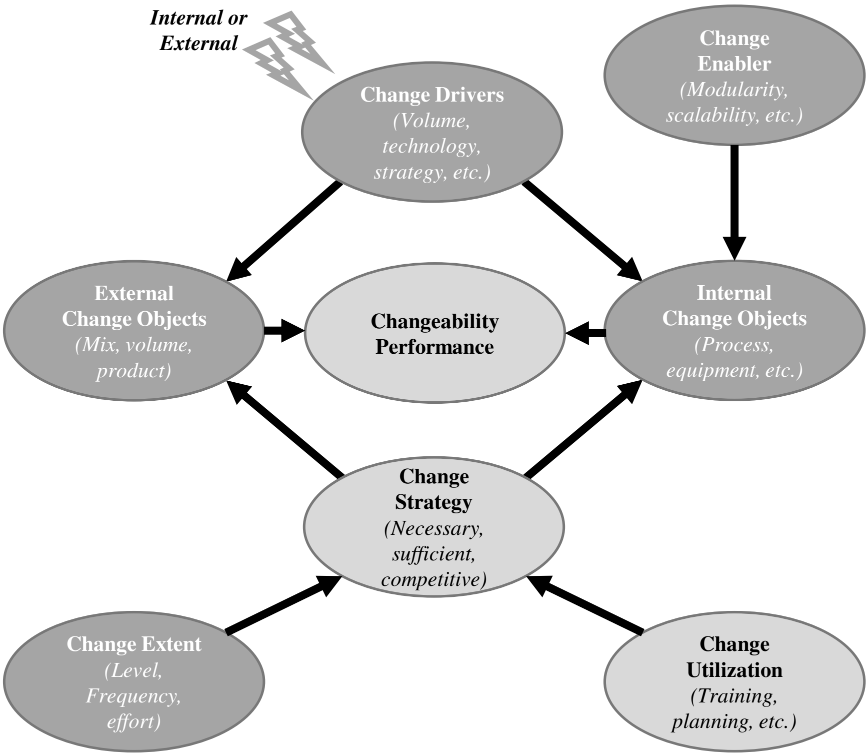

Figure 5. Fundamental concepts of changeability. Adapted from Wiendahl et al. (2007) and ElMaraghy and Wiendahl (2009).

Table 6. Changeability constructs and related system design decisions.

Changeability construct	**Relation to manufacturing system design**	**Examples**
Change drivers	Specification and analysis of lifetime requirements of changeability that the system should be designed to meet dynamically and efficiently.	Uncertainty of product demand, increase of product variety, new processing technology, various new product introductions, increase/decrease of demand, etc.
Change objects	Specification of the internal and external objects that should be changeable.	The product mix should be changed frequently, the volume should be increased step-wisely, processing steps should be upgradable, equipment should be able to change functionality, etc.
Change enablers	Decisions regarding changeability enablers in the system solution in terms of the type, level of implementation, and the constituents of the system they should be embodied in.	Modularity on system level for convertible and scalable layout, machine tools with scalable production rate, mobility of fixtures along production line, scalable workforce, etc.
Change extent	Decisions regarding extent of changeability in the designed system, in particular in terms of selecting a suitable combination of flexibility and reconfigurability to achieve required changes.	Investing in larger range of machine functionality than initially needed to meet future change requirements, investing in modular equipment to gradually increase functionality, etc.

3.2. LEVELS AND CONTITUENTS OF CHANGEABILITY

The changeability implementation can be distinguished based on the level of implementation, applying a hierarchical systems perspective, or based on the system constituents in which the change enablers are implemented, applying a structural systems perspective. Some common hierarchical levels of manufacturing are the network, site, segment, system, cell, and machine or workstations (Wiendahl *et al.* 2007). Reconfigurability and flexibility are defined for levels below and including the manufacturing system, whereas transformability and agility apply to higher structuring levels (Wiendahl *et al.* 2007), which goes beyond the scope of this thesis. In Figure 6, this hierarchical aspect of changeability implementation is presented.

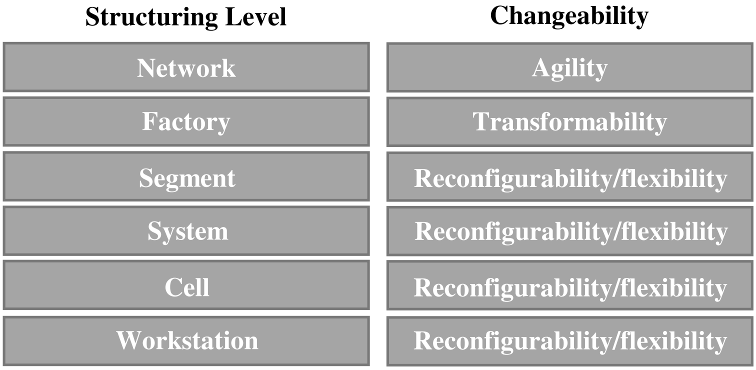

Figure 6. Hierarchies of manufacturing and changeability. Adapted from Wiendahl et al. (2007) and ElMaraghy and Wiendahl (2009).

On the different system levels, different manufacturing system constituents can be distinguished, e.g. material handling, machines, storage, buildings, software programs, tools, fixtures, operators, etc. (Azab *et al.* 2013, Benkamoun 2016, Rösiö 2012b). All these system constituents cover the system's physical and logical parts, which depending on the context and the required change can be designed for reconfigurability and flexibility in various ways, by implementing the changeability enablers. In Figure 7, an example of a structural perspective of manufacturing and changeability is presented.

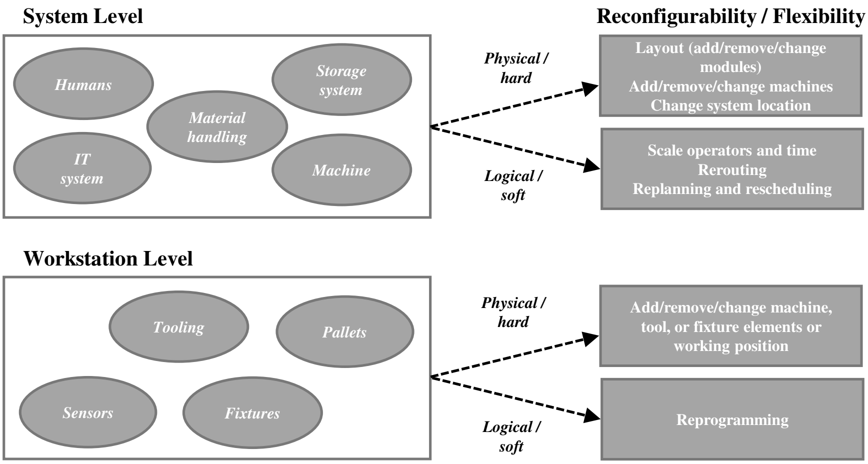

Figure 7. Constituents of manufacturing system and workstation levels and corresponding examples of changeability implementation. Adapted from Rösiö (2012b) and ElMaraghy (2005a).

When designing manufacturing systems that are changeable, it is fundamental to determine on which levels the implementation is required (Schuh *et al.* 2009). Likewise, it is essential to understand the specific challenges regarding the development of changeability at the different levels and within the different manufacturing constituents. Therefore, in the appended paper 1, a literature review is conducted in order to investigate how the different structuring levels of manufacturing are dealt with in previous research. In the review, specific attention is on reconfigurability research, as reconfigurability is an essential means for dynamic and profound change in a changeable manufacturing system.

In the literature review, a rather broad search is conducted in order to include various research themes and adequately investigate the entire body of research on reconfigurability. A total of 152 publications on reconfigurable manufacturing remained from the literature retrieval and exclusion process. Hereafter, a classification is conducted based on the aforementioned six structuring levels of manufacturing; from network level to workstation level. Additionally, dominant research themes or issues at each level are identified. The main findings of this review are that design and development issues related to hard reconfigurability enablers are dominant on lower structuring levels, such as design of reconfigurable machines or tools, whereas logical design issues are dominant on higher structuring levels, e.g. scalability management, reconfiguration selection, process planning, etc. Moreover, the review confirms that reconfigurability to large extent is addressed on system level and below, whereas the implication of having a reconfigurable manufacturing system on higher structuring levels are left rather unexplored. Lastly, the findings of the review indicate that reconfigurability research to large extent covers separate design issues or design sub-problems, e.g. designing the machines, managing scalability, determining optimal configuration, reconfigurable control systems, etc., whereas system design methodologies that cover the entire process and task of designing a reconfigurable systems are less present.

3.3. DESIGN METHODOLOGIES FOR CHANGEABILITY AND RECONFIGURABILITY

Considering the fundamentals of changeability and related design decisions, as presented in Table 6, well-established system design approaches need to be revised, in order to adequately support design of dynamically changeable manufacturing systems. For instance, explicit consideration of change drivers, their varying nature over the system's lifetime, and their impact on the manufacturing system must be considered at the outset of design, in order to lead to systems that are dynamically changeable over its lifetime. Furthermore, designing a system that meets these lifetime requirements for change can be accomplished in various ways, as changeability enablers are numerous and can be implemented in various levels, and in various constituents of the manufacturing system. Furthermore, with the vast amount of design choices regarding the changeable system solution, support for designing a context-specific and appropriate system with the right changeability enablers and extent is essential. However, design methodologies for changeability and reconfigurability are represented only to a limited extent in previous research. In the appended paper 2, a literature review of this limited number of existing design methodologies for changeability and reconfigurability is presented. Once again, particular focus is on design methodologies supporting reconfigurability and not only flexibility. A total of 21 design methodologies were identified for the review, selected through a combination of systematic literature retrieval and exclusion, as well as an additional snowball approach. In this regard, a design methodology for changeability is defined as a description of working procedures that at some level of detail is able to guide practitioners through the steps of developing a changeable manufacturing system, thereby providing knowledge of the structure of design decisions and specific techniques or tools to apply.

The aim of the literature review is threefold: 1) identify steps and phases that make up the design process of changeable and reconfigurable manufacturing, 2) determine whether existing methodologies supplement or oppose each other, and whether a generic methodology can be recognized, and 3) identify supportive tools and procedures that can be applied during the design process. In order to address the first research questions, all identified design methodologies are thoroughly reviewed and characterised in terms of their structure, sequence of design steps, and coverage. Through this comparative analysis of the design methodologies, considerable inconsistencies in applied terminology are indicated, as well as differences in their support for continuous design changes of the system throughout its lifetime, integration with product design, and support for various levels of changeability implementation. However, similarities are also emphasised, as the reviewed design methodologies to large extent can be divided in two generic classes of design conceptualizations; one being predominately of cyclic problem solving character and one being mostly of phased character, which are well-known ways of conceptualizing the design task (Bellgran and Säfsten 2009, Hall 1969, Roozenburg and Eekels 1995). In the phased design methodologies, decisions are largely sequential and similar design activities are grouped in phases with milestones in between. In the design methodologies with outset in the generic problem solving cycle, focus is on the iterations between analysis, synthesis, evaluation, and decisions, being the cyclic flow of the actual design task.

In each of the two classes of design methodologies, a generic structure or process of design for changeability and reconfigurability is identified. As such, these two types of generic design conceptualizations complement each other, by offering both structure and logic to the process of designing, thereby adhering to the notion of design being both the task of planning the process and conducting the actual design (Bellgran and Säfsten 2009). Therefore, a generic structure of design for changeability and reconfigurability is identified, based on a synthesis of the phased design methods and the problem solving methods, covering decisions related to making a requirement specification, making a system solution, implementing the physical manufacturing system, operating the system, and continuously evaluating its ability to fulfil requirements leading to reconfigurations. Within each of these design phases, cycles of analysis, synthesis, evaluation, and decisions can be recognized, leading to sequentially more concrete phases of design. The synthesized generic design methodology for changeable and reconfigurable manufacturing systems highlights some specific challenges related to each step of the design process, e.g. determining requirements for changeability and reconfigurability in the system's lifetime, determining how the enablers of change should be implemented, quantification of the potential of changeability and reconfigurability, evaluation of changeable system concepts, etc. Available supportive tools and procedures are lastly reviewed for each of these challenges, which highlight some considerable limitations regarding how to conduct the design in practice. In particular, the review reveals a lack of support for conducting changeability requirements discovery and limited support for deciding and evaluating the right enablers, level of implementation, and extent of changeability.

3.4. THEORETICAL REQUIREMENTS FOR DESIGN OF CHANGEABILITY

The findings of the literature reviews presented in the appended paper 1 and 2 indicate limited theoretical support for an industrial transition towards changeable and reconfigurable manufacturing systems, due to lack of a systematic and generic design methodology that adequately supports fundamental design decisions related to changeability and reconfigurability. Additionally, the following theoretical requirements for creating a methodology for changeability and reconfigurability have been identified:

- There is a need for applying both sequential/phased and iterative/cyclic design, which represent two different perspectives of the design process that supplement rather than oppose each other.
- Design of changeable and reconfigurable manufacturing systems requires consideration of both hierarchical and structural aspects of changeability.
- Support for anticipating changes throughout the entire lifecycle of the manufacturing system, and converting these into a suitable changeable system solution should be offered in the design methodology.
- Changeability enablers should be considered in terms of their level of implementation, type, extent e.g. pre-built flexibility range or ability to reconfigure, and the elements of the manufacturing system in which they should be embedded.
- Supportive tools and procedures that can be applied to aid the design process are required, in order to adequately identify changeability requirements, develop a system solution with the right change enablers and extent, and evaluate its appropriateness.

CHAPTER 4. EMPIRICAL FOUNDATION

It is widely acknowledged that changeability and reconfigurability are key competitive concerns in today's global manufacturing environment (Zhang *et al.* 2006). Some of the commonly discussed industrial challenges that changeability and reconfigurability are able to respond to are:

- Shorter time-to-market and time-to-profit of new products (Bi *et al.* 2008b).
- Need for increasing productivity and reducing cost (Bi *et al.* 2008a).
- Need for increasing utilization of production equipment (ElMaraghy and Wiendahl 2009, Koren 2010).
- Increasing uncertainty and volatility in product volumes (Bi *et al.* 2008b).
- Increasing variety, customization, and personalization (ElMaraghy *et al.* 2013).
- Rapid technological innovations (Bi *et al.* 2007, ElMaraghy *et al.* 2013).
- Faster establishment of production and ramp-up of volumes (Koren 2006).

The abovementioned challenges represent different change objects, which may require different ways of realization depending on the context. Therefore, changeability should be regarded as a multi-faceted manufacturing capability, rather than as an absolute feature of the manufacturing system (ElMaraghy and Wiendahl 2009). In other words, changeability is multi-dimensional and can be designed in unlimited ways in order to provide context-specific and appropriate ability to cope with changes. However, this context-dependency of changeability has not been treated widely in previous research, where reconfigurability originally was proposed for mid-volume manufacturing (ElMaraghy 2005a, Koren *et al.* 1999). Moreover, only a minority of publications are empirically founded or has a strong focus on the industrial transition towards changeability in specific production settings. In Table 7, an overview of publications on changeability in specific production contexts is presented, based on literature searches related to reviews presented in Chapter 3. Evidently, only few publications present actual case studies or empirically founded contributions on changeability and reconfigurability. Consequently, limited evidence and knowledge exist regarding objectives and realization of changeability in various production settings, which limits the ability of research to establish a practically applicable design methodology and support an industrial transition towards changeability. Therefore, in the appended paper 3 to 6, changeability implementation, importance, objectives, and realization in different production contexts are investigated, e.g. differences in changeability application to support ramp-up reduction, differences in types of changeability benefits, and differences in appropriateness and importance of changeability enablers. A sequential and exploratory mixed-method research approach is applied, where findings resulting from collaboration with the two polar-like case companies are supported and expanded by findings from an industrial survey, in order to adequately explore changeability and its context-dependency.

Table 7. Overview of previous research on changeability and reconfigurability in different production contexts.

Publication	**Production or industrial context**	**Changeability objective**
(Koren 2010)	High-volume production.	Using changeability and scalability on production system level to avoid the issue of excess or limited capacity.
(Al-Zaher *et al.* 2013)	Automotive company.	Using changeability on production line level for multiple part variants of the same family.
(Jefferson *et al.* 2013, Jefferson *et al.* 2014)	Aerospace company.	Using changeability in cells and fixtures for wing assembly in order to reduce ramp-up time and development of equipment.
(Benkamoun 2016)	Automotive supplier.	Designing a changeable site to accommodate both short-term and long-term changes to demand, products, and processes.
(Spena *et al.* 2016)	Italian SMEs predominately characterised by one-of-a-kind production, high variety, and manual work.	Application of variant flexibility and universality as the most important changeability enablers, whereas capacity scalability and mobility have lower importance.
(Rösiö and Säfsten 2013)	Automotive production sites.	Consideration of changeability enablers during design, e.g. customization for the product and its lifecycle, modularity in production system design, and diagnosability.
(Azab *et al.* 2013)	Medium-sized supplier for aviation industry.	Using changeability in machinery, material handling, organisation and staff, in order to introduce new product for a new market in an existing production site.
(Deif and ElMaraghy 2006)	PCB assembly.	Application of reconfigurability on assembly line and machine level in order to respond to rapid new product introductions and mass customization.

4.1. RAMP-UP REDUCTION THROUGH CHANGEABILITY

One of the fundamental drivers of changeability implementation is reduction of production development and ramp-up time for new products and production systems. Usually, production ramp-up is specified as the range of time from production start-up to targets of quality, volume, and variety have been reached, which is the final stage of production development (Bellgran and Säfsten 2009, Surbier *et al.* 2014). By utilizing changeability, the time for developing production systems for new products and ramping up volumes is decreased through reuse rather than replacement. Both flexibility and reconfigurability have the potential to reduce the time for introducing new functionality or capacity in production, which is illustrated in Figure 8.

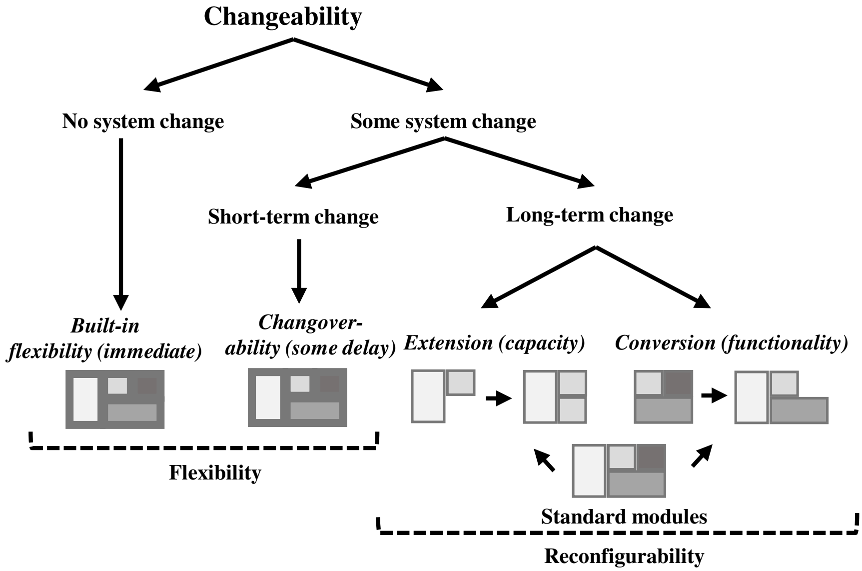

Figure 8. Manufacturing system reuse strategies for different changeability types. Combined from the work of Benkamoun et al. (2015) and Jørgensen (2013).

Regardless of the extent and type of changeability being utilized, some degree of reuse of already tested, implemented, and operating equipment and systems is enabled, which reduces time-to-market in contrary to dedicated production systems that must be replaced to accommodate new functionality. Usually, production ramp-up has been studied in high-volume industries (Surbier *et al.* 2014), where relying on reconfigurability appears particularly promising in order to mitigate the effect and amount of problems typically encountered, e.g. high cycle times, numerous process disturbances, quality issues, etc. However, production start-up and ramp-up have been less investigated in low-volume settings (Javadi *et al.* 2013, Surbier *et al.* 2009), where the potential of reconfigurability may differ in accordance with the nature of problems encountered specifically in this type of context. Therefore, in order to adequately understand how changeability and reconfigurability can be applied in different production contexts to aid new product introductions, a multiple comparative case study has been conducted and presented in the appended paper 3. The aim of the paper is to identify critical challenges during production development and ramp-up in relation to new product introductions, and determine differences across companies with varying product volume and variety.

The research presented in the paper is built on investigations in case company A and case company B, regarding problems encountered during production start-up and ramp-up of new products. The findings suggest that there are numerous considerable differences in the two companies, which can be attributed to their varying product variety, production volume, and company characteristics. In the high-volume case, the manufacturability of the product was identified as a main problem source, resulting in simultaneous adaption of product and processes. In the low-volume case, ramp-up initiated in the existing production set-up with necessary changes in tooling occurring in the normal production stage, resulting in reduced efficiency and increased planning uncertainty in the ramp-up phase. In both cases, intensive time and resource usage during new product introduction was emphasised, which potentially can be reduced by a higher degree of reuse of existing production resources, meaning reuse of a system platform in the high-volume case, and reuse of reconfigurable tooling in the low-volume case. Thus, in both cases, changeability and reconfigurability appears to be able to reduce production development and ramp-up time in relation to new product introductions, however, with notable differences in changeability objectives and realization.

4.2. POTENTIAL BENEFITS FROM CHANGEABILITY

In order to further investigate the differences in the potential of designing and implementing changeability and reconfigurability, two additional case studies were conducted; one in each of the collaborating case companies. In the appended paper 4, a case study in company A is presented, with the aim of determining the potential of implementing reconfigurability in companies characterised by high production volume and moderate variety. Moreover, in the appended paper 5, the potential and major challenge in implementing reconfigurability in small and medium sized companies characterised by low volume and high product variety was investigated through the collaboration conducted with case company B.

Both of the studied case companies operate highly dedicated manufacturing systems, where resources are more or less replaced when new products are introduced. In case company A, multiple generations of product families at different stages in their product lifecycles are produced simultaneously, however, each generation is made on its own dedicated and fully automatic assembly line. Thus, pooling of capacities and reuse across the generations are main drivers for changeability implementation, as well as ability to more quickly introduce future new generations and adapt gradually to uncertain introductory stages of demand. In case company B, the primary drivers of changeability implementation are the high variety in parts produced, which creates significant changeover time, and the inefficiency and extensive resource-usage related to introduction of new parts. Thus, changeability on both a short-term daily basis and more long-term basis are relevant in this case, which appears realizable by deploying changeable fixtures.

To summarise, the research presented in paper 3, 4, and 5 suggest that notable differences in both changeability drivers, objects, and enablers exits in manufacturing contexts with opposite size, volume, and variety characteristics. In Table 8, an overview of the primary differences identified in the cases is presented.

Table 8. Differences in changeability constructs in the two collaborating case companies.

Changeability construct	**Case Company A**	**Case Company B**
Change drivers	Frequent introductions of new generations of product families creates low utilization rates for dedicated lines. Uncertainty regarding demand volume and market acceptance of new products.	Increasing frequency of introductions of new parts creates significant time for production development. Frequent and uncertain changes in product and part mixes, in particular with one-piece flow, create significant changeover time.
Change objects	The production capacity should be changed gradually to meet demand over the products' lifecycle and demand uncertainty, thereby avoiding low utilization rates.	The product/part mix should be changed on a daily basis to accommodate one piece flow.
Change enablers	A changeable assembly setup, where reconfigurable parallel lines are utilized, appears to be a solution, with particular focus on physical scalability.	Changeable fixtures appears to be a solution, with particular focus on reducing time for new product introductions and changeover time for one-piece flow.

4.3. INDUSTRIAL IMPLEMENTATION AND IMPORTANCE OF CHANGEABILITY

In order to further explore differences in changeability application in different contexts and expand the findings from the two collaborating cases, an industrial survey has been conducted. The aim of the survey is to investigate the implementation and critical importance of changeability and reconfigurability in different industrial and manufacturing settings, with particular focus on physical enablers on system and workstation level, as these were indicated as being context-dependent in the collaborating case companies.

In order to provide generalizable empirical evidence across various industries and production types, thereby identifying potential significant differences across change enabler importance and implementation, a questionnaire survey was conducted. The collected data primarily cover Danish manufacturing companies, however, additional countries are represented as well, and the sample is approximately equally divided between small and medium enterprises (SMEs) and large enterprises. Through the questionnaire, data regarding the level of implementation of enablers of changeability, the perceived criticality of these, and context of the responding manufacturing companies were collected. In this regard, the manufacturing context is described through a number of fundamental characteristics; firm size, industry type, production volume, degree of automation, degree of product variety or customization, and the type of production policy being deployed. Likewise, the changeability enablers are delimited to the physical reconfigurability enablers; modularity, integrability, customization, scalability, convertibility, automatibility, and mobility, which are assessed on both equipment level and on system/line level. Thus, changeability is investigated as a multi-faceted concept, which can be enabled in various ways in companies.

Generally, the findings indicate that the level of implementation of changeability enablers is limited, however, with higher perceived importance. Through non-parametric significance tests and post-hoc analyses, significant differences in enabler implementation and importance across production contexts were identified, which confirms the context-dependent nature of changeability. Among the main findings are that mobility has a higher level of implementation in companies with low sales volumes, is perceived more critical in small companies compared to medium sized companies, and is perceived less critical in companies with a low to medium degree of manual work than in companies with higher degrees of manual work. Moreover, scalability of lines is implemented to higher extent in companies dominated by make-to-stock production.

In Table 9, the main findings of the survey are compared to findings from the two collaborating cases, which to large extent confirms and explains some aspects of the context-dependent nature of changeability and reconfigurability.

Table 9. Meta-inferences from case collaboration and industrial survey regarding changeability implementation and context-dependency.

Changeability implementation	**Industrial survey**	**Collaborating cases**
Level of implementation	Limited implementation, however, with higher perceived importance.	Fully dedicated production setups are used in the collaborating cases, however, changeability appears beneficial in numerous ways.
Mobility	Mobility of equipment and lines has higher level of implementation in companies with low sales volumes. Mobility of lines is perceived more critical in small companies compared to medium sized companies. Mobility of equipment is perceived less critical in companies with a low to medium degree of manual work than in companies with higher degrees of manual work.	Mobility of fixtures is a main objective of changeability implementation, in order to reduce changeovers from having a one-piece flow in case company B, which is a SME with low-volume, high variety, and a highly manual production setup.
Scalability	Scalability of lines is implemented to higher extent in companies dominated by make-to-stock production.	Scalability of assembly lines is a main driver of changeability implementation in case company A but not in case company B, which has high-volume and make-to-stock production.

4.4. PRACTICAL REQUIREMENTS FOR DESIGN OF CHANGEABILITY

The findings of the empirical research presented in this chapter and the corresponding appended papers highlight important practical requirements for design of changeability. First of all, it has been indicated that enablers of changeability and reconfigurability are only rudimentarily implemented in industry, which emphasises a need for an applicable design methodology for changeability and reconfigurability.

Moreover, several distinguishing aspects of changeability potential and implementation were identified depending on the production context, which confirms the context-dependency of changeability and provides an important foundation for creating a design methodology for changeability. In regard to this, the following requirements have been identified:

- A design methodology should support context-specific design of changeability and reconfigurability in order to be practically applicable.
- Changeability and reconfigurability is not only beneficial in high-volume production settings with a high degree of automation, but also in low-volume settings with higher degrees of manual work.
- A design methodology should consider different hierarchical levels and objectives of changeability and reconfigurability, as high-volume cases to high extent can benefit from pooling capacities and reuse lines across variants and for new products, and low volume cases can benefit from reconfigurability on tooling level to accommodate frequent mix changes and new products.
- A design methodology for changeability should be predicated on the premise that change drivers, change objects, and change enablers are different and depend on the company context.

CHAPTER 5. DESIGN METHODOLOGY & PRACTICAL IMPLICATIONS

Based on the theoretical and empirical foundation outlined in the previous chapters, the need for a design methodology for changeable and reconfigurable manufacturing systems was emphasised and detailed requirements were established. To summarise, these requirements reflect both the need for supporting and planning the process of design for changeability and the need for supporting the actual design task:

- The design methodology should support context-specific design of changeability and reconfigurability in order to be practically applicable and be predicated on the premise that change drivers, change objects, and change enablers are different and depend on the company context.
- Changeability enablers should be considered in terms of their level of implementation, type, extent e.g. pre-built flexibility range or ability to reconfigure, and the elements of the system in which they should be embedded.
- Support for anticipating changes throughout the entire lifecycle of the manufacturing system, and converting these into a suitable changeable system solution should be offered in the design methodology.
- Supportive tools and procedures that can be applied to aid the design process are required, in order to adequately identify changeability requirements, develop a system solution with the right change enablers and extent, and evaluate its appropriateness.

Based on these requirements, a design methodology and a supportive tool for concept evaluation are proposed and described in the appended paper 7 and 8. Moreover, the appended paper 9, 10, and 11 evaluate and discuss practical implications and barriers related to actually conducting design for changeability in manufacturing companies. In the present chapter, the findings of these papers are briefly summarised.

5.1. PARTICIPATORY AND SYSTEMATIC DESIGN FOR CHANGEABILITY

Design is generally defined as the act of making or planning something with a specific purpose in mind (Oxford University Press 2017). Thus, design is largely an innovative process involving intuition, individuality, experience, and creative thinking. However, when the designed objects are complex engineered system, e.g. a manufacturing system, design cannot purely be approached as an art that is conducted intuitively, as simultaneous consideration of technological, organisational, managerial, and human factors are required to fulfil and balance stakeholder needs (Birkhofer 2011, Farid 2016). Moreover, with the increasing complexity currently being introduced by product development, e.g. variety, customization, and personalisation, by markets, e.g. global competition, turbulence, and demand uncertainty, and by manufacturing systems, e.g. changeability, reconfigurability, and flexibility, the rationalization of design through the use of suitable design methodologies becomes even more prevailing (Adams 2015, ElMaraghy *et al.* 2012b). In this regard, a design methodology is defined as a prescriptive and systematic way of rationalizing and providing knowledge of the design process (Adams 2015, Pahl and Beitz 2013).

Design methodologies prescribe how design should be conducted, by providing useful models of the design process, methods and techniques to use within the processes, and corresponding terminology (Bellgran and Säfsten 2009). Some essential design processes are; defining stakeholder requirements, transforming stakeholder requirements into a technical view of system requirements, synthesise a solution that satisfies system requirements, realise the elements of the solution, and verify and confirm the technical solution (Adams 2015). However, while most well-established design methodologies concern functional requirements that express what the system should do, non-functional requirements such as changeability that express properties the system should have, e.g. being rapidly and efficiently responsive to change, are less treated and more difficult to articulate, find solutions for, and evaluate (Adams 2015, Benkamoun 2016, de Weck *et al.* 2011).

As such, non-functional system requirements can be viewed as constraints which the system must operate under, e.g. the system should be convertible to a different function, the system should be easily changed, the system should be easily interfaced with another system, etc. (Adams 2015). In order to achieve fulfilment of non-functional requirements during the design process, specific attributes related to what the system must do should be captured and related to specific system characteristics (Adams 2015). Thus, various levels of detail of non-functional requirements should be supported during design, which is outlined in Table 10 with both general examples of non-functional requirements and specific changeability requirements.

The examples in Table 10 indicate that in order to design manufacturing systems with changeability, detailed attributes must be captured, which as described in previous chapters, cover both physical and logical aspects, various hierarchical system levels, various types of enablers, and various system elements. Therefore, in order to provide meaningful treatment of changeability during manufacturing system design, a design methodology is proposed in the appended paper 7, which specifically addresses changeability concerns and attributes, guides practitioners through specific design decisions related to changeability, and provides useful techniques and tools to complete the design process.

Table 10. Levels of detail in design and evaluation of non-functional requirements for manufacturing systems. Adapted from Adams (2015).

	General examples	**Changeability examples**
Concern (Overall non-functional design concern)	Design concern, viability concern, sustainment concern, adaptability concern, etc.	Changeability concern.
Attribute (A non-functional requirement defining one aspect of what the system should do)	Simplicity, safety, reusability, efficiency, robustness, reliability, testability, usability, etc.	Reconfigurability or flexibility including their detailed aspects, e.g. modularity, scalability, convertibility, diagnosability, customization, etc.
Metric (Measurements to evaluate the non-functional requirement)	Variety for measuring simplicity requirements. Time for measuring efficiency requirement. Ease of training for measuring usability.	Configuration convertibility of assembly line. Assembly line scalability. Machine reconfiguration smoothness.
Measurable characteristic (System characteristic that should be measured in relation to the non-functional requirement)	Number of system states for variety. Cycle-time for efficiency / capacity utilization over time for efficiency. Time for user to learn how to operate the system.	Number of machines to shut down for introducing new products / Number of routing connections between machines. Smallest incremental capacity by which the system throughput can be adjusted. Number of added machines modules versus total number of machine modules.

The aim of the design methodology is to systematically support fundamental design decisions regarding changeability type, extent, and enablers in order to ensure consistency between company specific requirements for changeability and the designed manufacturing system. The methodology fosters a participatory approach to design, where relevant organisational members can be actively involved in the different stages of design. Moreover, the methodology can be applied to both design of new manufacturing systems and redesign of existing manufacturing systems, building on the premise that the recipe for handling changes is different in every company, depending on change requirements and the suitable enabling constituents of the manufacturing system.

The design methodology engages both a systematic phased approach to design, which aids planning of the design task, as well as a more participatory and iterative approach to design that involves mapping between design domains. Generally, three abstraction levels of design can be distinguished; conceptual design, embodiment design, and detailed design, where different criteria for each solution's level of detail exist (Pahl and Beitz 2013). The design concept generally covers broad definitions of the overall functions of the system and the fundamental solution principles. In regard to designing changeable manufacturing systems, this can be translated into the decision on how to realise the changes in the important objects, which requires different dimensions of changeability to be present in the manufacturing system. Embodiment design is generally regarded as the task of determining the layout of the solution or the task of giving shape to the conceptual functions and principles, which in terms of a changeable system design relates to detailing the change enablers that will realise the solution paradigm. The detailed design is beyond the scope of the proposed design methodology. Reasons for this are manifold. First of all, initial and conceptual design phases most often cover the most critical design decisions, where estimates indicate that 80% of resources used during design are committed by decisions taken in the first 10% of design activities (Benkamoun 2016, Hague and Taleb-Bendiab 1998). Secondly, in initial stages of design, uncertainty is generally high and the design problem may only be vaguely defined. Thirdly, detailed design often involves tasks that are highly case specific and can be regarded as detailed sub problems.

Within each of the design phases in the design methodology, different design domains are involved. In axiomatic design, design is essentially the transformation and mapping between domains, covering the stakeholder domain, the functional domain, and the physical domain. This forwards and backwards mapping between domains is also utilized in the proposed design methodology, which helps practitioners in achieving a suitable manufacturing system design, thereby eliminating the inefficient trial-and-error approach to design. In Table 11, an overview of the phases and domains covered in the proposed design methodology is presented, and related to the fundamental changeability constructs that should be supported during design.

The strength of the design methodology is that it supports decisions related to all fundamental changeability constructs, while offering a systematic rationalization of the design process. This is demonstrated through the application of the design methodology in the two collaborating case companies. In both cases, context-specific design of changeability was supported, which resulted in recommended transitions from traditionally highly flexible and dedicated manufacturing systems towards reconfigurability on various hierarchical levels.

Table 11. Phases and domains in the proposed design methodology for changeable and reconfigurable manufacturing systems.

Design domain	**Design phase**	**Changeability construct**
Stakeholder domain	Requirement specification: Specification and analysis of lifetime requirements of changeability that the system should be designed to meet dynamically and efficiently.	Change drivers
Functional domain	Conceptual design: Decisions regarding extent of changeability in the designed system, in particular in terms of selecting a suitable combination of flexibility and reconfigurability to achieve required changes. Specification of the internal and external objects that should be changeable.	Change objects Change extent
Physical domain	Embodiment design: Decisions regarding changeability enablers in the system solution in terms of the type, level of implementation, and the constituents of the system they should be embodied in.	Change enablers

5.2. EVALUTATION DURING DESIGN FOR CHANGEABILITY

Evaluation is an essential part of design and development, e.g. in initial design stages where the best system solution to work further with should be selected from various alternatives (Bellgran and Säfsten 2009). Often this process is conducted based on opinions or subjective evaluation of some criteria. However, when designing changeable and reconfigurable manufacturing systems where the non-functional requirements of changeability can be satisfied in various way and some of the designed changeability properties are first realised after the system has been put into its initial use, alternative evaluation methods are needed. Therefore, in the appended paper 8, a concept design evaluation method is presented, which can be applied in initial stages of design for evaluating the investment feasibility of changeable and reconfigurable manufacturing concepts, based on future demand predictions and their uncertainty.

Generally, when evaluating the feasibility of changeability and reconfigurability, a long-perspective is needed, as changeability and reconfigurability are lifecycle properties that most often reduce long-term operating costs, however, at an additional initial investment (Wiendahl and Heger 2004). The expected cost developments for dedicated and changeable manufacturing systems are described in Figure 9.

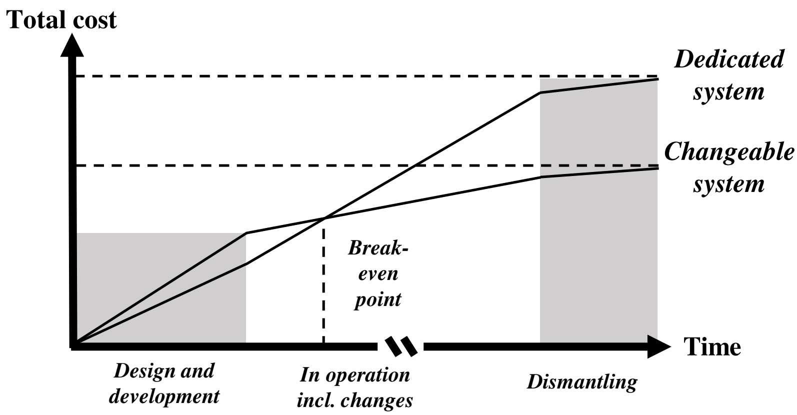

Figure 9. Lifecycle costs of dedicated and changeable manufacturing systems. Adapted from Wiendahl and Heger (2004).

The trade-off related to the curves in Figure 9 indicates important aspects that should be evaluated during initial stages of design, e.g. between flexibility and productivity, between postponement of capacity investment and the associated increases in reconfiguration costs, and between lower costs of functionality changes and new product introductions versus increased initial system investments. In the method proposed in paper 8, a quantitative model is presented which evaluates the discounted value of capital and operating costs of changeable manufacturing concepts, based on essential concept characteristics, e.g. the cost of changeability in terms of capacity scaling, mix changes, and adding new products. The concept characteristics have been selected in order to reflect essential design decisions; the combination of reconfigurability and flexibility and the objectives of changeability. Furthermore, the method evaluates the impact of uncertainty regarding demand and the ability of the different concepts to respond to this, which is one of the main benefits of changeability and reconfigurability.

The proposed design evaluation method and quantitative model were developed through collaboration with both case company A and B. Thus, model conceptualization, the actual modelling, model solving, and model implementation were conducted as a collaborative project with the case companies as support for evaluation and decision making during initial design stages. In both cases, the implementation of the model suggests that a reconfigurable manufacturing setup is more feasible than currently employed dedicated setups. Moreover, differences in changeability drivers and implementation are emphasised by the model implementation in the two cases, where changeability design primarily is driven by capacity changes and introduction of more long-term changes to the functionality of the system in case company A, and changeability is driven primarily by rapid introduction of new variants and frequent mix changes in case company B. Thus, the proposed design evaluation method supports consideration of changeability as a multi-dimensional ability, that can be designed in different ways, in order to provide context-specific and appropriate ability to cope with changes.

5.3. IMPLICATIONS OF DESIGN FOR CHANGEABILITY

Design and development of manufacturing systems is a process that to high extent is affected by contextual aspects, e.g. attitude of participants, resources available, priority of design project, company culture, knowledge of system designers, etc. (Bellgran 2003, Bellgran and Säfsten 2009). Thus, the successful design of changeable and reconfigurable manufacturing systems depends not only on the availability and application of a suitable design methodology, but also on the manufacturing company's ability to plan and perform the design process. Therefore, an equally important aspect related to supporting an industrial transition towards changeability and reconfigurability, is to address the double-task of design, meaning that not only the actual design task should be supported, but also the planning and execution of the design process.

Planning and executing a successful design process involves consideration of contextual factors or the company's design preconditions that may impact the ability to perform the design process (Bellgran and Säfsten 2009). Examples of such preconditions for design success are selection of participants in the design team, competences of designers, division of tasks within the design project, experience of designers, managers' attitudes, company culture, traditions, company knowledge, etc. (Bellgran 2003, Bellgran and Säfsten 2009). These contextual preconditions for successful design are widely and generally relevant for all types of design processes. However, preconditions specifically related to designing changeable and reconfigurable manufacturing are less understood and addressed, despite the inherent complexity and challenges of this type of design compared to design of traditionally static manufacturing systems that may represent barriers towards the successful implementation of changeability in industry. Therefore, in the appended paper 9, 10, and 11, implications regarding the planning and execution of design for changeability and reconfigurability are addressed, and essential design preconditions are identified.

5.3.1. INTEGRATED PORTFOLIO DEVELOPMENT

In the appended paper 9, the challenges related to establishing a strategic alignment between product and production development is addressed, which is fundamental in order to realise changeability. Compared to design of traditional dedicated manufacturing systems, a fundamental aspect of changeable manufacturing systems is that they evolve in accordance with products and variants (AlGeddawy and ElMaraghy 2009). This idea of co-evolution means that changes in products cause changes in manufacturing systems. Likewise, new processing or technology updates in manufacturing present new opportunities for product design (AlGeddawy and ElMaraghy 2011). Essentially, this idea of co-evolution requires that production systems are able to respond to changes efficiently and that they are continuously and strategically matched with the product portfolio. In other words, the production design and development is conducted as a result of the technology portfolio in line with the product portfolio, which can be labelled as integrated portfolio development (Bruch and Bellgran 2014). A visualization of this integrated portfolio planning is presented in Figure 10, where production systems are designed, developed, and updated for multiple product generations, rather than being dedicated to one specific generation.

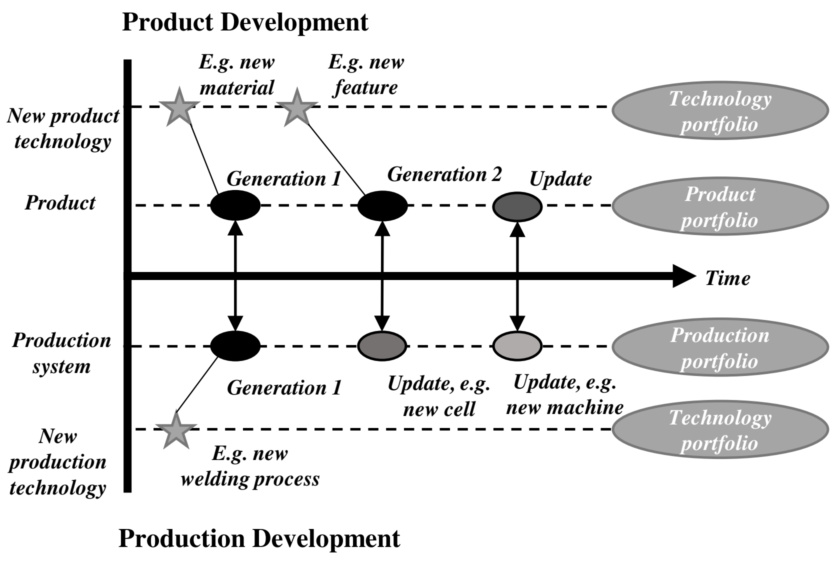

Figure 10. Integrated product and production portfolio development. Adapted from Bruch and Bellgran (2014).

The integrated planning or co-evolution between products and production depicted in Figure 10 is one of the essential objectives of changeability, where principles of reconfigurability can be applied to enable this in the production system. However, numerous challenges have been identified in previous research in relation to integrated portfolio planning, e.g. insufficient information management, lack of resources and competences, lack of long-term mindset, insufficient collaboration with equipment suppliers, lack of monitoring the environment, and lack of a development process (Bruch and Bellgran 2014). As reconfigurability enables integrated portfolio planning, conducting design for changeability and reconfigurability could potentially aid some of these challenges. Therefore, in the appended paper 9, two production development projects focused on reconfigurability are studied with the aim of identifying mechanisms that can aid the previously experienced challenges related to establishing an integrated portfolio. One of the studied cases is a production development project conducted in the collaborating case company A, whereas the second studied case is a similar development project in a Swedish company in the automotive industry, here denoted as case company C. Both cases are large enterprises in a transition towards changeable and reconfigurable manufacturing, in order to handle increased variety and market uncertainty. However, at the time of the case studies, case company C was already in the system concept testing phases, whereas case company A was in the early concept development phase. Moreover, in case company A, focus remained on a particular production site with reuse over time and across variants as the main objective, while case company C focused on multiple geographically dispersed sites, meaning that reuse over both time and space were in scope.

The main findings of the case studies include mechanisms that respond to the challenges of developing a production portfolio, as well as directions for future research. For instance, in both cases it was concluded that running a joint product and production development project not tied specifically to a new product relieved the trade-off between fire-fighting and long-term development, and created a solid foundation for integrating product and production portfolios. Moreover, the ability to initially structure information on both existing products and production systems, and categorize uncertainties and knowledge regarding future technologies, demand, etc. that would impact the integrated portfolio, proved particularly valuable to respond to the challenges of handling and managing information. Thus, the findings presented in the appended paper 9 essentially indicate both aspects of planning and executing design for reconfigurability, which can aid challenges in regard to transitioning towards changeability and co-evolution of products and production.

5.3.2. PRECONIDITONS FOR DESIGN OF RECONFIGURABILITY

In the appended paper 10 and 11, preconditions specifically related to conducting design for changeability and reconfigurability are addressed through an in-depth case study in the collaborating case company A and an industrial survey. Thus, a sequential exploratory mixed method research approach is once again applied. In paper 10, a number of design prerequisites specifically related to conducting design of reconfigurable systems are identified from previous research, e.g. having a lifecycle perspective on systems, having knowledge about reconfigurability, having a structured system design process, etc. These prerequisites represent contextual factors such as conditions that should be present in the company, e.g. knowledge, competences, etc. Depending on their degree of presence in a company, these preconditions affect the success and ability to design changeable and reconfigurable manufacturing systems. In other words, if the preconditions are not present, they may represent critical barriers towards the successful design and development of changeability and reconfigurability. Through the long-term collaboration with case company A, the existence of these design preconditions were investigated and significant challenges and supporting actions that could aid their development were identified. Generally, the findings indicate noteworthy challenges in regard to successful design and development of changeable and reconfigurable systems, in particular in relation to identifying long-term requirements for changeability and reconfigurability and having knowledge and skills regarding reconfigurability and its development and potentials.

In order to further explore the presence of these design preconditions and provide more generalizable empirical evidence, an industrial survey was conducted based on the same fundamental design preconditions. Respondents were in the questionnaire asked to indicate the extent of agreement with a collection of statements representing measured variables, which were established to reflect the latent variables being the design preconditions. 60 full responses were included in the analysis of the survey data, primarily covering Danish companies. Moreover, each response, which represented a manufacturing company, was described through a number of fundamental characteristics; firm size, industry type, production volume, degree of automation, degree of product variety or customization, and the type of production policy being deployed. Thus, the presence of design preconditions across different manufacturing contexts could be explored. The findings of the survey generally support the findings of the in-depth case study presented in the appended paper 10, as the preconditions only appears to be rudimentarily existing in industry, where knowledge and skills regarding reconfigurability appear to be least present. Furthermore, the presence of some of design preconditions appeared to be contingent on the context, where e.g. a long-term view on investment in production capacity was less present in companies with highest degrees of manual work and in companies with low levels of semi-automated production processes. In Table 12, the findings of the in-depth case study and the industrial survey are compared, which indicates some notable challenges in industry regarding the preconditions for designing reconfigurable manufacturing systems. In order to support a transition towards changeability, a viable first step is to address the presence of these design preconditions and identify potential difficulties in this regard, thereby creating a solid foundation for identifying essential aspects that impact the success of the design process and conducting the actual design process.

Table 12. Meta-inferences from case study and industrial survey regarding preconditions and barriers for design of changeability and reconfigurability.

Precondition	**Collaborating case company A**	**Industrial survey**
A lifecycle perspective on production systems / Having a holistic perspective on production systems	Separation between product and production development and separation of responsibilities between development and operations in typical production development projects limit this precondition. Knowledge regarding system constituents and interdependencies between products and production is required in order to have this precondition.	Focus on reusing production equipment across products and for new generations appeared to be the most present precondition.
Correlation between production system design and the product portfolio development	Considering future product generations, new variants, and their timing is a complicated task that needs to be supported in order to develop this precondition.	Mostly present in the electronic industry, where lifetime of products is significantly short.
Having long-term view on investments in production capacity	Traditional approaches to investment plans limit this precondition.	Appears mostly present in companies with highest degrees of manual work and companies with low levels of semi-automated production processes.
Having a structured production system design process	A stage-gate like design process model is in its traditional form not able to support design for changeability.	Appears to be one of the most significant barriers towards development of changeability.
Having staff that are skilled in system design and have knowledge of reconfigurability	Appears limited, e.g. in terms of identifying differences between reconfigurability and changeability. Analysis of reconfigurability potential and dissemination of this were	Appears to be the most significant barrier towards development of changeability.

Table 12. Meta-inferences from case study and industrial survey regarding preconditions and barriers for design of changeability and reconfigurability.

	identified as an initiative to support this precondition.	
Existence of product families for customized flexibility in production	Dissimilar knowledge and views regarding grouping of products in families limit this precondition, however, this could be enabled by shared overviews of existing products and corresponding production systems.	Appears to be one of the most present preconditions.

CHAPTER 6. CONCLUSION

The objective of this thesis was to create a systematic design methodology for changeable and reconfigurable manufacturing systems applicable in various manufacturing settings to support context-specific design of changeability. Thus, the contribution of this thesis is two-fold; 1) new theoretical concepts and models that contribute to advancing state-of-the-art research in the light of the limited ability of previous systems design methodologies to support design of dynamically changeable manufacturing systems, and 2) knowledge that is applicable in industry for actually conducting design of changeable and reconfigurable systems. For this reason, an interactive research approach was applied in order to create novel research contributions, which were also of high industrial relevance. Through this collaborative research process where to primary case companies participated, the research problem was increasingly understood and addressed through a combination of complementary research methods. In the following, the main contributions of the thesis are summarised and future directions for research are proposed.

6.1. RESEARCH CONTRIBUTIONS

- *Knowledge regarding context-dependency of changeability:* In this thesis, changeability and reconfigurability are regarded as multi-faceted manufacturing capabilities that can be designed in unlimited ways in order to provide context-specific and appropriate ability to cope with changes, rather than as absolute features of the manufacturing system. This context-dependency has not been treated widely in previous research, however, in this thesis, important aspects of this are addressed. Fundamental differences in hierarchical levels and objectives of changeability and reconfigurability are emphasised, as well as differences in change drivers, change objects, and change enablers. This represent a valuable foundation for creating a practically applicable design methodology that captures all detailed aspects of changeability in practise.
- *A systematic design methodology and supportive concept evaluation method:* The participatory and systematic design methodology for changeable and reconfigurable manufacturing systems proposed in this thesis is able to provide design support for various types of manufacturing contexts, as it is predicated on the premise that change drivers, change objects, and change enablers are different and depend on the company context. The methodology rationalizes the design process and supports essential design task in relation to changeability, e.g. specifying requirement, determining extent of change, and determining enablers of change. In combination with the proposed evaluation method for changeable and reconfigurable concepts, the design methodology constitutes valuable support for initial phases of system design in manufacturing companies.

- *Knowledge regarding preconditions and barriers related to conducting design for changeability:* In the thesis, not only the actual task of designing changeable and reconfigurable manufacturing is addressed, but also prerequisites and barriers for the practical design and development, the so called design preconditions. These aspects of design have not been widely addressed in previous research, but are critical for the industrial transition towards changeability.
- *Knowledge regarding changeability and reconfigurability in practise:* In this thesis, a collaborative research approach is applied which results in knowledge that is largely driven by empirical data and findings. Previous research on changeability and reconfigurability is to very limited extent empirically founded, which represents a gap between research and practice. This thesis contributes with knowledge that can potentially aid the transition towards changeability in practice, which is important as changeability and reconfigurability appear particular promising in practice.

6.2. FUTURE WORK

- *Include the detailed design phases:* The research presented in this thesis primarily covers initial phases of system design that end with recommendations regarding generic dimensions of enablers that should be embedded in the manufacturing system. Thus, the detailed design phase is largely omitted. However, further work should be done in regard to supporting detailed design decisions regarding the plethora of options for how to actually design the system constituents with the recommended change enablers, e.g. modularity.
- *Investigate the impact of changeability and reconfigurability on firm performance:* At present, very few examples of the impact of implementing changeable and reconfigurable manufacturing systems are reported in previous research. Therefore, investigating the actual relation between critical parameters of firm performance, e.g. time-to-market, return-on-investment, etc. and implementation of changeability is a viable direction for future research.
- *Disseminate knowledge of design for changeability and reconfigurability in industry:* In the light of the findings of this thesis, it can be concluded that designing and developing changeable and reconfigurable manufacturing is promising and highly beneficial in manufacturing companies. However, the findings indicate that critical barriers exist in this regard. In particular, having a structured system design process and knowledge of reconfigurability appear to be the most significant barrier towards development of changeability. Therefore, disseminating the knowledge and findings of this thesis in industry is believed to be both critical and valuable directions for future work.

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