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Elisabeth Lervåg Synnes

Investigating Product Design and Development Capabilities for Transformation to Automated Assembly in a Low-Volume Industry Context

Doctoral thesis

NTNU
Norwegian University of Science and Technology
Thesis for the Degree of
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Department of Mechanical and Industrial
Engineering

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Preface

The thesis has been submitted to the Department of Mechanical and Industrial Engineering at the Norwegian University of Science and Technology (NTNU) and Kongsberg Maritime (Rolls-Royce Marine until 2019).

The project started in June 2014 and ended in December 2022. This work is supervised by Professor Torgeir Welo (main supervisor). Internal supervisors have been Magnar Førde, Svein Kleven, Hans Johansson and Hildegunn McLernon from Kongsberg Maritime in the given order. Funding was provided by the Industrial Ph.D. program 241103.

The thesis is paper-based meaning that the core of the thesis is a series of scientific papers published in peer reviewed conference proceedings and submitted to peer reviewed journals.

As part of the Industrial Ph.D. program, I have been introduced to a series of industrial challenges and allowed to experience how KM copes with these challenges. Of particular interest was to get insight into internal product development projects and the obstacles to overcome and enablers to leverage to enable a transformation towards more automated assembly. In this work, KM collaborated with external partners to find automated assembly solutions in the low-volume industrial context.

Participation in conferences worldwide opened the possibility of exchanging knowledge with other researchers. Also, spending time at NTNU in the first phase of this thesis, attending lectures, and discussing ideas with other students and researchers, was a valuable and necessary experience to bridge the world of industry and academia. These experiences have allowed me to grow personally and professionally as an academic.

Elisabeth Lervåg Synnes

Ålesund, May 2022.

Acknowledgements

I would like to thank the people who have supported and helped me to complete this thesis.

First, I would like to express my gratitude and thank my supervisor Professor Torgeir Welo for guidance and feedback throughout the scientific work. A special thanks for helping me navigate between industry and academia.

I would also like to thank my supervisors and mentors in Kongsberg Maritime (and Rolls-Royce Marine) Magnar Førde, Svein Kleven, Hans Johansson and Hildegunn McLernon for making this research possible with their support and helpfulness. Thanks for knowing when to push and when to give me space. A special thanks to my managers during the work on this thesis, Rune Longva, Steve Wittering, Hans Johansson, and Kellieann Hukins, for facilitating my workdays and allowing me to grow as a researcher and as a KM employee.

I would also like to thank all my colleagues in Kongsberg Maritime who contributed to this research with their assistance and invaluable insights. Your guidance and engagement in discussions were an inspiration in different stages of my research. A special thanks to the employees that agreed to be interviewed and all other participants who participated in the study and made the research possible. I would like to express my gratitude to Oda Ellingsen for walking the road with me and guiding the way with her kindness, knowledge, and reflections. A special thanks to Arild Djupvik for sharing his knowledge and insights about the maritime industry, manufacturing and assembly: we both share the vision of sustainable automated manufacturing and assembly in Norway.

My friends and family need a special thanks for all the love and practical- and mental support during the Ph.D. journey. My beloved family deserves gratitude for the overhearing patience, encouragement, and filling in where I do not stretch. Thank you all for giving me perspective on life. A special thanks to my husband and children for their unconditional love. You are exceptionally important to me!

I gratefully acknowledge that Kongsberg Maritime AS and the Research Council Norway`s Industrial Ph.D. program project 241103 funded this work.

List of publications

The following gives an overview of the publication outputs of the Industrial Ph.D. program project. The work resulted in 5 conference papers and two papers that are submitted to peer reviewed journals.

Main paper 1: Synnes, E.L. & Welo, T.

Industrialization of Automated Assembly in a Marine Low-volume context: A Case Study of product development (in review with the International Journal of Product Development)

Main paper 2: Synnes, E.L. & Welo, T. (2017)

Applicability of Lean Product Development to a company in the marine sector

IEEE International Conference on Industrial Engineering and Engineering Management (IEEM): 10-13 Dec Singapore

Main paper 3: Synnes, E.L. & Welo, T. (2022)

Using Lean to Transform the Product Development Process in a Marine Company: A Case Study (Procedia CIRP)

Main paper 4: Synnes, E.L. & Welo, T. (accepted with minor revisions)

Data-driven product optimization capabilities to enhance sustainability and environmental compliance in a marine manufacturing context (accepted with minor revisions in the journal Concurrent Engineering: Research and Applications)

Supportive papers for the thesis:

Supportive paper 1: Synnes, E.L. & Welo, T. (2015)

Design for Automated Assembly of large and complex products: Experiences from a marine company operating in Norway (Procedia Computer Science)

Supportive paper 2: Synnes, E.L. & Welo, T. (2016)

Bridging the gap between high and low-volume production through enhancement of integrative capabilities (Procedia manufacturing**)**

Supportive paper 3: Synnes, E.L. & Welo, T. (2016)

Enhancing Integrative Capabilities through Lean Product and Process Development (Procedia CIRP)

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SUMMARY

This thesis context has been the maritime low-volume manufacturing industry undergoing change and restructuring due to markets affected by a shift in energy sources and digitalization. More cost-effective production methods are needed to sustain competitiveness while ensuring sustainable and environmentally friendly products and manufacturing processes. Forward-looking businesses increase in-house production by investing in advanced technology, reducing labour to a less significant portion of the production cost. Successful product development, including productivity improvement promised by *new-to-the-company* manufacturing technology, relies heavily on creating a strong interface between design and manufacturing, such that product- and process design considerations are collectively considered.

How to enhance product design and development capabilities needed to enable automated assembly of large and heavy marine low-volume products still need to be fully accounted for in existing theoretical frameworks. This thesis aims to contribute to and extend theory about the complex nature of product development to the low-volume industrial context. Through the lens of (Lean) product development theory, this thesis explores product design and development capabilities for transformation to automated assembly in the given context. As Lean is primarily a management approach, the present problem makes it necessary to include engineering strategies as a starting point for the study. The thesis has adopted *Design for X* strategies to supplement Lean in identifying necessary changes in product design.

The investigation is guided by three overarching research questions (RQ):

RQ1: What are the obstacles of the existing product development system and product design practices to enable the transformation to automated assembly in a low-volume industrial context?

RQ2: How can an industrial company operating in a low-volume context best combine people, processes and technology & tools in an LPD system to optimize product development to facilitate automated assembly?

RQ3: How can the combination of Industry 4.0 and precise product information (data accuracy) contribute to more sustainable choices and improved ways of working in product development?

The three research questions are investigated through the literature, retrospective and longitudinal case studies, and interviews with case company employees involved in recent and ongoing product development projects: four main and three supportive papers answer the thesis's overall research objective. The individual research papers apply different perspectives. However, what they have in common is investigating product design and development capabilities for transformation to automated assembly in a low-volume (industrial) context. The research objective is answered by and contributes to the theoretical perspective of Lean PD and DfX, providing operational insights from product development in KM.

All four main papers have some overlapping contributions to the RQs in this thesis. The answer to the first research question (RQ1) is mainly based on data from semi-structured interviews with 18 KM respondents. These interviews and the initial LPD workshop helped identify obstacles to enabling automated assembly in the given context.

The answer to the second research question (RQ2) is mainly based on the longitudinal study presented in main papers 2 and 3, assessing company PD practice against the 13 management principles presented by Morgan and Liker (2006) and how these capabilities can improve product design and development practice in KM. As a follow-up, the effect of introducing *new* PD practices outlined for the development stage of a new, optimized tunnel thruster (TTC) for closing observed capability gaps was analysed.

In answer to the third research question (RQ3), main paper 4 presents a participatory research study of two projects in KM, aiming to autogenerate process output based on adequate data input. Main paper 4 contributes to Design for X and Industry 4.0 literature investigating concerns related to product data and digital data flow when aiming to automate and improve working practices using tools in the context of Industry 4.0. A prerequisite for digital tools to support sustainable decision-making in PD is adequate data to be available early in the PD process and throughout the entire lifecycle.

The three supportive papers have overlapping findings based on product and process development case studies, including automated assembly in KM. These findings contribute to and support answering this thesis's overarching RQs.

In total, this thesis makes nine contributions to answer the overarching research questions in this thesis. In answer to RQ1, this thesis identifies obstacles to address to transform toward more automated assembly in the given context. These obstacles include 'project-like' PD practices and heritage within existing design practices for manual assembly (C1). Moreover, it identifies obstacles in PD within the three categories of people, process, and technology & tools (C2). This thesis emphasizes making major trade-offs between Engineer-to-order (what the customer wants) and the standardization of products and components. When a prototype is sold to a customer, there is extensive work to prepare documentation and ensure quality. This can lead to point-based design focusing on the optimization of the chosen (customized) solution rather than exploring alternative solutions (C5). In answer to RQ2, main paper 1 argues that in the early design phase, company design practices must include leveraging automated assembly in terms of more conventional product and component engineering (DfX). Moreover, to carefully consider synergies within a product, product family, and product variants to facilitate standardized operations in production (C3). Main paper 2 & 3 identifies several areas that have the potential to strengthen the PD process once contextualized to the marine sector (C6). The reassessment based on new design practices in a PD benchmark project identifies six lean capability improvements and one new capability gap (C7). In answer to RQ3, this thesis identifies how product data must be made available early in the PD process and connected throughout the lifecycle through harmonization, integration, and automation to utilize digital tools efficiently and effectively (C8). The two case studies emphasize the digital thread in engineering and manufacturing as a promising start toward more data-driven and sustainable decision-making (C9).

This thesis can serve as a source for practitioners and the academic audience to understand better what product development capabilities within lean PD and engineering strategies within Design for X are relevant for the transformation towards more automated assembly in the low-volume industry context.

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1 INTRODUCTION

1.1 Background

The competitive pressure is increasing due to globalization, and companies must develop and deliver more desirable products ahead of competitors and before technology and market changes. European-based manufacturing companies cannot sustain competitive in commodity markets solely by efficiency improvements, price cuts and outsourcing. One of the most effective measures for creating competitive advantage is to improve the design and development of products and corresponding production processes for minimum cost.

Norwegian companies operating within industry sectors such as automation, shipbuilding, and ship equipment have proven to be competitive in developing and manufacturing low-volume, highly customized and knowledge-based, often assembly-intensive large and heavy products with a high degree of advanced engineering. However, manufacturing such products includes a high degree of manual labour, a challenge in Norway and other high-cost countries due to labour cost. As a result, this type of manufacturing has been frequently offshored to low-cost countries. Simultaneously, the production of complex, knowledge-based products, which require advanced engineering, strict quality requirements, and high degree of customization, remains in Norway. Even for these products, more cost-effective product realization methods must be established to strengthen long-term competitiveness.

One of the problems associated with offshoring products with a high level of advanced engineering is that it becomes challenging to bring new products to market without offshoring the engineering and other related support activities. Thus, offshoring of manufacturing will, in many cases, imply a drain of competence, first in manufacturing and subsequently in engineering. It is difficult to regain this capability at a later stage. Table 1 summarizes some of the challenges and opportunities for sustainable manufacturing in Norway.

Table 1Taking the pulse on sustainable production in Norway

CHALLENGES	OPPORTUNITIES
High labour cost	**Vertically integrated value chains** (e.g., maritime cluster Møre)
Global vs. local company strategy (Continuous evaluation of outsourcing)	**Skilled work force** at all levels. Flexibility.
Lack of investments in manufacturing (research) during the last decades (hindrance to innovation)	**Close to universities and research partners** Co-innovation with many customers.
The manufacturing industry has been suffering from the success (!) of the oil and gas industry Has created a split economy	**Industrial 'sharing economy'** – four major industrial clusters. Coopetition (complete and cooperate)
	Norwegian model (organization with flat hierarchy). Work culture: e.g., informal communication; high productivity.

This thesis presents results from case studies in the two divisions, Propulsion and Engines and Deck Machinery Motion Control in Kongsberg Maritime (KM). These two divisions were Rolls-Royce Marine up until the 1st of April 2019. They operate in the B2B market, serving customers in different markets and competitive environments. The product portfolio varies but consists primarily of large and heavy products. These products include complex, high-tech, advanced materials and components from a broad global supplier network. Products are typically produced in volumes of less than 1,000 units p.a. In-service time of a vessel and belonging products is long, and repair and maintenance are used systematically to ensure a long lifetime. In this industrial context, finding more cost-effective product realization methods is essential to ensure long-term competitive advantage. One alternative business strategy in this connection is to increase in-house production by investing in advanced production technology, reducing labour to a less significant portion of the production cost.

In the marine low-volume context, manual labour is traditionally preferred over automation. However, the development of 3D Computer Aided design (CAD) and Product Lifecycle Management (PLM) software, computer vision, sensor technology, and new programming methods will increase the use of robots in the coming years, thus making automatic assembly economically feasible in lower production volumes than in the past. For companies with limited experience in the mass production domain of automated production, it is challenging to take full advantage of such new technologies. The shift to automated production will impact engineering design practices and the knowledge basis for making viable design choices and trade-offs. Successfully utilizing new technology requires this to be considered during product design. Successful PD, including productivity improvement promised by new-to-the-company manufacturing technology, relies heavily on creating a strong interface between design and manufacturing to integrate product and process design fully.

This thesis focuses on various inter-collaborative product development (PD) processes, particularly between manufacturing and design engineering. More specifically, attempts are made to determine what changes are necessary for product design and development to enable automated assembly in the marine low-volume context. The approach towards researching this problem is made through Lean thinking, originating from Toyota. The Toyota Production System (TPS) is perhaps the most well-known example of successful production strategies systematically implemented. However, the application of Lean, especially in functions outside the manufacturing area, is not straightforward and there are only a few examples outside Toyota (Morgan & Liker, 2006). As Lean is primarily a management approach, the present problem makes it necessary to include engineering strategies as a starting point for the study. Therefore, the thesis has adopted *Design for X* (DfX) strategies to supplement Lean in identifying necessary changes in product design to enable automated assembly of low-volume marine products.

1.2 Objective and research questions

This thesis's research objective (RO) is to identify changes in product design and development capabilities necessary to facilitate a shift to automated assembly in production. Because the utilization of manufacturing technology depends on product design (Stoll, 1986) (Schuh, et al., 2016), there is a need to focus on the inter-collaborative processes, particularly between product design and manufacturing engineering. Three overarching research questions guide the thesis work:

(RQ1): **What are the obstacles of the existing product development system and product design practices to enable the transformation to automated assembly in a low-volume industrial context?**

(RQ2): **How can an industrial company operating in a low-volume context best combine people, processes and technology & tools in an LPD system to optimize product development to facilitate automated assembly?**

(RQ3): **How can the combination of Industry 4.0 and precise product information (data accuracy) contribute to more sustainable choices and improved ways of working in product development?**

Lean Product Development (LPD) views PD as a socio-technical system including the three categories' people, process and technology & tools (Hoppmann, et al., 2011) (Morgan & Liker, 2006). This system is considered an appropriate framework for data collection, aiming to answer RQ1. In addition, from an engineering perspective, it is necessary to identify obstacles concerning the product design for transformation toward more automated assembly in the low-volume industry context. In answering RQ2, the thesis seeks to analyse the operational low-volume marine context up against the framework of Morgan and Liker (2006) to identify Lean capabilities appealing to facilitate the shift to automated assembly in the given context. Thus, RQ1 and RQ2 partially overlap and can be conducted in parallel. In answering RQ3, the thesis aims to investigate concerns related to product data and digital data flow when aiming to automate and improve working practices using tools in the context of Industry 4.0. Challenges to be solved are related to sustainable manufacturing. Figure 1 gives a schematic overview of the development of the three RQs in this thesis.

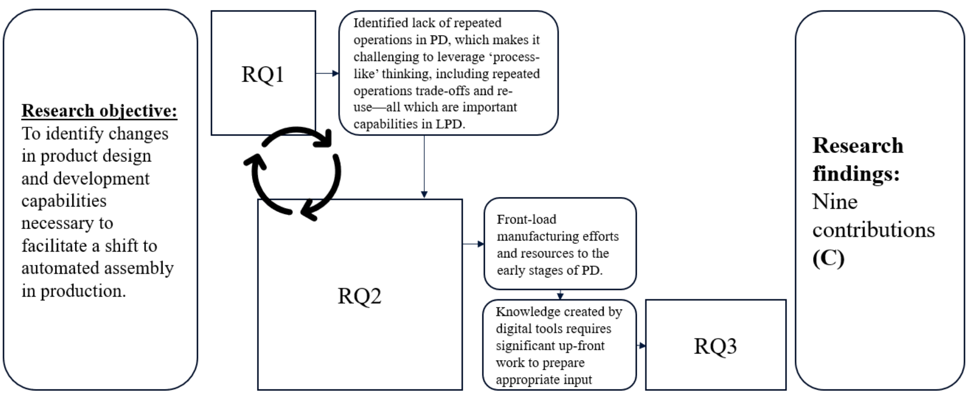

Figure 1Visualization of the development of this thesis research questions

Four main research papers answer to the thesis three overarching research questions:

- Main paper 1: Industrialization of Automated Assembly in a Marine Low-volume context: A Case Study of product development
- Main paper 2: Applicability of Lean Product Development to a company in the marine sector
- Main paper 3: Using Lean to Transform the Product Development Process in a Marine Company: A Case Study
- Main paper 4: Data-driven product optimization capabilities to enhance sustainability and environmental compliance in a marine manufacturing context

Three supportive papers are forerunners to the main papers providing additional insights to answer the three overarching research questions:

- Supportive paper 1 (Ps1): Design for Automated Assembly of large and complex products: Experiences from a marine company operating in Norway
- Supportive paper 2 (Ps2): Bridging the gap between high and low-volume production through enhancement of integrative capabilities
- Supportive paper 3 (Ps3): Enhancing Integrative Capabilities through Lean Product and Process Development

This thesis aims to make both a scientific and a practical contribution. Operational insights from product development in Kongsberg Maritime are the basis for answering the RQs in this thesis. Thus, the targeted contribution of this thesis is to identify LPD practices and engineering DfX capabilities in the marine low-volume (industrial) context appealing to enable automated assembly. The three research questions are investigated through the literature, retrospective and longitudinal case studies, and interviews with case company employees involved in recent and ongoing product development projects. Table 2 gives an overview of the thesis-specific research questions (RQ) and the nine contributions (C) from the four main papers.

Table 2 Main Paper overview to answer the thesis-specific research questions

Main Paper 1: Industrialization of Automated Assembly in a Marine Low-volume context: A Case Study of product development	
RQ1	**C1.** The study identifies obstacles to a transformation toward more automated assembly operations to address: - Heritage with existing design practices for manual assembly. - Current PD practices are 'project-like' in the sense that designs are unique to each product, which implies a lack of repeated tasks and operations in PD.
	C2. Within the *process* category, late involvement of manufacturing resources is a major obstacle. Within the *people* category, functional resources tend to reside in their functional units. Within the *tools & technology* category, value-added knowledge created by digital tools requires significant up-front work to prepare appropriate input. In addition, cross-functional engineering tools are mostly focused on design evaluation instead of proactively predicting how to avoid a particular problem in the first place.
RQ2	**C3.** To enable a transformation towards automated assembly, building the following two capabilities should be embedded in the PD system and conformed at an early stage in the PD process: 1. Leveraging automated assembly in terms of more conventional product and component engineering (DfX) and; 2. to carefully consider synergies within a specific product and across a product family to facilitate repeated and standardized operations in production.
RQ3	**C4.** Digital tools for assembly simulation, virtual testing, and verification can enable fast and efficient learning loops as a foundation for a physical assembly process. Design iterations can accordingly be performed in much shorter cycles.
Main Paper 2: Applicability of Lean Product Development to a company in the marine sector **Main Paper 3: Using Lean to Transform the Product Development Process in a Marine Company: A Case Study**	
RQ1	**C5.** The assessment made and presented in main paper 2 emphasized major trade-offs to be made between what the customer wants (ETO) and standardization of products and components. When a prototype is sold to a customer, there is extensive work to prepare documentation and ensure quality. This can lead to point-based design focusing on the optimization of the chosen (customized) solution rather than exploring alternative solutions.
RQ2	**C6.** KM's operational context was analysed against Morgan and Liker's framework (2006), including 13 LPD principles presented in their earlier study of the Toyota Product Development System. The study identifies the LPD capabilities' current and desired future state, the gap between current and future state, and the difficulty to change. Several areas can strengthen the PD process once contextualized to the marine sector. The most apparent are: - Use a set-based approach in combination with demonstrators to leverage rapid learning and optimized solutions. - Seamless integration between functional areas, especially the integration of manufacturing early in the PD process to prevent waste later in the process, e.g., design loopbacks. Avoid formal, gate-type handovers and *an over the wall approach* that can hinder the pace of the project. - Equal authority between functional units ensures that both manufacturing and design are driven as far as the other.

	C7. The (Lean) PD reassessment identified 6 improvements and 1 capability with an increased gap between the current and future state compared to the initial assessment. The capabilities relative to 6 principles remained unchanged.
Main Paper 4: Data-driven product optimization capabilities to enhance sustainability and environmental compliance in a marine manufacturing context	
RQ3	**C8.** Study of two case projects aiming to autogenerate process output based on adequate data input. Both projects demonstrate how precise product information, i.e., data quality, is key for effectively and efficiently utilizing virtual simulation of production and managing and reporting compliance, improving sustainability. Product data must be made available early in the PD process, and data must be strongly connected throughout the entire product lifecycle through *harmonization*, *integration*, and *automation*.
	C9. The two case studies emphasize the *digital thread* in engineering and manufacturing as a first step. Further focus and knowledge development include the operational and use phases of the product lifecycle. It is suggested that this is a promising start on the digital transformation journey towards more data-driven and sustainable decision-making.

1.3 Scope

This thesis investigates product design and development capabilities appealing for transformation to automated assembly in a low-volume industrial context. Krishan and Ulrich (2001) defined product development (PD) as transforming a market opportunity to available for sale. PD covers all processes concerning product concept and design where requirements are subsequently transferred into a concrete product design by increasing level of detail (Dombrowski & Schmidt, 2013). PD processes are complex; every process contains several interacting factors, such as resources, tools and methods, culture, and team members. Research on PD processes is generally conducted either from a management point of view or from a technical engineering point of view (Ottosson, et al., 2006). This thesis uses a hybrid approach, considering both the management view and the technical point of view. Lean Product Development (LPD) is a school of thought that has its origin in design, business management and social science, viewing PD as a socio-technical system (Hoppmann, et al., 2011) (Morgan & Liker, 2006). As Lean is primarily a management approach, the present problem makes it necessary to include engineering strategies to supplement Lean from an engineering point of view to answer the RQs of this thesis. Therefore, the thesis adopts *Design for X* (DfX) strategies to supplement Lean in identifying capabilities in product design that are appealing to enable automated assembly of low-volume marine products. DfX guidelines are intended as a set of recommended design practices that include design rules and implementation strategies, informing the design team of ways to optimize a design and minimize costs for the 'X' under consideration (Chiu & Kremer, 2011). Figure 2 shows a sketch indicating operationalization of integration of design for X guidelines in the PD system, with the aim of creating improved product and process design.

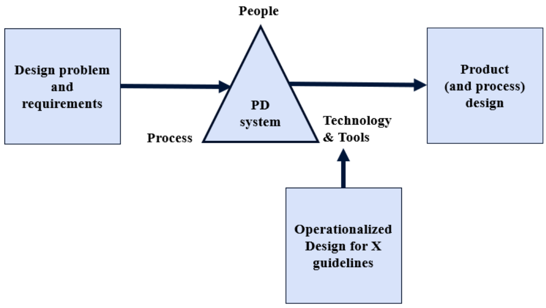

Figure 2 Sketch indicating the role of engineering practices (DfX) in the PD (management) system

This thesis uses the methods of participatory research and case study research (retrospective and longitudinal) in a single company to answer the overarching research questions in this thesis. The thesis primarily draws upon the results of four corresponding main papers. In addition, it draws upon insights from three supportive papers. Chapter 5 presents the characteristics of these seven papers. Figure 3 gives an overview of how RQs in the four main papers contribute (C) to answering the overarching RQs of this thesis and how they are connected.

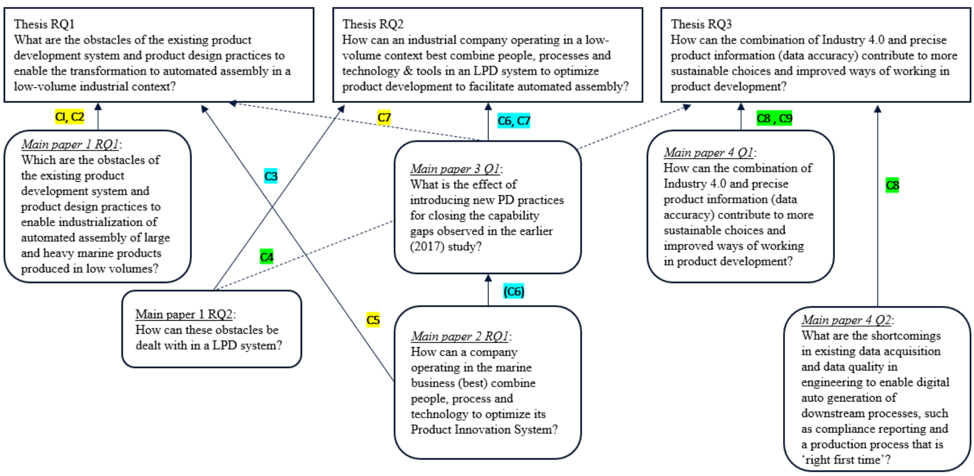

Figure 3 Main paper RQs, contributions and the connection to the overarching RQs of this thesis

Main paper 1 is based on this thesis's primary data collection process, provides input to the three RQs in this thesis, and is the main contributor to RQ1. Main papers 2 & 3 focus on appealing lean capabilities within the categories of people, process, and technology & tools to enable a shift toward more process-driven PD. The methodology used is an internal LPD assessment of case company PD practices to identify capability gaps between literature best practice and company practice. As a follow-up, a re-assessment was done based on a benchmark PD project for *new* PD practices to identify potential capability improvements. Main paper 4 investigates product and digital data flow concerns when aiming to automate company processes. The paper reports findings from two projects within the same company, intending to identify factors enabling data-driven product and process optimization.

The remainder of this thesis is organized as follows: Chapter 2 presents the research setting, including the case company and relevant research- and product development projects for this thesis. Chapter 3 presents the thesis's theoretical perspectives and serves the purpose of outlining the overall theoretical foundation. Chapter 4 presents the methodology, including datasets and validation methods. Chapter 5 presents an overview of this thesis's four main and three supportive papers, including their publication status. Chapter 6 discusses contributions from the research papers and industrial implications. Finally, Chapter 7 presents concluding remarks, limitations and future research.

2 RESEARCH SETTING

2.1 Kongsberg Maritime

Kongsberg Maritime (KM) is part of the Kongsberg group—a leading global technology corporation delivering mission-critical solutions with extreme performance for customers that operate under challenging conditions (Kongsberg, 2022). Kongsberg group is divided into three main segments: Kongsberg Digital, Kongsberg Defence & Aerospace and Kongsberg Maritime. Figure 4 gives an overview of the Kongsberg group size and scope.

Figure 4 Kongsberg group size and scope

With a portfolio of leading technologies, KM equipment is installed on over 33.000 vessels across the globe, providing a range of products from a bridge to propellers (Kongsberg, 2022). KM is involved from the planning and design phase to maintenance, service and recycling, providing a complete end-to-end service for customers. KM is divided into the following divisions: Integrated Solutions, Propulsion & Engines, Sensor & Robotics, Deck Machinery & Motion control, Global Customer Support and Global Sales & Marketing. The Deck Machinery & Motion Control and Propulsion & Engines divisions (former part of Rolls-Royce Marine) are mainly located in the Nordics.

KM seeks to increase competitive advantage by improving capabilities in automation solutions for manufacturing. Automation is believed to be an effective means of cost reductions. However, the production of large and heavy products is regarded as particularly difficult to automate from an economical perspective. The opportunity to automate production is influenced by, among other, materials, production volume and cost considerations. Deck machinery and propulsion products, as illustrated in Figure 5, are generally viewed to be outside the domain suited for automated assembly. However, introduction of new technologies makes automatic assembly economically feasible at lower production volumes than in the past. Thus, KM aims for an improved product design practice to facilitate a transformation to more automated assembly.

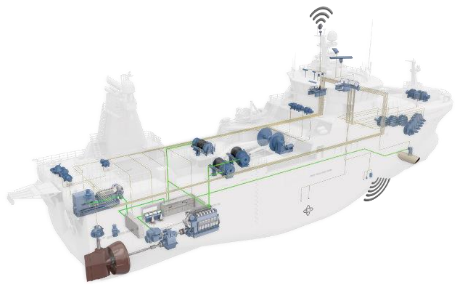

Figure 5 Deck machinery motion control and Propulsion & Engines equipment onboard a vessel

During this study, the maritime market has changed and is more dynamic than the company experienced earlier. As an example, for KM propulsion system products, the market has shifted from the offshore market towards a more complex merchant market with fewer margins. KMs competitive advantage in the offshore market has traditionally been to offer customers the most technically advanced and high-end equipment. In addition, for some KM products, the merchant market has a more considerable variation in demand than the more standardized offshore market. This shift takes place at the same time as the introduction of different and new energy solutions introduces more uncertainty in the market. As a result, the company has experienced that a new product has been designed for a market that is no longer there when the product is ready for launch. Thus, there is a need to reduce time to market by focusing on product development (PD) and design while reducing manufacturing costs and maintaining flexibility to accommodate product variants demanded by different customers.

The company defines PD as *developing an entirely new or significantly modified product or product family, from concept to defined product*. The variety of PD activities spans from product line extensions to the development of unproven technologies and processes. The company is mainly concerned with the two phases, Concept design and Product Realization in PD, see Figure 6. The process also includes an initial planning phase for innovation and opportunity selection, which is out of the scope of this research. Manufacturing involvement in the PD process is mainly through design for manufacturing (DFM) workshops, regular cross-functional meetings, and design reviews.

PD phase	**Concept design**		**Product Realization**		
	Preliminary concept	Full concept	Development	Pre-production	Production

Figure 6 High level PD process in KM

The defined product is offered in the marketplace through Engineer-To-Order (ETO) contracts. ETO refers to the strategy by which design, engineering, and production commence once a customer order is confirmed (Powell, et al., 2014). Typically, in the case company, the product's functionality is standardized and built on known technology for each ETO project, while the customization towards each ship is unique for each project.

In literature, the categorization of products is described through the customer order decoupling point (CODP); see Figure 7. The CODP is defined as *the point in the value-adding material flow that separates decisions made under uncertainty from decisions made under certainty concerning customer demand* (Rudberg & Wikner, 2004). Rudberg and Wikner (2004) adjust the typical CODP typology showing how the engineering resources can be integrated with the production process to consider the features of mass customization environments. This two-dimensional distinction between CODPs illustrates that the ETO in the purest form differs from the other three overall strategies in that the engineering work must be done for each order, while for the other strategies, the engineering work has already been carried out; i.e., the product design is in principle in stock before a customer order.

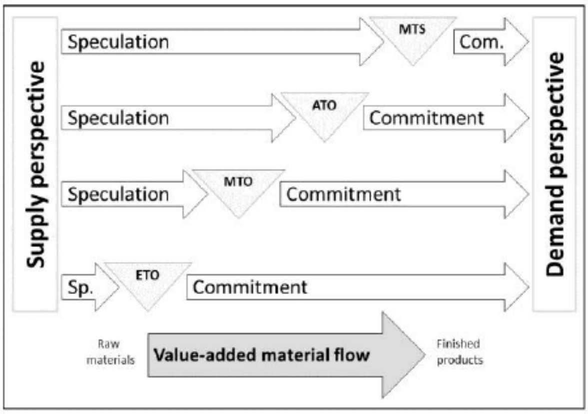

Figure 7 The customer order decoupling point reproduced from (Rudberg & Wikner, 2004)

As automation usually concerns repeating operations for volume applications, its application in the low volume manufacturing context of high value-added (ETO) products is not straightforward. It is of particular importance to find the balance between standardization and uniqueness to ensure maximum customer value. Modular design is one strategy to become more process driven and thus suitable for automation. This is a way of faster adapting to the market and run families of modules through the product development process. The work of developing modules is comprehensive, but it will be easier to make adjustments that is right for the market once modular design is in place.

ETO companies that move to *mass customization* must optimize internal processes and standardize their engineering work, e.g., pre-defining a solution space in which customized products can be configured. This requires changes, e.g., in the form of limiting the product variance, automation of engineering tasks using knowledge-based systems, and improvement of manufacturing techniques (Haug, et al., 2009).

2.2 Context of industrial research and PD projects

Throughout the work with this thesis, the researcher has accompanied both internal and external research projects and PD projects in KM. The primary ones are three externally funded research projects, *Innovasjonsprosjekt I næringslivet* (IPN), exploring automated assembly in the company context since 2012. When assessing suitable case products for the first project, it was early concluded that automating the assembly of low-volume marine products without product redesign was infeasible. A strong need for improved design practice for automated assembly in the context of KM was identified, representing the starting point for this thesis. The related in-house activities are mainly in two PD projects: Rim-driven Tunnel Thruster (RD-TT) and Tunnel Thruster Commercial (TTC). The RD-TT was named Permanent Magnet Tunnel Thruster (PM-TT) until 2022. RD-TT and TTC are case products in the IPN research projects Autoflex and DAMP, respectively. Table 3 presents the industrial goals and key findings of these IPN projects.

Table 3 Research project exploring automated assembly in the marine low-volume context (Kongsberg, 2022)

PROJECT	CASE PRODUCT	INDUSTRIAL GOALS	FINDINGS
AUTOFLEX (2012-2015)	 **Rim Drive Tunnel Thruster (RD-TT).** PM motor integrated as part of the thruster. Propeller diameter of 1600 mm and weight of more than 7,000 kg.	More cost-effective and HSE-friendly manufacturing processes of large and complex marine products.	A working industrial demonstrator for a complex assembly process. Product redesign is a key enabler.
FLEXCELL (2016)	N/A	To implement a prototype assembly cell in the existing factory.	In-house assembly cell set-up.
DAMP (2017-2020)	 **Tunnel Thruster Commercial (TTC).** Combining new (digital) knowledge with several years of experience. E.g., built on a well-proven Tunnel Thruster design modularised and simplified for optimized auxiliary use. A module unit has a weight of approximately 450 kg and has a diameter of 830 mm.	Digital integrated product and process development.	Demonstrated the process from a virtual product and process model to a physical automated assembly process.

Autoflex – Flexible automated manufacturing of large and complex products

The Autoflex project`s main idea was to develop cost-effective and Health Safety & Environment (HSE) – efficient methods for developing, engineering, and manufacturing low-volume, customized, assembly-intensive, large, and complex products (Sintef, 2015). This includes developing automated manufacturing and assembly solutions for products and tasks that are generally viewed as outside the traditional automation domain.

The project was a cross-sectorial collaborative research effort between maritime and automotive companies and originated in the SFI Norman (2007-2014) consortium (Sintef, 2013). The Autoflex project had three industrial partners and one R&D partner:

- Rolls-Royce Marine (now Kongsberg Maritime),
- Benteler Aluminium Systems – an automotive parts supplier providing lightweight (aluminium) structures such as bumpers and wheel suspension,
- Intek Engineering – an engineering and automated manufacturing equipment supplier, whose role in the project was as systems integrator,
- Sintef Raufoss Manufacturing – R&D partner in the project.

Substantial work was put into a new, more automation-friendly design of the chosen KM demonstrator and case product (RD-TT). The project's goal of achieving a functional physical demonstrator for a complex assembly process in only two years was motivated by KMs vision for a future automated manufacturing and assembly of the case product, which was communicated in an animated movie. A product redesign was a vital part of the project challenge. KMs vision provided a framework for all participating professionals and researchers in multiple disciplines to develop flexible and practical solutions. The first business case for automated assembly of the new RD-TT showed promising results, indicating a significant reduction in hourly costs and substantial cost savings for materials. Both hours and material cost savings are uniquely due to the product redesign and the assembly process automation.

The use of virtual manufacturing technologies and *Augmented Reality*, combined with automated programming methods from CAD models of the products to a simulation of the assembly process, has significantly reduced the lead time from design to assembly verification. The frequency of design iterations in product and process development has increased. One iteration can be performed in hours compared to physical iterations that take days or weeks. At the same time, the product-specific machine code needed to perform the physical manufacturing was generated automatically with the aid of digital tools in design.

The research project delivered a demonstrator for KM, including product re-design, automated solutions to achieve tight assembly tolerances, and a physical robot assembly cell.

FlexCell – Flexible Assembly Cell for Permanent Magnet Machine

The Flexcell project was an extension of the Autoflex project established to support the industrialization of the Autoflex assembly cell. Flexcell aimed to *demonstrate that the Autoflex-concept can function in a real factory environment and build competence in automated production* within the engineering and manufacturing departments (Flexcell, 2016).

The project had one industrial partner and one research partner:

- Rolls-Royce Marine (now KM),
- Sintef Raufoss Manufacutring – R&D partner in the project.

A robotized cell was implemented at the Rolls-Royce Marine's (now KM) site in Ulsteinvik for *Permanent Magnet* (PM) thrusters based on the robot cell developed in Autoflex. In addition to setting up the physical cell, the main project task was to develop a solution aligned with the existing IT infrastructure. The tool selected was *Process Simulate*, which is part of the Siemens Teamcenter package.

For KM, this project has built in-house competence in robotics and automation and provided a robust basis for further industrialization of automated assembly of company products.

DAMP – Fast Development of new Automated Manufacturing Processes through digital integration and testing

The objective of the DAMP research project was to reduce the programming component of building a robotic system, including reduced preparation time and product realization cost. For KM's different products, there are many relatively similar operations, but the robot path will vary due to size. Another important aim was to reduce lead time in the development process through digital integration and testing. Digital simulation, virtual testing, and verifications provide a basis for fast and efficient learning loops. In the DAMP project, efforts were made to get as quickly and effectively as possible from a) a digital product twin to b) a simulated assembly process to c) a digital process twin that can be transferred directly to the physical robotic assembly cell and run there.

The project had one industrial partner and two research partners:

- Kongsberg Maritime CM AS,
- Sintef Manufacturing (research partner),
- Sintef Digital (research partner).

The chosen case product is Tunnel Thruster Commercial (TTC), a modularized thruster based on standardized components. Based on the results from Autoflex, this product is better suited for automated assembly than other existing company products. In addition, the project results resulted in a more cost-competitive product. The TTC module assembly includes:

- Two collaborative robots,
- sensor technology for calibration and force transducer technology,
- flexible grippers and tools that are developed in-house.

A demo of the main sequence from the CAD model to a virtual robot assembly process for a TTC module was demonstrated in October 2020.

This project has contributed to the following benefits for KM:

- Reducing cost and lead time in developing new products and processes for KM,
- reducing the risk of costly changes late in the development process,
- flexible manufacturing concerning reuse, project-specific investments, and reduced factory floor footprint.

3 THEORY

3.1 Lean Product Development

The flow of information and decision-making in PD is crucial for successfully implementing new design tools and capabilities. However, this broad topic includes processes, tools, procedures, working models and methods. Several schools of Thought (ST) exist in the literature for product and process development strategies and methodologies. Wynn and Clarkson (2018) review Design and Development Process (DDP) models and clarifies their relationships. The design and development process involves many interrelated issues, and each DDP model embodies a particular viewpoint. A state-of-the-art understanding of a DDP and best practice is not embodied in any one model – but in the set of models and the relationships between them (Wynn & Clarkson, 2018).

Lean Product Development (LPD) is an ST originating from design, business management and social science, viewing PD as a socio-technical system (Hoppmann, et al., 2011). What we today know as LPD is mainly derived from the Toyota Production System in the 1980s, and the legacy of manufacturing optimization is present in the LPD framework (Ward, 2007). In this thesis, the works of Morgan and Liker (2006), Liker and Morgan (2006) (2011), Kennedy (2003) (Kennedy, et al., 2008), Ward (2007), Sobek (Sobek, et al., 1999), and other influential scholars in the field of Lean PD and engineering have been studied. Positioning key models of design and development within a framework, Wynn and Clarkson (2018) place SBCE, LeanPPD, and the Toyota Product Development system as macro-level procedural models. Procedural models convey best practices to guide real-world situations, and a macro-model focus on project structures and design process in context (Wynn & Clarkson, 2018).

Studies conducted in the 90s emphasized simultaneous development and supplier involvement as the main reasons for superior performance of Japanese car manufacturers compared to European and North American car manufacturers in PD concerning engineering hours and lead time (Hoppmann, et al., 2011). These reasons were challenged by Ward et al. (1995), pointing out that the best in class, Toyota, neither collocated its teams nor intensively communicated with its suppliers. Paradoxically, in the case of Toyota, delaying decisions and following many alternatives for the product module contributed to better and faster product development. This was the basis for developing the term Set-Based Concurrent Engineering (SBCE) (Ward, et al., 1995). The theory of SBCE was a strong impulse for the revision and expansion of existing LPD concepts. In the following years, Kennedy (2003) emphasized 'SBCE', 'system designer entrepreneurial leadership', 'responsibility-based planning and control', and 'an expert engineering workforce' as critical elements of Lean PD. Similarly, Ward and Sobek (2014) describe a Lean PD system consisting of five major principles: 'value focus', 'entrepreneur system designer', SBCE, 'cadence, flow and pull' and 'a team of responsible experts'.

Morgan conducted a two-and-a-half-year, in-depth study of Toyota`s PD system, aiming to identify the underlying characteristics making Toyota`s PD approach so successful. In 2006, Morgan, together with Liker, who was also extensively involved in the investigation of SBCE, presented 13 management principles, which can be considered as a foundation for LPD, emphasizing a system`s model where all principles are supportive without being mutually exclusive (Morgan & Liker, 2006). The core idea of these principles is to reduce variation while preserving creativity in PD. The former is closely connected to standardization, providing the foundation for Toyota to develop smart solutions to traditionally highly cyclic resource demands inherent in most PD systems. The framework of principles, divided into the three categories of *people*, *process* and *tools & technology*, is central to this thesis.

In brief, the people category includes a Chief Engineer system as a systems integrator from concept to production launch, along with a matrix organization that allows technical specialists to reside in functional units (Liker & Morgan, 2006). The Chief Engineer serves as the technical voice of the customer throughout the entire process, from concept to market release (Qudrat-Ullah, et al., 2012). Cross-functional development teams support the Chief Engineer in keeping an overview of the project (Al-Ashaab, et al., 2015). The process category of the framework focuses on precise cross-functional integration, including SBCE and front-loading in the development process. Unlike a point-based design strategy, SBCE successively excludes the weaker, non-feasible solutions by identifying limits and constraints (Sobek, et al., 1999). The design team gradually narrows the respective sets of solutions based on the knowledge gained through simulations, prototyping and testing (Sobek, et al., 1999). Finally, the tools & technology category of Morgan and Liker's framework of principles includes tools such as Computer-Aided Design (CAD) and Computer-Aided Engineering (CAE) with a strong focus on standardization and visualization.

The insights of Liker and Morgan`s (2006) research indicate that changes made to one subsystem will always have implications for the other. According to a literature review on Lean Engineering by Baines et al. (2006), successful implementation of lean requires organization-wide changes to systems, practices and behaviours. Hence, more is needed than implementing a few lean tools since achieving leanness in PD requires transformation into a *learning organization* (Liker & Morgan, 2006). The ability to learn and improve is perhaps a company`s most sustainable competitive advantage. For example, the knowledge and skills generated while working with multiple ideas will pay off later, either directly through incorporation into the next project or indirectly through expanded skill sets and knowledge (Liker & Morgan, 2006).

In their research, Hoppman et al. (2011) systematically investigate overlaps between components in an LPD framework, aiming to combine them to achieve a robust definition of Lean PD. The framework is built on 13 publications meeting the criteria of explicitly mentioning the keywords *Lean Product Development*, *Lean Development* and *Lean Innovation* and describing at least one LPD system component. The only approach that comprises all eleven components building the framework is the comprehensive approach by Morgan and Liker (2006). Similarly, Welo (2011) presents a model of lean practices in PD that includes six essential components. With a basis in this model, an assessment tool of lean practices was used with chosen companies to identify areas where lean PD provides more significant potential for payback. The purpose was to make LPD more applicable to companies that develop high-end products. Considering the application of lean principles in PD, the greater potential lies in extending lean principles into methodologies for more radical product innovations, focusing on knowledge as the common denominator. Welo (2011) concludes that although several authors and researchers have made significant contributions to the prior art by transforming lean principles into several characteristics applicable to PD, there is no standard model or recipe for application in PD. Welo (2011) argues that this is because lean being more a philosophy than a technique or a method, especially when applied to PD. In their studies of Toyota, Liker & Morgan (2011) argue that implementing a tool itself will not transform PD; it is as much about how people are managed and developed as a technical methodology.

According to Al-Ashaab et al. (2015), it is recommended to measure the initial leanness of the enterprise and their desired level of employment of lean practices before the actual implementation of lean in PD. Al-Ashaab et al. (2015) present the development and application of a tool that helps identify the actual status of the organization concerning the lean principles as presented in the conceptual Lean Product and Process Development (LeanPPD) model with enablers by (Khan, et al., 2011), see Figure 8. Also, in this model, SBCE is considered an essential component representing the process that guides LPD under the support of four components.

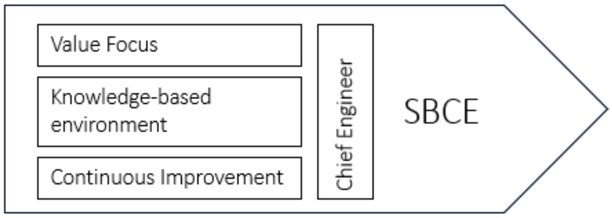

Figure 8 Conceptual LeanPPD model with enablers reproduced from (Khan, et al., 2011)

Improving PD capabilities based on Lean theory seems promising to support the transformation required to enable more automated assembly in the low-volume marine context. In particular, the LPD system, as presented by Morgan and Liker (2006), is considered in preparing and answering RQ1 and RQ2.

RQ1: What are the obstacles of the existing product development system and product design practices to enable the transformation to automated assembly in a low-volume industrial context?

RQ2: How can an industrial company operating in a low-volume context best combine people, processes and technology & tools in an LPD system to optimize product development to facilitate automated assembly?

3.2 Design for X

The outcome for any 'X' starts with the product design. Design for X (DfX) represents a series of target-oriented design methodologies that assists designers when developing products (Benabdellah, et al., 2019). DfX approaches typically deliver specific recommendations for a specific property (cost, quality, environment) or stage in the product life cycle (manufacturing and assembly) (Schuh, et al., 2016) (Dombrowski & Schmidt, 2013). Design for X-capabilities is an integral part of an interconnected product realization process (Prasad, 2016) and highlights optimization aspects of design (Tichem, 1997). The effort to design products and processes for cost-effective, high-quality downstream operations from design and manufacture to disposal is a concurrent and integrated approach. The concept of DfX emphasizes the need to investigate the effects of design decisions as early as possible (Kuo, et al., 2001). Several studies indicate that while the design stage takes a short period in a product life cycle, it dictates around 70-80% of product lifecycle cost (Chiu & Kremer, 2011).

The literature concerns both philosophical and methodological aspects associated with the DfX concept and engineering knowledge formalization. The most common concepts are design for manufacturing (DFM) and design for assembly (DFA), which involve simultaneous considerations of design goals and manufacturing constraints (Prasad, et al., 2008). The works of Bralla (1999), Eskilander (2001), Groover (2014), Boothroyd et al. (2011), Dombrowski & Schmidt (2013), and Dombrowski et al. (2014) and other influential scholars in the field of DfX and Design for Manufacturing and Assembly (DFMA) are studied in work with this thesis.

DfX support can be design guidelines, stand-alone evaluation tools, and software programs. Design guidelines for good design practice are derived empirically from experience. These embody the concurrent engineering philosophy of considering the downstream impact of decisions being made (Prasad, et al., 2008) (Edwards, 2002). According to Chiu & Kremer (2011), DfX guidelines are intended as a set of recommended design practices that include broad design rules and specific implementation strategies, informing the design team of ways to optimize a design and to minimize costs for the 'X' under consideration. The primary sources of design guidelines include literature, direct experiences of practicing designers and established best design practices in engineering organisations. The two last sources are less accessible (Edwards, 2002), not always formally captured in design guidelines, and often related to a specific context or process. The applicability of design guidelines must be questioned in the context of the conditions of the company (Fiksel, 2009). Design guidelines can evolve and be applied to specific company issues and infrastructure. These guidelines then become organizational knowledge of the company (Sassanelli, et al., 2018) and enable compliance with companies' internal constraints. A CAD-integrated tool analyses the design and provides feedback to the designer. In addition, it allows for automating the interpretation of the design and the evaluation steps. CAD-integrated tools are often applied at the more detailed stages of design, which makes them more suitable for DFM than DFA since DFM considerations require relatively detailed product information (Tichem, 1997). However, Favi et al. (2022) emphasize that there still is a gap in the state-of-the-art CAD-integrated DfX methods and tools and the opportunity to share engineering knowledge in the early PD phases. Despite the long history of DfX methods in engineering design, these methodologies need more real integration of tools and computer-aided systems (Favi, et al., 2018).

Design for Manufacturing and Assembly (DFMA), as presented by Boothroyd et al. (2011), is commonly known as a methodological procedure for evaluating and improving product design for manufacturing and assembly and is one of the most well-known DfX approaches. According to Boothroyd (1994), design for assembly (DFA) should always be the first consideration, leading to simplification of the product structure. The economic selection of materials and processes and early cost estimates follow this. In this process, cost estimates for the original and new (or improved) designs will be compared to make trade-offs. Once the materials and processes have been decided, a more thorough design for manufacturing (DFM) analysis can be carried out for the detailed design of parts. Figure 9 illustrates the typical DFMA process as described by (Boothroyd, 1994).

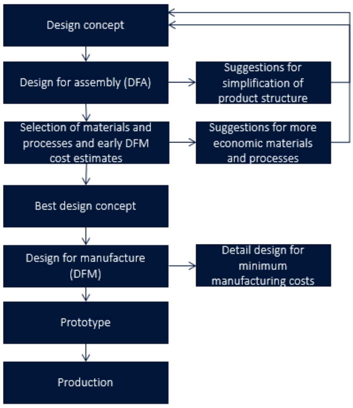

Figure 9 Typical steps taken in the DFMA process inspired by Boothroyd (1994)

Most of the first efforts to develop systematic procedures for assembly analysis concentrated on product design for ease of automatic assembly. When a company was anxious to automate assembly, it was forced to reconsider its design (Boothroyd, 1994). As a starting point for automated assembly, Eskilander (2001) emphasizes modularization of the product. Modular design simplifies final assembly because fewer parts must be assembled, and each module can be fully tested before installation. Eskilander's (2001) Design for Automated Assembly (DFA2) method consists of structured design rules at the product and part levels.

Product design and development in low-volume production is often characterized by an extensive focus on the functionality of the products instead of their manufacturability (Javadi, 2015). According to Bralla (1999), design guidelines are also helpful in a low-volume production context, although the application strategy will vary from those used in a high-volume production context. In low-volume production, significant upfront investments are more difficult to justify due to the cost of tooling, the cost and lead time for the development of the manufacturing process, and the selection of production equipment and materials (Bralla, 1999). On the other hand, design guidelines also consider synergies between product portfolio products that can be developed, for example, by using a modular structure or common parts in different products (Dombrowski & Schmidt, 2013). Hence, opportunities remain in how low-volume production can be standardized for a product, a product family, and product variants to enable knowledge reuse in product and process design.

External drivers such as environmental sustainability and the introduction of new materials and technologies influence the way products are designed and developed. The design is often constrained by the fabrication method, which implies that a new manufacturing technology will create a so-called technology push in design. An example is 3D printed parts, which facilitate lighter parts and improved material utilization, provided that the design fully utilizes the opportunities of the processing process. Accordingly, the DfX literature evolves based on trends such as eco-design and environmental sustainability, see e.g., Design for Additive Manufacturing (see Thompson et al. (2016)), Design for Environment (see Liu & Boyle (2009)) and Design for disassembly (see Soh et al. (2014)). Schuh et al. (2016) present a Design for Industrie 4.0 framework as existing DfX approaches are no longer entirely relevant in this new context and must be supplemented by different aspects and elements. For example, products in the context of Industry 4.0 must provide the capability to be maintained from a distance. Madappilly & Mork (2021) shed light on the potential modifications that can be done to an existing DfX method depending on the needs of a particular industry. They discuss the DFA2 methodology in the maritime industry, suggesting prioritization of the design rules and additional product-level rules to be added for the maritime industry.

Large and heavy low-volume marine products are seldom designed with automated assembly in mind. Accordingly, there is a need to also investigate the changes and capabilities needed in engineering design practices and knowledge formalization to support the transformation to automated assembly in the given context. DfX is supplementing lean from an engineering point of view aiming to answer RQ1 and RQ2.

3.3 Industry 4.0

Figure 10 illustrates the industrial evolution in terms of four industrial revolutions. The first revolution came when mechanical production started, enabled by water and steam power. Mass production and assembly lines enabled by electricity represented the second revolution. The third revolution was the utilization of computers for the automation of manufacturing. The revolution currently taking place is Industry 4.0. Because of this paradigm shift, manufacturers must challenge their assumptions regarding their traditional design processes and practices. Over the last decade, there has been a high focus on outsourcing in high-cost countries, and companies in the marine low-volume context are barely at Industry 3.0. How Industry 4.0 technologies can be integrated into existing production environments and the processes they can support are still under investigation (Kolberg & Zühlke, 2015). Industry 4.0, from a manufacturing perspective, also affects the entire organization and cannot be fully separated, despite technology`s direct influence and implementation in manufacturing. According to a Roland Berger report (Blanchet, et al., 2014), it is expected that businesses in Industry 4.0 need both enhanced social and technical skills. Organizational learning and social and technical skills become increasingly important since realizing value is likely to depend more on integrative capabilities than on the invention and implementation of new technology and tools (Blanchet et al., 2014).

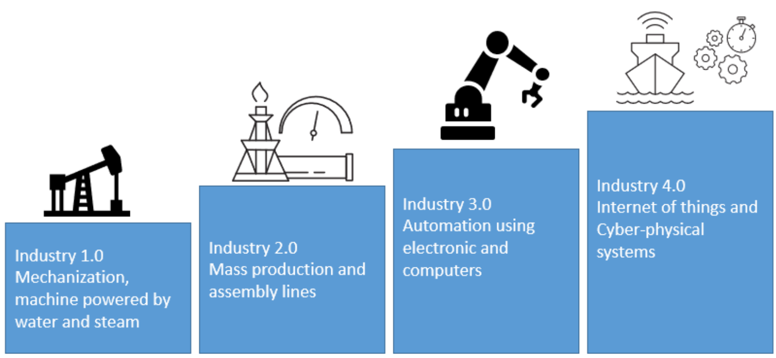

Figure 10 Industrial evolution inspired by Ellingsen (2019)

Industry 4.0 is regarded as service-centred and oriented toward digital and virtual technologies. It addresses the interconnection of machines, people and products. It is driven by real-time data interchange and flexible manufacturing, enabling customized production. Industry 4.0 can be understood through its fundamental components, cyber-physical systems (CPS), internet of things (IoT), cloud manufacturing, and additive manufacturing. CPS systems and IoT are higher-tier technologies depending on sensors, networking processes, protocols, cloud, operations technologies, and human components (Santos & Martinho, 2020). Consistently, the deployment of higher-tier technologies of Industry 4.0 relies on a strategic and staged roadmap complemented with a certain degree of digital transformation maturity and readiness (Santos & Martinho, 2020). Industry 4.0 is also viewed as a strategy designed to build a communication system between production equipment and products through a connected *Smart factory*. Such a connected smart factory is defined as *a hyper-connected network-based, integrated manufacturing system that promotes the monitoring and autonomous control of all processes, replacing raw materials and preventing waste of supplies and energy and adding value and coordinating synergy of products and services, all underpinning low-cost, high-variety and flexible production* (Park, 2016).

Schuh et al. (2016) focus on four main PD challenges that must be faced in the context of Industry 4.0:

- *Orientation*: Products that have been *stupid* in the past will be connected in the future. This means intelligent products that can communicate with each other.
- *Data*: There needs to be a systematic approach for collecting and analyzing high-resolution data for products and PD. Transport times, position data etc. can be tracked in production by, for example, RFID.
- *Interaction*: New mechanisms and ways of interacting must be defined to ensure contact with the product throughout the entire life cycle.
- *Resources*: The resources for merging the physical and virtual worlds must be defined and organized. For example, complex and heterogeneous IT structures prevent the full implementation of the potential benefits. (Schuh, et al., 2016)

The physical or virtual realization of prototypes is necessary for early feedback loops and the integration of customers into the development process (Schuh, et al., 2016). The *build-it-and-tweak-it* approach that has characterized many design projects can no longer be afforded. Instead, these projects must take a more system design approach that has proven to be an essential part of the design process within the aerospace and automotive industry for several years (Goossens, 2017). Through formal requirements management and the development of realistic dynamic models used in system simulations, the design can be validated against the requirements early in the PD process (Goossens, 2017). This so-called Virtual Engineering is claimed to enable intuitive interaction with the object. It is decision-oriented, and it works in real-time (Schuh, et al., 2016). The *digital twin* is a virtual (and simultaneous) representation of physical components, systems, and processes. The digital twin reproduces the state and behaviour of systems and products to optimize performance by combining the real and the digital world (Akanmu, et al., 2021). In the early phase of PD, data on the usage of the product reveals essential information on the usefulness of different functions or design elements. Building a *digital twin* of every product in the field is a step towards data-driven product optimization. However, collecting valuable data often requires using cost-effective active sensors (Schuh, et al., 2016).

The sustainability discipline holds high hopes for the contribution of Industry 4.0 to environmental preservation. This contribution mainly includes resource consumption, waste, and emission reduction. The alignment of sustainability with Industry 4.0 forms a recent line of knowledge called *Sustainability 4.0*, which can be understood as a strategy to support achieving a state of sustainability through intelligent technologies to meet a balanced development of economic, environmental, and social demands (Reis, et al., 2021). Implementing enabling technologies for Industry 4.0 provides 'intelligence' to production processes. It can improve the conditions of sustainability in production by increasing energy efficiency, reducing production costs, promoting more excellent connectivity, and reducing environmental impacts (Reis, et al., 2021).

Industry 4.0 can contribute to improved ways of working in PD. Building on the strengths promised by digitalization and automation requires precise and extensive product and process information. As new (*Industry 4.0*) technology becomes available and customer and regulative expectations change (*Sustainability 4.0*), there is a need to adapt the product development system accordingly. Industry 4.0 literature corresponds to RQ3 in this thesis:

RQ3: How can the combination of Industry 4.0 and precise product information (data accuracy) contribute to more sustainable choices and improved ways of working in product development?

4 METHODOLOGY

4.1 Research approach

This section will provide an overall rationale of this thesis's methodical approach, research design, and ethical reflections. The RO is to identify changes in product design and development that are necessary to facilitate a shift to automated assembly in production. The initial phase of this thesis work started with iteratively reviewing the literature to identify critical knowledge gaps and phenomena that fit with the RO of this thesis. Literature can guide in several directions regarding improving product design and development practices for automated assembly. This research aims for a holistic approach viewing PD as a system while including engineering strategies for DfX. The research questions are posed in response to literature gaps and are validated to be relevant to the industry. The goal is to provide an in-dept understanding of what product development capabilities are needed for a transformation towards automated assembly for a company operating in the low-volume marine context. Due to the thesis's relation to a real industrial context, a qualitative case design was identified as fit for the purpose (Yin, 2014).

Managing PD processes is complex as they change with time and often in an unplanned or unforeseen manner. Every PD process is unique, meaning theories cannot be proved true or false in a traditional fashion (Andreassen, 2003). Ottosson et al. (2006) discuss different research approaches to PD processes, emphasizing *action-oriented research* as a suitable approach due to closeness and presence. In addition, to make qualitative studies having an insider position enables one to understand what happens in the development project, reflect upon it, contribute to the knowledge of PD, and give recommendations on developing products better (Ottosson, et al., 2006).

Table 4 presents the Design Research Methodology, indicating the flow from problem formulation to problem validation for this study. Section 4.2 describes the qualitative study, and Section 4.3 discuss validity and reliability of this study.

Table 4 Design Research methodology inspired by (Jilcha, 2019)

Input	Methodology steps	Output
Automated assembly exploration activities in KM identified a need for research competence in product design and development capabilities for transformation to automated assembly in a low-volume industry context.	**Gap identification**	Developing research objective.
• Consultation with supervisor and internal company experts. • Justification of research objective.	**Formulation of research objective**	• Literature gaps and assumptions. • Research objective definition.
• Literature familiarization.	**Theoretical background**	• Gap identification. • Framework for interview guide and LPD assessment (Morgan and Liker). • Three overarching research questions.
• Research design. • Preparation of three data collection sets (A, B and C).	**Research design and methodology**	• Gap identification. • Framework for interview guide and LPD assessment (Morgan and Liker). • Three overarching research questions.
• Population and sample size for interviews and workshops. • Case study area: IMM proof of concept and DAMP research project.	**Data collection, analysis, and presentation**	• Interview transcription, • workshop and case study documentation, • assessments and analysis of results.
Result discussion.	**Discussion and synthesis of results**	Research findings.
Developing concluding remarks.	**Conclusion and recommendation**	Recommendation further work.

4.2 Qualitative study

The principle of triangulation was applied to both the data sources and the data collection method to strengthen the study's validity (Patton, 2015). In triangulation, the researcher interacts with the studied situation and intends to change it. The data sources in this study included project managers (PMs), manufacturing engineers (ME), and design engineers (DE) employed in PD operations in the case company both in the present and in the past. This thesis consists of three datasets collected over eight years. Throughout the research study, the datasets were triangulated, which contributed to developing the theoretical saturation of the data (Fusch & Ness, 2015). Employing multiple data sources through triangulation increases the reliability of results (Denzin, 2012). The datasets are reviewed chronologically, and their characteristics are presented in Table 5.

Table 5 Qualitative data collection overview

DATASET	A	B	C
Focus area	To identify enablers and obstacles in PD for transformation to automated assembly.	(Lean) Product Development capabilities assessment.	Required data quality to automate and improve working practices and decision making in PD.
Method	Semi-structured interviews.	Participatory research. LPD company assessment and workshops.	Case study and participatory research of digital transformation projects: DAMP and Integrated materials management.
Purpose	Understand obstacles and enablers in the company PD system for industrialization with automated assembly.	Identify gaps between company and literature best practices, including the company`s desired future state.	Investigate how Industry 4.0 technology strategies, considered helpful in automating and improving working practices, can be utilized in (the context of) KM.
Literature	Lean Product Development and Design for X.	Lean Product Development.	Industry 4.0 and Design for X.
Paper	1	2 & 3	1 & 4

The motivation for dataset A – *semi-structured interviews* – was to perform a qualitative study to map factors that impacts how to achieve an improved design practice for automated assembly in the low-volume (industrial) context. This includes identifying enabling and restraining factors based on experience in the company. The university and company supervisors contributed to developing the research design and interview guide. Individual experiences of the people involved in PD projects were essential for the study, meaning that interviewing was considered an appropriate method of collecting data (Yin, 2014).

Respondent selection from the two divisions, Propulsion & Engines and Deck Machinery & Motion control, was based on input from KM employees to define a representative sample out of the company population. The respondents were nominated by representatives from the two divisions based on the main criteria that they recently participated in product development projects in KM. The respondents held either of the following three roles: Design Engineer (DE), Manufacturing Engineer (ME), or Project management (PM). An interview request was sent to 23 persons, resulting in 18 interviews (two PMs, nine DEs, and seven MEs). Respondents were mainly based in Norway, with a few in Finland and Sweden. Interviews were conducted at the end of 2017 and the spring of 2018. Table 6 summarizes characteristics associated with the interviews.

Table 6 Interview characteristics overview

Interviews	Amount of data	Role	Documentation
Semi-structured interviews with case company employees.	18 interviews.	Project management (2), Design Engineer (9), Manufacutring Engineer (7).	
Group interview with research partner.	One group interview with three respondents.	PLM experts (2), Manufacturing strategy expert (1).	Transcription of recorded interviews. Presentations and reports sent from respondents.
Interview to get in-depth understanding of manufacturing development projects.	One group interview and three individual interviews.	Manufacturing Engineer (1), Project management (3), Design Engineer (1).	

The interview guide for semi-structured interviews is enclosed in Appendix 3. The face-to-face interviews between the author of this thesis and each interviewee took place at different KM locations. Three of the interviews were conducted over the phone. Most of the interviews lasted for approximately one hour. All interviews were recorded, transcribed, and analysed. In addition, one group interview with respondents from one central research partner, which has worked closely with the company to implement automated assembly design activities, was conducted.

The sample of dataset B – *Participatory research, LPD company assessment and workshops* – were identified based on the need to close PD capability gaps towards LPD best practice. The data collection was arranged in the form of a series of workshops. The input from key internal stakeholders provided deep insights from PD projects in the case company. The overall purpose of the workshops was to assess company practice against the 13 management principles presented by Morgan and Liker (2006). This longitudinal study can be divided into two main phases, as illustrated in Figure 11.

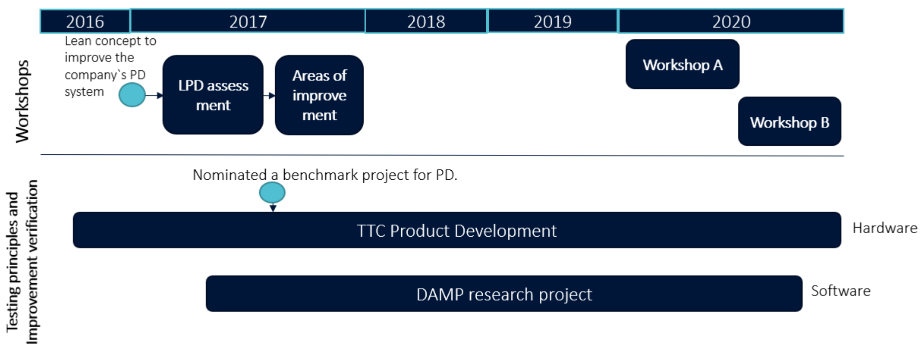

Figure 11 LPD assessments and workshops

Phase 1: An assessment sheet with the 13 Lean management principles was sent out to the three workshop participants for individual scoring regarding the current and desired future state in June 2017. The study included a project manager, a design engineer, and a manufacturing engineer. The assessment sheets were collected and analysed prior to a physical workshop. The *LPD assessment scorecard* is enclosed in Appendix 4. As a follow-up, a two-hour workshop was held to analyse the material and discuss results from the assessment sheets to agree upon a common final scoring relative to the LPD principles. After the workshop, each attendee was allowed to review the result and provide additional input. Findings from this workshop are presented in detail in main paper 2.

Phase 2: A new thruster product development project was launched in 2016. It was defined as a benchmark project for new PD practices in KM. As a follow-up on the initial LPD assessment, two half-day workshops with two key stakeholders, a manufacturing engineer, and a design engineer, involved in the benchmark project were held remotely on Teams in November 2020. One of the participants also contributed to Phase 1. Experience from the DAMP research project was used as a reference in workshops A and B.

Workshop A focused on best practice PD, particularly in the front end of the PD benchmark project and the efforts required to deliver demonstrators of technical solutions and industrialization. The baseline for the workshop discussion was three opportunities identified in main paper 2. Workshop B revisited the 2017 assessment and rescored it based on experiences from the benchmark project. The workshop sought to answer if new design practices outlined for the PD benchmark project could close the capability gap relative to the LPD principles outlined by Morgan and Liker. The author of this thesis led all the above workshops.

The motivation for dataset C – *case study and participatory research of digital transformation projects* – was to collect operational data from ongoing activities in the case company. The topic of concern was an exploration of automated assembly and digital transformation activities with a focus on understanding how data can improve PD processes. A *participatory research* approach was used to study two projects that are part of the company`s digital business transformation initiative aiming to digitalize and autogenerate downstream processes. The first case study (2017-2020) focused on developing cost-effective, new, and automated processes depending on the automation level. The underlying idea was to develop new automated manufacturing processes significantly faster through digital integration and testing. Design Engineers (3), Manufacturing Engineers (3), CAD experts (2), and external production technology and PLM experts (3) made up the core team. The second project (autumn 2021) investigated how data quality impacts the opportunity to autogenerate compliance reporting and facilitate sustainable choices in early product development. The core team participants were an IT PLM expert, a Development Engineer, a Design Engineer, an Engineering Operations Lead, a Supplier Technical Engineer, and external PLM experts (2).

Datasets also consist of insights based on secondary data, such as reports and workshops. Secondary data include Design for Manufacturing workshops (as part of Autoflex and the TTC projects), value stream mapping of the PD process, project meetings, and a product design review. The internal company supervisor helped facilitate participation in these activities. In addition, multiple discussions with colleagues enlightened the research objective from different angles. Notes from both formal and informal meetings were analysed and used for overall problem understanding.

Table 7 presents enablers for the automated assembly of the RD-TT demonstrated in Autoflex. The results were part of the presentation of Supportive paper 1 at the CSER conference (Conference on Systems Engineering Research) in 2015. These statements are based on correspondence and informal interviews with project participants to clarify what has been achieved.

Table 7 Unstructured interviews with Autoflex project team members

Statements Autoflex/RD-TT enabler`s	How	Interviewee
Small adjustments to product design to facilitate automated assembly with minimum impact on product function **can have a huge impact on production and quality cost**. Provided examples of DFAA.	Informal interview.	Mechanical designer (System integrator)
Design the product for common tooling and equipment. Standardization is key, especially in low-volume production due to cost.	E-mail correspondence and interview.	Special adviser (research partner)
Early process simulation leads to leaner product and process development. Simulations supporting corrective action to be taken before investments.	Informal interview.	Manufacturing Engineer (internal)
Reduce the need for geometric precision Use **simple tools**	E-mail correspondence and interview.	Mechanical designer (System Integrator)
Weekly 'war room' meetings ensured a common understanding of problems. Functional **requirements had to meet up with manufacturing** solutions—and vice versa.	Informal interview.	Manufacturing Engineer (internal)
Benefits of **automation-friendly components became an eye opener** for engineering.	E-mail survey.	Manufacturing Engineer (internal)

4.3 Validity and reliability

The following acknowledged types of validity were considered to assess the rigour of the theoretical contributions: Construct validity, internal validity, external validity, and reliability (Yin, 2014). These four tests have been commonly used to establish the quality of empirical research. These tests are also relevant to case study research.

There are three datasets used to answer the research questions in this thesis. Using multiple sources of evidence encourages convergent lines of inquiry, which is relevant during data collection. The triangulation principle is used to verify the study's findings (Patton, 2015), collecting converging evidence from different sources.

The semi-structured interview guide, enclosed in Appendix 3, was consulted with the internal KM supervisor and university supervisor to *construct validity*. For the LPD assessment and workshop, the creation of the assessment sheet in Appendix 4 was supported by three internal respondents that initially answered the scorecard. They provided feedback on explaining the *theoretical terms* used in LPD. This feedback was used to clarify the LPD principles with an explanation text for each principle.

Internal validity refers to the causality of relationships observed and to what degree this is justified in the researcher's conclusion. However, qualitative research is not fit to test causality;

rather, it can be very helpful in describing how a phenomenon operates and testing preliminary hypotheses and theories (Yin, 2014).

An Industrial Ph.D. project is an excellent opportunity for gaining unique insights by combining research in industry and academia. The author has had access to informants and knowledge. However, the challenge has been maintaining focus as a researcher and not taking the role of a consultant solving problems for the company as part of daily work. Moreover, it has been challenging to isolate knowledge-based results and facts while at the same time being exposed to nuances and different viewpoints of colleagues. Paradoxically, this is also a strength as it can ensure *internal validity*. The role of an Industrial Ph.D. employed in the case company provides opportunities for intervention supporting the study's validity. *Intervention* concerns the presence of the researcher observing how participants react as a further way of confirming and validating results (Maxwell, 2013). Interventions include observation of project activities, (informal) interviews, workshops, and reading and discussing project documentation.

External validity includes defining the domain to which a finding in a study can be generalized. This study is limited to a single case company operating in a low-volume marine context. Hence, generalization has yet to be the primary intent of this thesis, and care should be taken in generalizing the findings in this thesis to other settings.

The LPD framework has been used as inspiration for the interview guide. Thus, the operational context was analysed up against the framework of Morgan and Liker (2006). The contribution is accordingly to shed empirical light on applying the LPD principles in the low-volume industrial context. This study can provide value to organizations and industries with similar characteristics aiming to improve product development capabilities for automated assembly. The limitations of the study are further discussed in section 7.2.

The *reliability* objective is to be sure that if a later researcher follows the same procedures described by an earlier researcher and conducts the same case study over again, the later investigator should arrive at the same findings and conclusions (Yin, 2014). *Reliability* relates to obtaining data, analysing data and the methodologies applied, and establishing a replication logic. This relates to obtaining and analysing data and the methodologies applied (Yin, 2014). Total objectivity is neither achievable nor desirable in qualitative research (Ahern, 2016).

This study conducts interviews with 18 respondents involved in past and present PD projects in KM. According to Ottosson et al. (2006), as every PD project is unique, obtaining many measures of a few objects is valuable. A study of PD within a single company can give useful insights. For a researcher to be able to understand what happens in a development project and its complex nature, to be able to contribute to the knowledge of product development, and to be able to give sound recommendations on how to develop better products, it is favourable to use qualitative studies having an insider position. The researcher's understanding and experience of the product development context will influence the *reliability* of the interviews (Ottosson, et al., 2006). The author of this thesis is employed in the case company (Industrial Ph.D.) and accordingly holds a good understanding of the context. Still, it is necessary to take action to decrease the chance of biases influencing the data collection and data analysis process (Miles & Huberman, 1994). Semi-structured interviews allow respondents to speak freely with little influence from pre-established theoretical frameworks. At the same time, structuring part of the interview guide similarly to the LPD framework of people, process, and technology & tools ensured focus to contribute to the theoretical literature.

4.4 Ethical concerns

Revealing the game behind the scenes can cause problems for the people taking part in the game (Ottosson, et al., 2006). As a researcher with much inside information from KM, it has been carefully judged how and what to present publicly. Information that respondents referred to as confidential has been left out of the interview transcriptions. In addition, the role of an Industrial Ph.D. researcher employed by the case company may introduce loyalty problems. Therefore, it is essential to emphasize the role of the researcher to the academic audience. The finance from the Industrial Ph.D. program is mentioned in the individual papers Acknowledgement and Declaration of interest. On the other hand, there is also the role of an employee and colleague of the respondents. As an example, a respondent needed clarification about participating and sharing information from internal PD projects. A pre-meeting with the respondent and his/her manager was held before the interview to clarify the expected outcomes of the interviews and what information was to be revealed. In this pre-meeting, the researcher presented the interview guide and the objective of the Ph.D. work. This pre-meeting made the respondent confident to proceed with the interview.

In the invitation e-mail for the interviews making up dataset A, the purpose of the research was explained in detail. All respondents approved recording the interviews before the interview started and were promised anonymity.

5 OVERVIEW OF MAIN AND SUPPORTIVE PAPERS

5.1 Main paper 1

Main paper 1 presents a case study of product development in KM with the aim to identify enablers and obstacles in PD for transformation to automated assembly in the marine low-volume context. It covers results from semi-structured interviews (dataset A). Main paper 1 is the main contribution to RQ1 in this thesis, asking what the obstacles of existing product development system and product design practices are to enable a transformation to automated assembly in the low-volume marine context. In addition, the paper asks how these obstacles can be dealt with in a LPD system and accordingly also contribute to answer RQ2 and RQ3 of this thesis. Table 8 presents an overview of selected characteristics related to the paper.

Table 8 Overview of main paper 1

Main paper 1	**Industrialization of Automated Assembly in a Marine Low-Volume Context: A Case Study of Product Development**
Authors	Elisabeth Lervåg Synnes (main author) and Torgeir Welo.
Journal	International Journal of Product Development.
Status	In review with International Journal of Product Development (May 2023).
Aim	Main paper 1 aims to investigate needs for transformation in product development (PD) capabilities, when a company is going from manual to more automated assembly.
Research questions	1. Which are the obstacles of the existing product development system and product design practices to enable industrialization of automated assembly of large and heavy marine products produced in low volumes? 2. How can these obstacles be dealt with in an LPD system?
Method	Semi-structured interviews.
Contribution main author	Design study, planning execution, data collection, data synthesis/analysis, interpretation of results, structuring paper, writing paper, editing paper and writing conclusion.
Contribution co-author	Input to design study, supervision during planning and execution, input to structure of paper, input to editing paper, reviewing paper, structuring conclusion.
Contributions	C1, C2, C3 and (C4).

Main paper 1 is submitted to the International Journal of Product Development and is in the review process (May 2023). The paper is included in Appendix 1. In addition, the interview guide for identifying enablers and obstacles in PD for automated assembly is presented in Appendix 3.

5.2 Main paper 2

Main paper 2 discusses opportunities of using the Lean concept to improve a company`s product development system. Main paper 2 is together with main paper 3 the main contribution to answer RQ2 in this thesis. It also gives a contribution to RQ1, emphasizing obstacles related to current PD capabilities to enable automated assembly. Table 9 summarizes characteristics associated with the paper.

Table 9 Overview of main paper 2

Main paper 2	**Applicability of Lean Product Development to a company in the marine sector**
Authors	Elisabeth Lervåg Synnes (main author) and Torgeir Welo.
Published in	Proceedings of IEEE International Conference on Industrial Engineering and Engineering Management.
Status	Presented by main author at the IEEE International Conference on Industrial Engineering and Engineering Management (IEEM): 10-13 Dec Singapore 2017.
Aim	Main paper 2 aims to investigate the applicability of Lean to the context of product development of high-value products produced at low volumes in the marine business.
Research questions	How can a company operating in the marine business (best) combine people, process and technology to optimize its Product Innovation system?
Method	LPD company self-assessment and workshop.
Contribution main author	Design study, planning execution, data collection, data synthesis/analysis, interpretation of results, structuring, writing and editing paper, and writing the conclusion.
Contribution co-author	Input to design study, supervision during execution planning, input to structure of paper, input to editing paper, reviewing paper and structuring the conclusion.
Contribution	C5 and (C6).

Main paper 2 is published in the Proceedings of IEEE International Conference on Industrial Engineering and Engineering Management. The paper is included in Appendix 1. The LPD assessment sheet used as a baseline for data collection in different workshops is attached in Appendix 4.

5.3 Main paper 3

Main paper 3 builds upon the initial assessment of Lean practices in the case company presented in main paper 2. The purpose of this paper, as a follow-up to main paper 2, is to present findings related to the application of *new* PD practices outlined for the development stage of a new, optimized tunnel thruster (TTC) for closing observed capability gaps and their effect on a Lean transformation in PD. Main paper 3 contributes mainly to answering RQ2 in this thesis. Together with main paper 2, this paper is part of the same longitudinal study. Table 10 summarizes characteristics associated with the paper.

Table 10 Overview of main paper 3

Main paper 3	**Using Lean to Transform the Product Development Process in a Marine Company: A Case Study**
Authors	Elisabeth Lervåg Synnes (main author) and Torgeir Welo.
Published in	Procedia CIRP 2022.
Status	Presented by main author at the 32nd CIRP Design Conference Design in a Changing World Paris Saclay 28th-30th of March 2022.
Aim	Main paper 3 aims to investigate the application of new practices in a thruster project in a transformation towards a leaner, more optimal product development process.
Research question	What is the effect of introducing new PD practices for closing the capability gaps observed in the earlier (2017) study?
Method	Participatory approach for observing team activities, including two workshops with key people in the thruster PD project.
Contribution main author	Design study, planning execution, data collection, data synthesis/analysis, interpretation of results, structuring, writing and editing the paper and writing the conclusion.
Contribution co-author	Input to design study, supervision during execution planning, input to structure of the paper, input to editing paper, reviewing the paper and structuring the conclusion.
Contribution	C6 and C7.

Main paper 3 is published in Procedia CIRP 2022. The paper is included in Appendix 1. The LPD re-assessment is enclosed in Appendix 4.

5.4 Main paper 4

Main paper 4 is a participatory research study of two cases in KM. Although the cases are different in terms of project objectives and tasks, both aiming to autogenerate process output based on adequate data input. Main paper 4 is the main contribution to RQ3 in this thesis. Table 11 gives an overview of the paper.

Table 11 Overview of main paper 4

Main paper 4	**Data-driven product optimization capabilities to enhance sustainability and environmental compliance in a marine manufacturing context**
Authors	Elisabeth Lervåg Synnes (main author) and Torgeir Welo.
Journal	Concurrent Engineering: Research and Applications
Status	Submitted November 2022 and admitted for review with Concurrent Engineering: Research and Applications. In April 2023 the paper is recommended publication with minor revisions. Paper is, per May 2023, re-submitted with revisions.
Aim	Main paper 4 aims to investigate concerns related to product data and digital data flow when aiming to automate company processes.
Research questions	- How can the combination of Industry 4.0 and precise product information (data accuracy) contribute to more sustainable choices and improved ways of working in product development? - What are the shortcomings in existing data acquisition and data quality in engineering to enable digital auto generation of downstream processes, such as compliance reporting and a production process that is 'right first time'?
Method	Participatory research of two case studies in the same company
Contribution main author	Design study, planning execution, data collection, data synthesis/analysis, interpretation of results, structuring paper, writing paper, editing paper and writing conclusion
Contribution co-author	Input to structure of paper, input to editing paper, reviewing paper, structuring conclusion.
Contribution	C8 and C9.

Main paper 4 submitted to *Concurrent Engineering: Research and Applications* is reviewed and recommended publication with minor revisions. The paper is, per May 2023, re-submitted with revisions according to reviewers' comments. A copy of the submitted paper is presented in Appendix 1.

5.5 Supportive papers 1-3

Table 12 gives an overview of the three supportive papers in this thesis. The supportive papers are enclosed in Appendix 2. The supportive papers are forerunners to the main papers leading up to the results. The results in the supportive papers helped leverage the research process. Ps1 explains the challenge of implementing new technology in parallel with developing the existing product platform and converging it into one final successful design. Ps2 sees efforts made by the case company to develop new automated solutions for low-volume products. Ps1 and Ps2 are based on a case study on the working methods and design principles developed to re-design the RD-TT for automated assembly and support answering RQ1 and RQ2. Finally, Ps3 also supports answering RQ1 and RQ2, addressing the challenge of introducing new technology and the related challenges in product and process development of low-volume, complex products for a competitive world market with a basis in Norway. Ps3 also discusses organizational capabilities and tools required to enable transformation into Industry 4.0. Hence, this paper is also a forerunner to answering RQ3.

Table 12 Supportive papers 1-3 overview

Supportive paper 1 (Ps1)	**Design for Automated Assembly of large and complex products: Experiences from a marine company operating in Norway**
Authors	Elisabeth Lervåg Synnes (main author) and Torgeir Welo.
Published in	Procedia Computer Science 2015.
Status	Presented by main author at the 13th Annual Conference on Systems Engineering (CSER) Stevens Institute of Technology March 19th 2015.
Aim	Supportive paper 1 aims to identify the multifaceted challenges of moving from a manual to an automated assembly process for large and complex products when this endeavour involves transferring technology from the early (low readiness) phase to full industrial implementation.
Research topic	Integration and implementation of 'new-to-the-company' type technology in product realization projects, leading to (radical) changes in existing practices and capabilities within design, process and technology.
Method	Case study.
Contribution main author	Design study, planning execution, data collection, data synthesis/analysis, interpretation of results, structuring, writing and editing the paper and writing the conclusion.
Contribution co-author	Input to design study, supervision during planning and execution, input to structure and editing of paper, reviewing paper, and structuring the conclusion.
Contribution	By developing new technology in parallel with an existing product platform, complex functional requirements can be verified simultaneously by establishing an optimal manufacturing process concept for industrial implementation. Converging into one final successful design from the sets of different options largely depends on inter and intra-organizational communication strategies.

Supportive paper 2 (Ps2)	**Bridging the gap between high and low-volume production through enhancement of integrative capabilities**
Authors	Elisabeth Lervåg Synnes (main author) and Torgeir Welo.
Published in	Procedia manufacturing 2016.
Status	Presented by co-author at the NAMRC/MSEC Conference 2016, Blacksburg Virginia, June 27th-July 1st.
Aim	This paper address new deployment strategies for integrated technology, product and process development. This paper aims to summarize the working methods and design principles developed in the Autoflex project.
Research questions	1. How to ensure systematic utilization of Integrated Product and Process Development (IPPD) to enhance the organization's integrative capabilities in developing a powerful system of people, process and technology? 2. Identify the tools required to facilitate communication between production and product engineering to build knowledge in design-for-automation of large and complex products produced in low volumes?
Method	Case study.
Contribution main author	Design study, planning execution, data collection, data synthesis/analysis, interpretation of results, structuring, writing and editing the paper, and writing the conclusion.
Contribution co-author	Input to design study, input to paper structure, editing of paper, reviewing paper and structuring the conclusion.
Contribution	Based on literature and experiences from a case study, the paper identified several enabling factors, including: - A company`s ability to absorb new technologies and provide flexibility within the work environment-production system to maximize capacity utilization, - processes that facilitate teamwork and iterative product and process development, - supporting tools such as design guidelines for sharing knowledge between production and product engineering. As a result, companies that enhance their integrative capabilities will gain a long-term competitive advantage.

Supportive paper 3 (Ps3)	**Enhancing Integrative Capabilities through Lean Product and Process Development**
Authors	Elisabeth Lervåg Synnes (main author) and Torgeir Welo.
Published in	Procedia CIRP 2016.
Status	Presented by main author at the 6th Conference on Learning Factories, Gjøvik, Norway June 29th-30th 2016.
Aim	This paper aims to address the challenge of developing and introducing new technology in a company that is producing products in a high-cost country.
Research question	How to enhance a company`s integrative capabilities, facilitating changes required to enable an emerging transformation into Industry 4.0?
Method	Case study.
Contribution main author	Design study, planning execution, data collection, data synthesis/analysis, results interpretation, structuring, writing and editing the paper and writing the conclusion.
Contribution co-author	Input to design study, input to paper structure, editing and reviewing the paper and structuring the conclusion.
Contributions	Results show that investing in the latest manufacturing technology alone will not provide the capabilities required. Investing in people skills, knowledge, and organizational learning is also necessary. Process design and design-for-automation must be considered from the conceptual product design to avoid expensive re-designs and design loops.

6 DISCUSSION

6.1 Research questions and contributions

Figure 12 illustrates the link between the thesis' research questions and the contributions (C) from the four main papers.

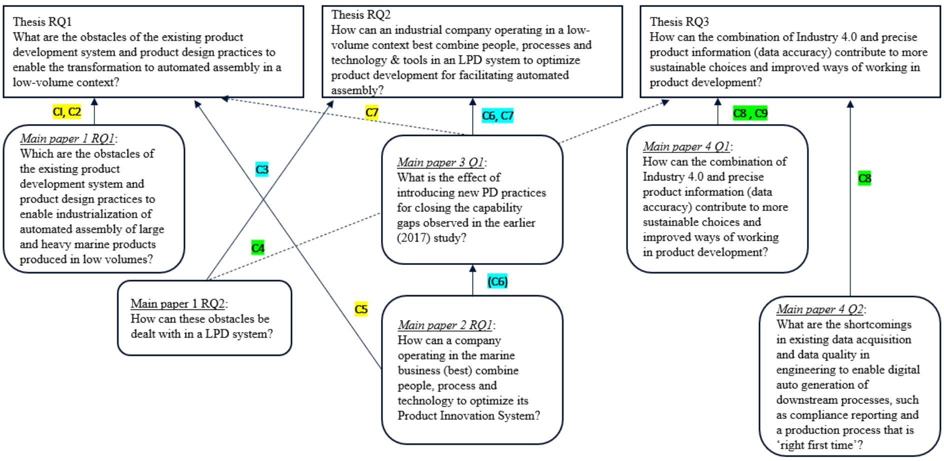

Figure 12 Thesis research questions, main papers RQs and their contribution

6.2 Main paper 1

Main paper 1 investigates the need for transformation in PD capabilities when a company goes from manual to more automated assembly. The paper presents obstacles in product design and development to industrialization with automated assembly in the marine low-volume context and how these obstacles can be dealt with in an LPD system. It also considers design practices for automated assembly from an engineering point of view (DfX).

For the case company, the main obstacles to providing a transformation towards automated assembly are low-volume production and lack of repeated 'process-like' operations in both product development and production. Current PD practices are *project-like* in that designs are unique to each product, implying a lack of repeated operations and tasks in PD. Although product designs, solutions, and documentation, to some extent, are reused and standardized, an ETO company usually needs to maintain more product variants than a traditional manufacturing company. There is little time to develop the manufacturing capabilities in the daily ETO work, and design variants must be conducted within the existing manufacturing limitations (Qudrat-Ullah, et al., 2012). According to Javadi (2015), reusing existing production systems is typical also for future developments of low-volume (ETO) products. Available production equipment and software define the standards for what the designer must consider. What manufacturing can and cannot do has sometimes been 'written in stone' for years in a company. In the case company, existing design capabilities are established for manual assembly, and accordingly, existing company products are not designed for automated assembly.

The company's design practices must leverage automated assembly in terms of more conventional product and component engineering (DfX) in the early phases of PD to overcome this barrier. Design for Automated Assembly (DFAA) guidelines and robotic practices in literature are found relevant in the marine low-volume context studied herein; see, e.g., Eskilander (2001), Boothroyd, Dewhurst and Knight (2011) and Madappilly & Mork (2021). These guidelines and Lean design guidelines, as presented by Dombrowski & Schmidt (2013), include considering synergies between, within, and across product families to facilitate repeated and standardized operations in production.

The development of design guidelines should not only be based on considering general principles but also be contextualized to the needs of the specific industry (Eskilander, 2001). A robot's lifting capacity will constrain the size and weight of both the product and associated production equipment. This will influence trade-offs, such as designing smaller, lighter components or investing in larger robots. Eskilander (2001) argues that design guidelines will become specific for a company`s assembly system and capabilities, which could be both an advantage and a drawback. The former refers to existing solutions and reusing what already exists and is proven. The latter may be the case when overshooting standardization such that solutions are re-used too long, thus limiting the technological evolution of products and becoming a barrier to innovation. According to Kampker et al. (2014) too much focus on standardization and modularization may hinder innovations. In addition, care should also be taken to prevent standardization and modularisation from reducing product functionality (Persson & Åhlström, 2006). Still, during this thesis, it has become evident that there is an opportunity for an ETO company to offer customer value while at the same time considering both standardization and modularization. A critical action in this regard is to understand what is uncertain, what is the reuse of knowledge, and what needs to be validated to ensure that new design capabilities enable product and process evolution.

The primary difficulty companies face is arguably the integration of systems, disciplines, tools, processes, and personnel (Wynn & Clarkson, 2018). Main paper 1 identifies obstacles associated with several company PD system elements. A primary obstacle in the existing PD system is the late involvement of relevant functions. The case company is identified to have practices for collaborative and integrated product and process development in the detailed design phase. However, similar practices should be adopted in the early stages of PD, where the opportunity to influence product design for automated assembly is higher than in the detailed design phase. This implies emphasizing design for (automated) assembly during concept design and DFM during detail design (Boothroyd, et al., 2011). The need to design right the first time (for automated assembly) is even more critical in the low-volume context, as many product variants cannot share the development cost. Similarly, within the *tools & technology* category, it was identified that existing cross-functional engineering tools are mostly focused on design evaluation instead of proactively predicting how to avoid a particular problem in the first place. Advancements in CAD, CAE. and product simulation technology make it possible to conduct problem-solving cycles using virtual instead of hardware models. However, there is still a gap in practice, as these technologies require high-resolution models. Accordingly, the opportunity to share engineering knowledge in the early PD phases is reduced (Kennedy, et al., 2014) (Favi, et al., 2022). In addition, PD foci, including engineering tools, are mainly related to product functionality and safety – sometimes at the expense of production optimization. Developing low-volume products has traditionally focused on product functionality rather than optimizing production (Javadi, 2015). Experiences from Autoflex indicate that relatively minor adjustments to product design to facilitate automated assembly with minimum impact on product function can significantly impact production and quality costs. Enabling a transformation to automated assembly in the low-volume context requires significant front-loading due to the knowledge and competence needed.

Wynn and Clarkson (2018) place LeanPPD (Al-Ashaab, et al., 2015), SBCE (Kennedy, et al., 2014), and the Toyota PD system (Liker & Morgan, 2006) as procedural models at the macro level. These models focus on avoiding rework by establishing an essentially funnelled structure in which the design is progressively narrowed; decisions expected to have the most significant consequence are taken earlier in the process, and efforts are made to communicate these decisions to all relevant stakeholders (Wynn & Clarkson, 2018).

Agile models, also considered macro-level procedural models, mainly aimed at IT development have developed significantly after the Agile Manifesto was published in 2001 (see, (Beck, et al., 2001)), prescribing structured, iterative cycles in which the design is repeatedly reintegrated as it progresses through increasing levels of definition. They may be instrumental in contexts where a customer's needs or technology evolve rapidly, in cases where requirements are difficult to specify, and where the emerging solution influences the nature of the problem. Agile models have also been proposed to manage product development (see (Turner, 2007). Wynn & Eckert (2017) emphasize that PD iterations entail good and bad effects. Progressive iterations directly create knowledge and value (although they also incur additional time, effort, and cost). Corrective iterations only occur because of issues that are preferably avoided at their source. Stare (2014) doubts that the agile approach will be widely used outside IT in the future due to the cost of frequent late changes in PD. Still, Stare (2014) argues that certain Agile practices can be utilized for traditional PD projects. To summarize, macro-level procedural models fit well with the product design and development capabilities needed for a transformation toward more automated assembly in a low-volume industry context.

6.3 Main paper 2 and 3

KM's operational PD context has been analysed against the framework of Morgan and Liker (2006). The first analysis was conducted in 2017, and the second was done in 2020. Main paper 2 discusses the possibility of using the Lean concept to improve the company`s PD system. The paper identifies gaps between company capabilities and lean capabilities and the difficulty of closing these gaps. The paper also identifies enablers and areas of improvement that can strengthen the PD process once contextualized to the marine industry. Main paper 3 presents a re-assessment of PD capabilities in KM and investigates if new design practices outlined for a PD benchmark project contribute to closing capability gaps relative to the LPD principles. The initial hypothesis for this research was that although the business context of the case company is radically different from Toyota, several principles and practices will still be applicable once contextualized.

Standardization is a prerequisite for process capabilities in the LPD management system (Liker & Morgan, 2006). In Toyota, design standardization is achieved through a common architecture, modularity, reusability and shared components (Liker & Morgan, 2006). Although initially considered as a need to contextualize standardization to ensure flexibility for customer value in the marine context, during this thesis, it has become evident that there is an opportunity to become leaner in the sense of less ETO and more Configure to Order (CTO). Moving from ETO towards CTO, combining design practices with a more conventional manufacturing mindset like DfX, including standardization and modular design, could be a promising strategy to create customer value in the given industrial context. A modular design also reduces lifecycle costs by making system modification more manageable (Engel & Reich, 2018) (Wynn & Eckert, 2017).

In the case company, product development activities span from product line extensions to developing unproven technologies and processes. The range of product requirements could be from a minor variation on a standard platform or a unique and unusual product in the application. Hence, the PD process must be prepared to provide a unique definition of value. According to the survey team in the initial LPD assessment, the mentality of making things work, operating in a start-up mode, being impatient in the concept phase can (early) lead to a point-based design, focusing on optimization of the chosen solution rather than exploring alternative solutions and development of product range. The use of more demonstrators upfront for rapid learning is highlighted as an essential countermeasure. Such demonstrators can be used at both sub-system and system levels. A set-based approach might be favourable when the outcome is unknown and the cost of rework is high. Also, the set-based approach is favourable when dealing with manufacturability issues, especially when relying on technology with limited experience (Vallhagen, et al., 2013). On the other hand, an iterative strategy – more point-based design – is usually beneficial when the quality of the first guess is high, the cost of rework is low, and feedback is fast.

The Chief Engineer system serves as a systems integrator from concept to production launch and a matrix organization that allows technical specialists to reside in functional units (Liker & Morgan, 2006). In Toyota, the Chief Engineer is known to own the product, while the functional organization owns the standards and knowledge (Sobek, et al., 1999). When assessing the Chief Engineer system principle, it became evident that the type of comprehensive Chief Engineer authority described in LPD literature is absent in the company. Also, during the second analysis in 2020, there was an identified gap in technical project authority to anchor project decisions in the cross-functional organization. In the case company's PD projects, there is a focus on getting consensus through acceptance from all stakeholders, which can be time-consuming compared to a comprehensive *Chief Engineer authority*. Still, it is not evident that the Chief Engineer system is the best solution to achieve optimal integration in the case company. Both pros and cons are identified for project autonomy and obtaining active participation from the functional organization. The use of a project manager, in addition to a technical lead, has been reported to work well in KM PD projects. Moreover, assigning a Chief Engineer to each customer order is expensive for ETO projects with a short product delivery timeframe. For ETO projects, Qudrat-Ullah et al. (2012) suggest that the product line manager take the project management role to ensure that customer orders receive the required attention. The *Chief Engineer system*, integrating multiple cross-disciplinary functions in the development from project start to finish, is scored as a desired capability. However, how to achieve the desired capability can be contextualized as the LPD principles are of a guiding nature.

In the PD benchmark project, the design was right the first time for automated assembly because of front-loading the PD process and early integration of manufacturing competence. New PD practices introduced for the benchmark PD project (TTC) are evaluated to affect reducing specific capability gaps towards the desired future state. Six capabilities are scored with a reduced capability gap between the current and desired future state. Closing some capability gaps initially identified in the first assessment requires changes in the broader cross-functional organization outside the PD benchmark project control. An example is *Organize to balance functional expertise with cross-functional integration.* Although early involvement of relevant competence in the PD project, cross-functional integration became challenging as the project evolved and more functions were involved. To involve and satisfy everyone, using the functional matrix organization to push the project forward is described as a heavy job generating a lot of non-value-added meetings. In addition, functional resources tend to reside in their functional units, maintaining the mismatch between existing standards and new knowledge developed in the early phase of the PD project. In the TTC project, principles were not communicated well enough across the functional organization resulting in different views on modularizing the design. According to Engel & Reich (2018), excessive modularity may increase interface complexity, and accordingly, there is a need for more design iterations. Still, when the new knowledge is established, appropriate modularity may decrease iterations in PD projects by increasing the number of parts that can be re-used instead of re-designed (Engel & Reich, 2018) (Wynn & Eckert, 2017).

The PD benchmark project introduces design, process, and skill-sets standards changes. Accordingly, when reassessing the *process* principle of *Utilizing rigours standardization to reduce variation,* a capability gap is failing to re-use existing design practices. New design practices must be further developed and verified before becoming a new company standard and a capability improvement relative to the LPD principle. The company differs from Toyota in terms of design standardization; however, the modular and standardized thruster design is a step in this direction once the new gap is reduced. Suppose new organizational design capabilities are continuously updated by systematically generating new knowledge (e.g., (Kennedy, et al., 2008), this will be an important step for successfully implementing automated assembly. A new company standard for design practices may also ease the cross-functional integration and reduce the capability gap identified for *Organize to balance functional expertise with cross-functional integration*. This supports the insights of Liker and Morgan (2006) that Lean is a highly interrelated system in which elements interact, overlap, are interdependent, and work together as a coherent whole.

6.4 Main Paper 4

Industry 4.0 technologies are important tools to support digital transformation and achieve sustainability for low-volume marine products and processes in the years to come. Building on the strengths promised by digitalization requires precise and extensive product and process information. Main paper 4 investigates product and digital data flow concerns when aiming to automate company processes.

Work methods and software that integrate product and process development support and improve the collaboration between different departments that work on the same product, yet often in separate, sequential phases. Digital tools for assembly simulation, virtual testing, and verification enable fast and efficient learning loops as a foundation for a physical assembly process. In addition, design iterations can be performed in much shorter cycles. A current obstacle to the value-added application of digital tools in both case studies is that data quality and information attributes must be more consistent and complete for existing products.

A digital product and process twin is one of the first steps toward improved data-driven product optimization (Schuh, et al., 2016). To enable feedback loops and improvements based on data, there is a need to integrate and communize digital product twins across the lifetime for different applications. Figure 13 shows a conceptual model of such a *digital thread* from engineering to operation, leveraging an understanding of the system-wide impact of changes. The DAMP case study demonstrates the digital thread from engineering to production. Virtual manufacturing and testing improve quality in PD, which can be measured in terms of effective risk mitigation in the design process and less re-design. According to Kušar et al. (2014), simulation supports a multidisciplinary project team to have a good problem understanding and early detection of potential disagreements. Taking this a step further, cost-effective sensors and advanced machine learning capabilities support real-time feedback and adjustments, thus strengthening the digital thread.

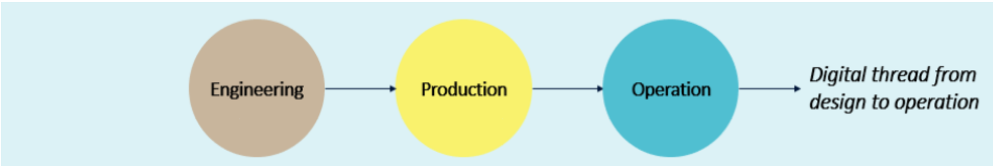

Figure 13 Conceptual model of the digital thread from design to operation

Programming an industrial robot system for a specific application is generally difficult, time-consuming, and expensive (Pan, et al., 2012). In the marine low-volume context, the assembly process preparation activities must also be automated when possible. The case company successfully demonstrated this. Process simulation in PD enables them to get the design right first time for assembly and avoid expensive iterations. In addition, simulation enables them to autogenerate the robot program. Still, the process of preparing the data is time-consuming. Accurate simulation of automated assembly requires access to usually unavailable information unless significant upfront work is done. The value-added application requires that identified design practices are followed to ensure standard methods and that product models include correct data. Mainly focusing on tools with the assumption that these will provide success by themselves would be an insufficient strategy.

A finding in main paper 4 is that required data quality to utilize tools within the context of Industry 4.0 demands focus on the three pillars of *harmonization*, *integration,* and *automation.* Regarding the automated creation of the production process, the software is currently available for all or most of the relevant tasks. However, the linkages between the different software and system modules are often weak and sometimes non-existent, requiring a vast amount of manual re-programming. An interconnected PLM system offers several unified 3D Concurrent Engineering and *knowledge management* capabilities to evaluate product designs as it goes through many facets of its life cycle constructs, like assembly and manufacturing (Prasad, 2016). An obvious lever is to have the PLM system as the strategic product information backbone.

Commonly observed shortcomings in existing materials data quality for autogenerated compliance reporting include manual information collected in excel sheets and the need for a system to connect material data to product data and to visualize and store information. Accurate material and substance data enables comparison of different materials and processes and will accordingly guide decision-making and support sustainable design, preferably in the early phase of PD when 'cost of learning' is low. In sustainable manufacturing, a systems view will help ensure the organization is not pulled in different, sometimes conflicting, directions. Moldavska and Welo (2017) argue that it is crucial to establish the core criteria of sustainable manufacturing to avoid misinterpretation of the concept depending on the preferences of the individual actors.

Sustainability 4.0 is a strategy aimed at achieving sustainability through intelligent technologies to meet a balanced development of economic, environmental, and social demands (Reis, et al., 2021). The use of real-time data from production systems and supply chain partners enables more sustainable manufacturing (design) decisions, including efficient allocation of resources (Jabbour, et al., 2018). This work indicates that a promising start towards *Sustainability 4.0* would be to ensure precise and consistent data that provides a baseline for future decisions while enabling responsive environmental compliance reporting to relevant stakeholders.

6.5 Supportive papers 1, 2 & 3

All supportive papers are forerunners to the main papers. The three supportive papers are based on case studies of existing and enabling PD capabilities, including working methods and design principles developed for the transformation toward more automated assembly in the given context. The supportive papers emphasize the challenge of developing a new product design (including new product technology) and a new process in parallel to a greater extent than the main papers. In this regard, the three papers emphasize and elaborate on front-loading the PD process and the use of learning cycles in the early phases of PD, see (Schipper & Swets, 2010).

Ps3 suggests that there are two directional paths for a company to enhance its integrative product development capabilities:

(a) To leverage agile strategies for product development
(b) To front-load resources in early phases when the cost of learning is low and the design space is wide, using methods such as SBCE.

In a transformation towards more automated assembly, the key is to master both a) and b) to ensure that neither manufacturing nor product technology is driven too far without support in the other as it creates investment risks. Trade-offs between function and production must be evaluated early in the design process when the cost of change and the risk of delaying the product in the marketplace is low. In re-designing the RD-TT and developing the TTC for automated assembly, the need for involvement and input from different functions, providing the right competence and resources in the conceptual stages of design, was vital. Multiple learning cycles have been used to ensure that the design for automated assembly fulfilled functional requirements (see (Schipper & Swets, 2010)). The use of simple (low fidelity) test samples to verify design changes before a more comprehensive prototype was built was practiced. Using simulation, learning cycles and virtual prototypes enabled a cost-efficient verification of design-for-automation solutions, ensuring that manufacturing did not compromise functional requirements. This also ensured a strong interrelationship between manufacturing and product engineering.

Sobek et al. (1999) emphasized SBCE on the product concept level. The case study presented in Sp1 identifies how the SBCE concept has been applied on a business level, re-designing the product and integrating verified solutions with an existing product platform. For the case company, it has been necessary to develop a conventional design in parallel with the design for automated assembly to manage risk. To do this appeared demanding yet necessary and searching for the optimal solution required several iterations.

Ps2 emphasizes that developing an automated solution for the RD-TT required concurrent development of a new technology, a new product design, and a new production process, leading to multiple changes in existing practices and capabilities; e.g., the manufacturing system puts some constraints on the product and vice-versa. Company manufacturing constraints (to enable automated assembly) helped define the gap between the problem and the solution. The subsequent efforts to make automated assembly more cost-efficient, triggered re-design and new solutions to problems. According to Schipper and Swets (2010), such constraints also represent opportunities for innovation.

6.6 Industrial implications

The business objective is to develop quality products, reduce cost, shorten time-to-market, and minimize the need for a complete product re-design after a prototype. This thesis aims to identify product design and development capabilities that will ultimately result in more viable products within the low-volume marine context. The case company started on the journey toward automated assembly a decade ago, in 2012. The initial learning, the starting point for the thesis, was that automated assembly of company products is only feasible with a product re-design. As highlighted by one of the participants in the Autoflex project:

'Buying a robot is easy compared to leveraging the process and people skills for incorporating it in the production environment.'

A historical example is the failed attempts to implement robotics and flexible systems as part of the third industrial revolution in the American manufacturing industry in the late 1970s (Stoll, 1986). Productivity improvements promised by new manufacturing technology rely heavily on creating a solid interface between design and manufacturing early in the PD process.

The vision a decade ago was achieving a fully automated assembly of the RD-TT product. Even though this was not fully realized, it has introduced a new mindset with promising initial results. In addition, the savings from product redesign exceeded those from the automated assembly. Savings were related to a simplified production process (eliminating process steps) and re-use of equipment. One of the advantages of introducing automation in the assembly of a product was that it forces a reconsideration of its design – thus also offering the benefits of an improved product design (Boothroyd, et al., 2011).

Today, KM develops the next-generation Rim Drive product range and assembly line in an integrated and parallel way. The newly launched Rim Drive Thruster Assembly line in Ulsteinvik includes learnings from the automated assembly journey started a decade ago. Integrated product and process development are highlighted by the assembly line manager as one of the main enablers. The following are examples of how integrated product and process development, tools, sensors, and robotics, have improved the production of the Rim Drive thruster product range:

- Robots for HSE (Health, Safety and Environment) operations,
- new service friendly solution to protect magnets,
- the need for production jigs and fixtures is reduced,
- difficult and dirty processes are removed.

This thesis, and parallel work in KM, provide rich data and information for developing leaner PD and engineering practices to transform toward more automated assembly. This thesis highlights the required product design and development capabilities to enable this transformation.

Heritage with existing design practices is identified as one of the main obstacles. Within the Industry 4.0 concept, a company must be able to absorb new technologies that change the premises for competitive production. A company must strengthen its absorptive capabilities to avoid being boxed in by current capabilities for designing a new product and its belonging processes. Accordingly, the company must begin the analysis of the current situation and its strategic goals, considering short and long-term horizons to define which technologies and systems are effectively implemented (Trevino, 2020). New products in the era of Industry 4.0 must at least be prepared for automation (Haim, 2019). According to Uhlemann et al. (2017), advantageous use of Industry 4.0 cannot be obtained until a vertical implementation of Industry 4.0 in the company is ensured. Similarly, as failed attempts to quickly focus on implementing advanced technologies in various industrial settings, investing in Industry 4.0 manufacturing technology and tools alone is insufficient to achieve significant sustainable benefits. A major change in product design practices is needed. *Design for X* practices must be integrated as early as possible in the product lifecycle for sound decision-making and viable design trade-offs.

7 CONCLUSION AND FURTHER WORK

7.1 Concluding remarks

Through the lens of (Lean) product development theory, this thesis explores product design and development capabilities for transformation to automated assembly in a low-volume industrial context providing operational insights from Kongsberg Maritime Commercial Marine (formerly Rolls-Royce Marine). As Lean is primarily a management approach, the present problem makes it necessary to include engineering strategies as a starting point for the study. The method used is a longitudinal case study of KM's product design and development practices. The starting point for the interview guide, identifying enablers and obstacles in existing product design and development capabilities for transformation to automated assembly, is Morgan and Liker's (2006) 13 LPD management principles. In addition, PD practices in KM are analysed against this framework. Finally, a *participatory research* approach is used to study two projects that are part of KM`s digital business transformation initiative. The topic concerns product data and digital data flow when aiming to automate company processes.

RQ1: What are the obstacles of the existing product development system and product design practices to enable the transformation to automated assembly in a low-volume industrial context?

For the case company, the main obstacle to providing a transformation towards automated assembly is heritage with existing design practices for manual assembly **(CI)**. It is particularly critical in the design process to eliminate the need for manual adjustments and visual inspections in assembly. Other product and part characteristics identified as obstacles to automated assembly include parts geometry, tight assembly tolerances, and weight and size of parts and components.

Current PD practices are 'project-like' in the sense that designs are unique to each product, which implies a lack of repeated tasks and operations in PD. This makes it challenging to leverage 'process-like' thinking, including repeated operations, trade-offs, and re-use—all essential capabilities in Lean practices **(C1)**. For the development of low-volume marine products, there has been a tendency to focus on optimizing the chosen customer solution (point-based design) rather than exploring alternative solutions **(C5)**.

Other obstacles to a transformation to more automated assembly are associated with several company PD system elements. Table 13 presents automated assembly transformation obstacles identified in the given context within the three LPD principle categories people, process and technology & tools **(C2)**.

Table 13 Obstacles within the categories people, process and technology & tools

Category	Obstacles
Process	Late involvement of manufacturing.
People	Lack of capacity to balance functional expertise with cross-functional integration when involving more functions and stakeholders during product realization. Functional resources tend to reside in their functional units, maintaining the mismatch between existing standards and new knowledge developed in the early phase of the PD project.
Technology & tools	Value-added knowledge created by digital tools requires significant up-front work to prepare appropriate input. Cross-functional engineering tools are mostly focused on design evaluation instead of proactively predicting how to avoid a particular problem in the first place. PD foci, including engineering tools, are primarily related to product functionality and safety—sometimes at the expense of production optimization.

RQ2: How can an industrial company operating in a low-volume context best combine people, processes and technology & tools in an LPD system to optimize product development to facilitate automated assembly?

This thesis identifies several areas that have the potential to strengthen the PD process once contextualized to the marine sector. The most apparent is to use a set-based approach combined with demonstrators to leverage rapid learning, seamless integration between functional areas, and enforce equal authority of all functions in the project team **(C6)**. A reassessment evaluated if new design practices outlined for a PD benchmark project contribute to closing capability gaps relative to the LPD principles **(C7)**. The assessment identified six improvements and one capability with an increased gap between the current and future state compared to the initial assessment. The capabilities relative to six principles remained unchanged. Principles that could mainly be managed within the project—such as front-loading the PD process—have improved capability.

Table 14 presents PD capabilities to transform to more automated assembly in the given context within each of the three LPD categories.

Table 14 LPD enablers for automated assembly

Category	Enabler
Process	Front-loading and integration of manufacturing competence and resources in the early stages of PD to conduct design evaluations and avoid costly design changes **(C3)**.
People	Integrating multiple cross-disciplinary functions in the development from project start to finish is necessary. - Seamless integration between functional areas to avoid formal, gate-type handovers that can hinder pace in the project. - Equal authority between functional units ensures that both manufacturing and design are driven as far as the other.
Technology & tools	Utilize virtual manufacturing to support design iterations. To combine the good practice of utilizing engineering tools during detailed design with utilizing design for automated assembly tools in the early phase of PD.

In the early design phase, company design practices must include the following capabilities to enable the transformation toward automated assembly **(C3)**:

1. leveraging automated assembly in terms of more conventional product and component design (DfX) and,
2. to carefully consider synergies within a specific product and across a product family to facilitate repeated and standardized operations in production.

Building these two capabilities should be embedded in the PD system and conformed early in the PD process. When supported by relevant tools and people capabilities, this will be a good starting point for the transformation required.

RQ3: How can the combination of Industry 4.0 and precise product information (data accuracy) contribute to more sustainable choices and improved ways of working in product development?

Product and manufacturing sustainability is closely related to product lifecycle, especially the design choices made early in the product design process. It is necessary to integrate and communize digital product twins across the lifetime for different applications to enable feedback loops and improvements based on data. The *participatory* study of two KM projects emphasizes the digital thread in engineering and manufacturing as a promising start toward more data-driven and sustainable decision-making **(C9)**. Virtual manufacturing, simulation, and testing improve PD quality by enabling fast and efficient learning loops as a foundation for a physical production process **(C4)**. Improved quality in PD can be measured in terms of reduced risk of late changes in the design process and less re-design.

Data being stored manually in different systems and lacking product data create inconsistency and are shortcomings to auto-generate downstream processes. Both case projects demonstrate how precise product information, i.e., data quality, is critical for effectively and efficiently utilizing virtual simulation of production and managing and reporting compliance. Improved ways of working, including more sustainable decision-making in PD, requires that product data is available early in the PD process. In addition, it requires that data is strongly connected throughout the product lifecycle through *harmonization*, *integration* and *automation* **(C8)**. Table 15 presents the steps to be taken to enable data-driven decision-making.

Table 15 Focus areas for data-driven decision making in KM

FOCUS AREA	DEFINITION	HARMONISATION	INTEGRATION	AUTOMATION
PROBLEM	3D models and product structures lack critical data.	Diverse ways of working. Multiple systems for the same task.	Systems that do not communicate with each other.	Manual tasks.
SCOPE	New design practices to include the critical data needed to utilize digital tools.	Common systems and ways of working.	Information and data accessed by other internal (and external) data-carrying systems. PLM as the single source of truth.	Reduce process preparation lead time (e.g., for manufacturing and sustainability reporting). Automate processes (e.g., manufacturing and assembly).

This thesis identifies product development capabilities needed for a transformation toward more automated assembly in the low-volume industrial context. For KM, this challenge is both real and ongoing. By gaining insights into KM product development and their ongoing automation transformation, this thesis provides insight into how Lean PD can be used to ensure the engineering and management capabilities needed.

7.2 Limitations and Future Research

This work is conducted within a single company as part of an Industrial Ph.D. project. The thesis's main limitations are related to context and industry. Firstly, this thesis mainly focuses on experience from a single case company. Accordingly, the LPD assessment and interviews focus on experience from (several) internal PD projects. Secondly, the thesis focuses on the design and development capabilities needed to transform toward one specific manufacturing technology, automated assembly.

Ideally, the thesis work should have been conducted with consistent boundary conditions. However, as PD takes time in the industrial context, this must be managed in the research work. The context of this thesis was a dynamic maritime environment. During the course of this thesis, company ownership was changed; Kongsberg Maritime acquired Rolls-Royce Marine in 2019. The production volume in the case company was drastically reduced compared to expectations a decade ago when the research projects forerunners to this Ph.D. work were initiated. Accordingly, there have been changes in production strategy due to a negative drop in the market. Nevertheless, KM has opened a new assembly line in Ulsteinvik for Rim Driven thrusters. Integrated product and process development, including learnings from the automated assembly journey started a decade ago, has been essential for the finished result. Still, how the changes in production strategies will impact future PD capabilities remain unknown. There is an opportunity for further research to follow up with longitudinal research design capturing the strategic choices impact on PD capabilities needed in the given context.

The future demands more sustainable products than today and more sustainable choices in PD. PD and engineering strategies are essential in supporting digital transformation and achieving a state of sustainability for KM products and processes in the years to come. According to Kulatunga et al. (2015), as much as 80 % of sustainability impacts from the product are decided in the product development stage. Thus, the environmental impact of a product's lifetime is largely caused by decisions made in the early design stage, such as material sourcing, manufacturing method, or type of propulsion technology. Future research could investigate how new technologies in the context of Industry 4.0 can build on the initial findings in this study: Are the *Lean* PD enablers identified for a transformation toward automated assembly applicable to other new-to-the-company technologies? The shift towards more automated assembly, Industry 4.0, or (any other) *new-to-the-company* technologies implies changes in product design and development capabilities.

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APPENDIX 1 – Main papers

MAIN PAPER 1

Industrialization of Automated Assembly in a Marine Low-Volume Context: A Case Study of Product Development.

Authors: Synnes, E.L. (main author) & Welo, T.

Status: In-review International Journal of Product Development. May 2023

Abstract. This paper investigates the need for transformation in product development capabilities when a company is going from manual to more automated assembly. The case is an engineer-to-order company operating in a low-volume marine business context. The impact of automated assembly activities on product development practices is studied by combining participatory research and semi-structured interviews, using an interview guide inspired by the Lean Product Development system described by Morgan and Liker (2006). The main obstacles within each system category are identified, in addition to challenges relating to specific product and parts characteristics. It is found that existing design capabilities established for manual assembly fail to leverage automated assembly. Furthermore, it is found that automated assembly requires significant front-loading due to the knowledge and competence that need to be in place to enable a transformation in PD capabilities.

Keywords: Lean Product Development system; Design for automated assembly; case study;

marine industry

This paper is under review for publication and is therefore not included.

MAIN PAPER 2

Applicability of Lean Product Development to a company in the marine sector

Authors: Synnes, E.L. (main author) & Welo, T.

Published in Proceedings of IEEE International Conference on Industrial Engineering and Engineering Management

Abstract. How can a marine company best combine people, process and technology to optimize its Product Innovation system for advanced, complex products produced at low volumes? This paper discusses the possibility of using the Lean concept to improve the company's product development system. The operational context of the case company is analyzed up against the framework of Morgan and Liker's 13 Lean Product Development (LPD) principles. Our hypothesis is that although the business context of the case company is radically different from Toyota, several principles and practices will still be applicable once 'contextualized'. A workshop was held with a multidisciplinary product team to assess the practices of the company relative to LPD. The team evaluated current company practices and desired future practices. The results are summarized and discussed herein. It is concluded that the original LPD principles have a varying degree of applicability to the context of the case company.

Keywords: Lean Product Development, marine sector, high-value products, low-volume

INTRODUCTION

The competitive pressure in the marine sector is steadily increasing due to globalization and the widespread economic crisis in the oil and gas industry. To sustain in this turmoil, companies must develop and deliver more desirable products ahead of their competitors—before technology or market changes.

However, it is not possible to sustain competitive in the market place solely by improving efficiency, reducing prices and outsourcing production. The key is to focus on value creation as a basis for successful innovation, and with this comes the need for development of novel products and manufacturing technology. In this context, the marine industry in Norway is challenged to develop more innovative products and manufacturing technology. However, the lack of investments in the marine sector during the last decades is a barrier for leveraging innovation capabilities.

In many industrial sectors—such as aerospace and automotive industry—lean has made a major contribution to manufacturing efficiency. In the long run, however, improvement in manufacturing alone will not ensure competitive advantage since the cost of a product is largely determined at the planning and design stage. For many type of products, as much as 70% of the manufacturing cost is locked-in in the design phase [1].

In the 1970s, companies experienced that the introduction of robotics, flexible manufacturing and computer integrated manufacturing did not provide the benefits expected. Many companies experienced that investing in a robot is easy compared to the challenge of successfully implementing a new product into production. In other words, successful new product introduction relies heavily on creating a strong interface between design and manufacturing, such that process and design considerations are collectively considered in order to deliver productivity improvements promised by new manufacturing technologies [2]. Design, function and implementation of advanced manufacturing technologies are directly related to the product to be produced—and vice versa.

In this paper, we ask the question: How can a company operating in the marine business (best) combine people, process and technology to optimize its Product Innovation system. We seek to answer this question by addressing Lean Product Development (LPD), discussing the applicability of Lean to the context of product development of advanced, high-value products produced at low volumes in the marine business.

The reminder of this paper is organized as follows: Section 2 present the operational context at glance. Section 3 presents relevant literature on LPD, including Morgan and Liker's 13 principles of LPD, which has been used as a basis for assessing the applicability of the Lean concept to the business context considered herein. Section 4 discusses the applicability of LPD in the operational context considered. Finally, Section 5 presents some concluding remarks.

2. OPERATIONAL CONTEXT

The applicability of Lean Product Development (LPD) principles will be investigated in connection with a large global company's marine division. This company operates in a B2B market, where the customer also typically is a marine company. Part of the marine division is located along the western coastline of Norway with local research and development, and production operations. The value chain is relatively dispersed with local responsibility for product and customer specific issues. The operational procedures and standards, on the other hand, are part of global cooperate practice s where sub-functions supporting the product value stream, such as Lean production, systems thinking, etc. are rolled out. The operational practices are very much heuristic with local site standards, thus forming strong sub-cultures within the global company.

The products are mostly large, complex products with strict requirements to operating life. Here, we use the term complex to reflect the large number of (customized) components in each product (typically more than 100), the multidisciplinary skills required to deliver the product to customer (production process) and the geometry of components (and products). Each product variant is produced in limited volume, and the production process/system can be characterized as Engineer-to-order (ETO). The products are mainly delivering a set of functions, and the customers' main concern is that the product is working according to a set of prescribed criteria and requirements, which commonly change during the course of the product development process.

Up until today high quality, functionality and productivity (lead-time) have been the basic elements for competitive advantage in the company. The production technology infrastructure is tailored to low-volume. For example, machining operations are largely already automated in CNC machining centres, whereas assembly operations, quality control and dimensional verification typically involve a large amount of manual labor. Due to high labor costs, it has been increasingly challenging to produce these types of products in Norway. A need has therefore been identified to extend the company's capabilities in new automation solutions for manufacturing operations. However, this type of products is not well supported by common arguments for automated assembly: Firstly, automation usually requires high volume of standardized parts. Secondly, the product size is another factor that adds complexity to automation.

The company uses a business process named Product Introduction & Lifecycle Management (PILM) to bring products and services to market, and to support the end-oflife cycle. While PILM is used for the whole product and supply chain, Manufacturing Capability Readiness Level (MCRL) and Technology Readiness Level (TRL) are internal subsystems on process and technology level, respectively. These cooperate processes are typically inherited in the marine sector from other business sectors, which operate under different terms and conditions. The interface between these processes can be difficult to manage, since competence is multidisciplinary and geographically spread in the dispersed value chain of the company.

3. LITTERATURE

3.1 Lean Product Development

Lean is usually associated with production of physical products, typically at high volumes. More recently, sources in the literature are discussing the application of the lean concept in the new product development (NPD) process [3- 7]. Lean product development (LPD) is a philosophy suitable to improve efficiency in product development with basis in customer value. The Toyota Production System (TPS) is perhaps the most well-known example of successful lean processes put into action. However, the application of Lean, especially outside the manufacturing area, is not straightforward and there are only a few examples outside Toyota[5]. In 2006, Liker & Morgan [8] presents 13 management principles that—right or wrong— can be considered as a foundation for LPD, emphasizing a system's model where all the principles are mutually supportive. Hence, Lean is a highly interrelated system, in which elements interact, overlap, are interdependent, and work together as a coherent whole. One of the key insights of Liker and Morgan's [8] research is that changes made to one subsystem will always have implications for the other. Also, to succeed in putting Lean into practice, it is not enough to implement a few tools since LPD requires a cultural transformation into a learning organization [8].

According to a literature review on Lean engineering by Baines et al. [7], a successful implementation of lean requires organization-wide changes to systems, practices, and behaviors. Lean is said to be as much about creating the right culture, strategy and environment as it is about developing tools and techniques. According to McManus [9], the most important element in Lean (engineering) is to focus on understanding the customer and end-user value expectations for the product. Another important element is to choose products and architectures, which may be upgraded or improved in future product offerings—i.e., standardization and continuous improvement.

One other important element of LPD is Set-Based Concurrent Engineering (SBCE). As opposed to a point-based design strategy, SBCE is successively excluding non-viable and non-sustainable solutions by identifying limits and constraints [10-12]. The designer looks first for the weaker design solutions, using a funnelling approach to reduce number of feasible design. Instead of designing from top down, the actual system configuration evolves from creative combinations of multiple solution sets [7]. SBCE imposes agreed constraints across different functions to ensure that a final sub-system solution, chosen from a set of alternatives from a particular function, will work with convergent solution from all other functions. SBCE focuses on keeping the design space open as long as possible. The paradox [5] of SBCE is that considering a broader range of concepts will delay some decisions, but in return the whole process will be faster and more efficient. During the design process each alternative is evaluated, trade-offs are made, weaker solutions are eliminated, and new ones are created, often by combining components in new ways [6, 7, 12]. Haque [6], with basis in literature, argues that a set-based design is a key element of LPD. Generally, “point designs”—i.e., highly optimized and specialized solutions to specific problems—are not good lean engineering candidates. This is according to McManus [9], due to the fact that a set-based approach is favourable to address uncertainty.

A related issue at management or system level is removing high-risk technology from the critical path of product development. For example, technology demonstrators can remove risk of unplanned delays [9].

Compared to other Product Development theories and methods, LPD has strong focus on value and waste—and separating the two categories—compared to Lean manufacturing, becoming “Lean” is more associated with increasing value than removing waste when applied in NPD [3]. Moreover, since the lean concept in NPD is related to information and knowledge transformation— unlike the production of a physical product—it is more difficult to separate value from waste in NPD [13]. One of the key elements is important to initiate and execute valuecreating activities with the correct information input. According to Browning [3], lack of value within the product development system is usually a result of having the wrong input rather than doing activities that are unnecessary. A design iteration that can be eliminated without value-loss is waste removal. Without an integrated and synchronized process to organize activities, however, doing value-added activities does not guarantee a valueadding result [3].

4.METHODOLOGY

The operational context of the case company was analyzed up against the framework of Morgan and Liker’s [5] including 13 LPD principles presented in their earlier study of the Toyota Product Development System. A workshop was held with a multidisciplinary product team to assess the practices of the company relative to the set of LPD principles. In addition, lessons learned from an internal technology project were used as input in the discussions with the survey team. This project particularly explored automated assembly of large, complex products, see [14]. The project was selected since it was considered too well represent the contextual challenges analyzed in this article. Hence, the development of an automated production solution for the case product required concurrent development of new technology, a new product design and a new production process, leading to multiple changes in existing practices and capabilities.

The workshop included people from the following functions: Programme Management, Engineering and Manufacturing Engineering. The workshop included the following steps: First, an assessment sheet was sent to each participant for an individual scoring. The input from the participants was collected and analyzed. This was followed by a workshop where the analyzed material was assessed and discussed to ensure common understanding. After the workshop, each attendee was given the opportunity to review the result and provide additional input. The result of the assessment is presented in Table 1.

5.RESULTS AND DISCUSSION

The variety of product development activities in the case company span from product line extensions to development of unproven technologies and processes. The team suggested that a so-called set-based approach might be favorable when the outcome is unknown, and the cost of rework is high. Also, when dealing with manufacturability issues the set-based approach is advantageous, especially when the product relies on technology with limited experiences, or involves new or advanced materials and processes [11]. On the other hand, an iterative strategy— more point-based design strategy—is usually beneficial when the quality of the first guess is high, cost of re-work is low and feedback is fast.

In the case company, prototype customized products are often sold to customers, which require extensive work for preparing documentation, ensuring quality, etc. According to the survey team, this can (early) lead to a point-based design, focusing on optimization of the chosen solution rather than exploring alternative solutions. Here the use of more demonstrators upfront for rapid learning was highlighted as an important countermeasure. Such demonstrators/ "proof of concepts" can be used both at subsystem and system level. Further, this can be used as learning and early feedback for field service, a function that is involved later in the product life-cycle. Prototypes and demonstrators are important artefacts [15] to verify that results are not achieved at the cost of functional requirements, or any other compromises that degrade the final value of the product.

One of the main findings in the workshop is that although all the LPD principles are considered important in themselves, they have a varying degree of applicability in the setting of the case company. As an example, due to lowvolume it is common to adapt a product to fit into a specific production process, thereby filling up the production line to achieve economies of scale. On the other hand, there are major trade-offs to be made between what the customer wants (ETO), and standardization of products and components. Another element regarding standardization and modularization emphasized by the survey team is the need for interface control for adding changes to design during ETO or later sub-optimization during sustained engineering

In the case project considered, it appeared that a small team was doing "skunk work" outside business-as-usual working outside the existing boundaries of their departments to develop the new capabilities necessary. This turned out to be an efficient way of resolving specific technology challenges. Moreover, introducing "new-tothe-company" type technology in product realization projects is a major challenge since it enforces the company`s existing capabilities to change [14].

TABLE 1 ASSESSMENT OF LPD PRINCIPLES IN THE COMPANY.

	Principle	Current state case company	Desired future state	Gap between current and future state	Difficulty to change	Bottleneck/critical action
Process	Establish **customer-defined value** to separate value from waste.	Considered very important.	Develop resources and competence to fully understand and define customer value.	Low	Low	Sub-optimization. Ship owner and ship operator have different needs.
	Front load the product development process.	The mentality of making things work creates a risk of operating in "start-up" mode, being impatient in the concept phase, and focusing on one solution.	Seamless integration of product and process. Demonstrators for rapid learning to optimize the solution both at sub-systems and systems level.	Medium	Medium	Allocate sufficient resources (funding) early on in the project, competing with short term tasks.
	Create a leveled Product Development process flow.	To some extent leveled today. Resources that are not fully dedicated to the project are more difficult to utilize. Main challenge is prioritization of daily production over PD in case of urgency.	Dedicated resources (human and machines) for PD.	Medium	Medium	Difficult to plan. How to ensure that temporary/less dedicated resources get ownership to the project.
	Utilize Rigorous Standardization to reduce variation.	Process level: good Product level: needs to be improved. Challenging due to differentiated product portfolio and limited volume.	Enforce product modularization and standardization; e.g., design for common tool and equipment.	High	Medium	Prevent trade-off customer value and standardization. Clarify what is assumption, what is verified, what is re-use of knowledge and what needs to be validated to ensure that standardization does not make the company reactive.
People	Develop a "Chief Engineer System".	Project leader (PL) that has several roles in a project. Generally high technical expertise. However, sometimes lack capacity to manage project. Today, rigid processes to ensure control.	PL of a dedicated team with clear responsibilities. Ensure seamless integration between functions. Strong network and understanding of life cycle.	High	Medium	Finding persons with the right skills. Management of TRL and MCRL processes. Difficult to have overview of the entire process.
	Organize to balance Functional Expertise and Cross-functional integration.	Interface between functions is not clear. For example, Design Engineer doing Manufacturing Engineer work and vice versa.	Provide equal authority of all disciplines. Early involvement from all functions.	High	High	Ensure access to resources. Understanding the mechanisms that are resulting in successful projects.
	Develop towering technical competence in all Engineers.	Experts and special competence are satisfying. The need for more T-shaped people is highlighted..	A mix between T-shaped and expert competence. More system competence. Utilize learning from previous projects.	Medium	Medium	Ideas often stem from Gemba. Key to follow these ideas to the project table without losing the original intention and drive.
	Fully integrate suppliers into the PD system.	To some extent existing today. However, there is lack of a formal process.	Suppliers to deliver a product with the correct cost and design.	Low	Medium	Early supplier involvement. However, many design changes result in changing premises during the project.
	Build in learning and continuous improvement.	Global company with local sub-cultures. Need to encourage knowledge sharing and cooperation (trust). Works on individual level.	Utilize learning in projects to develop more T-shaped people.	Medium	Medium	Strong sub-cultures.
	Build a culture to support excellence and relentless improvement.	Continuous improvement important to company	Cultural change to create additional awareness.	Medium	Low	Must "choose the right battles".
Tools	Adapt Technology to fit your people and process.	A tendency to favor technology over people and processes.	Manage technology and competence in a more digitalized world. Competence to read out results from new technology.	High	Medium	Need to systematize competence.
	Align your organization through simple, visual communication.	3D models.	Early simulation for common understanding.	Low	Low	
	Use powerful tools for standardization and organizational learning.	A3 has recently been introduced in the Research and Technology department.	Solve problem with Gemba and at the root cause.	High	Low	Problem solving can be too complicated.

The LPD principles proposed by Morgan and Liker [5] have a varying degree of applicability to the context of the case company studied herein. In practice, the principles need to be contextualized since they are of guiding nature. As an example, standardization is key, especially in lowvolume production due to cost. However, the assessment made emphasized major trade-off between standardization and flexibility to create value for the customer. Based on our assessment of LPD practices, and with support from the selected case project, we have identified several areas that have potential to strengthen the PD process in the case company once contextualized to the marine sector at glance. The most apparent areas are:

1. Use a set-based approach in combination with demonstrators to leverage rapid learning and optimized solutions.
2. Seamless integration between functional areas, especially integration of manufacturing early in the PD process to prevent waste later in the process; e.g., design loopbacks. Avoid formal, gate-type hand-overs and an "over the wall approach" that can be a hindrance to pace in the project.
3. Enforce equal authority of all functions in the project team.

This research supports insights of Liker and Morgan's [8] research reflecting that changes made to one subsystem will always have implications for the other. Hence, it is not enough to implement a few lean tools, as achieving leanness in PD requires transformation into a learning organization. Based on continuous learning from projects, following a set-based design strategy, the company can build T-shaped people [16] and improve integration between functions and phases in the PD process.

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MAIN PAPER 3

Using Lean to Transform the Product Development Process in a Marine Company: A Case Study

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Keywords: Lean Product Development, case study, marine sector, capability gaps

Abstract: The motivation of this research is to investigate if the Lean concept can be used to improve a company's product development (PD) process and thereby providing cost-effective methods for development, engineering and manufacturing of products to sustain competitiveness. This longitudinal study builds upon an initial assessment of Lean practices in a company in the Nordics Marine sector starting in 2017. An improvement opportunity identified was defining measures to ensure improved integration of functional areas, especially manufacturing, from the beginning of the PD process. As a follow-up of the assessment, we studied the application of a set of new PD practices outlined for the development stage of a new, optimized tunnel thruster. The purpose of this paper is to share our findings related to the application of these practices and their effect on a Lean transformation in PD. Data collection was done through a participatory approach for observing team activities, including two workshops with key people in the thruster project. The results indicate that early integration of manufacturing competence in PD is important to improve production (integration), reduce time and cost. In addition, the use of design demonstrators and physical testing enable improved cost control and leverage learning throughout the PD process. A re-assessment of company practices relative to Lean, made during the autumn of 2020, identifies that six out of thirteen capabilities are improved in terms of the gap between current and desired future states. However, increased capability gap is identified in utilizing rigorous standardization to reduce variations, since existing company standards are challenged by new project innovations. It is concluded that the effect of introducing new PD practices to reduce capability gaps in Lean Product Development (LPD) is promising, especially for principles that are managed within the project control.

1.INTRODUCTION

The marine industry in Norway is currently challenged to develop more innovative products and to introduce new products faster than their competitors. One of the most important factors for creating competitive advantage is to improve design and development of products and corresponding production processes for providing a low unit cost. The key is to focus on value creation as a basis for successful innovation through the development of novel products and manufacturing technology. Moreover, becoming successful means delivering products that both meet customer needs of operating flawlessly throughout their lifecycle and internal business goals in terms of return on investments.

The Toyota Production System (TPS) is perhaps the most well-known example of successful process strategies systematically put into action. However, the application of Lean, especially outside the manufacturing area, is not straightforward and there are only a few successful examples outside Toyota [1]. For other companies, it is not purposeful to establish practices exactly like Toyota. The key is to understand the 'nuts and bolts' of effectively applying lean in its own context in transforming into a lean organization [2].

This longitudinal study builds further on the initial findings made in a study conducted back in 2017, including an assessment of company practices relative to 13 Lean Management principles in an effort to identify gaps between company practices and those entailed in LPD.

An outcome was the need for defining measures to ensure improved integration between functional areas, especially manufacturing early in PD. Another result was the need to ensure equality and respect of opinions of all people representing different functions in the project team, since a high capability gap was identified for the LPD principle Organize to *balance functional expertise with cross-functional integration*. The difficulty in improving this capability was also scored high. The assessment also emphasized company practices of being 'point-based' in the concept phase [3], focusing on iterating on one solution only. Finally, the initial assessment indicated a capability potential in using both technical and manufacturing demonstrators to leverage rapid learning and optimize solutions both for product sub-systems and systems.

A new thruster PD project was launched in 2016 and defined as a benchmark study. The focus in the thruster project was to achieve significant cost reduction by utilizing modern technology, while linking 'old' and 'new' competence through cross-functional collaboration. The starting point for the PD project was to offer a completely new, optimized thruster, i.e., aiming for cost optimization in order to meet the demand from the merchant marine sector requesting a system that is less complex to install, easier to maintain, and more cost-effective to operate than existing thrusters of comparable size. An important project requirement was to avoid over-engineering (waste).

The final product is a modular mechanical system. The system is standardized, the number of components is significantly reduced, and the installation is optimized [4].

The aim of this study is to investigate the application of new practices in the thruster project in a transformation towards a leaner, more optimal PD process. The study asks the question: What is the effect of introducing new PD practices for closing the capability gaps observed in the earlier (2017) study? We seek to answer this question by studying the steps taken by a marine company to transform their PD process. We re-assess the 13 LPD principles presented by Morgan and Liker [2] and compare with the status back in 2017, see [5].

The remainder of this paper is structured as follows: Section 2 presents the theoretical background. Section 3 describes the methodology. Section 4 presents result and discussion of the findings in relation to theory. Finally, Section 5 gives concluding remarks.

2.LITERATURE REVIEW

2.1 Lean product development

Lean was introduced to processes outside the manufacturing floor, such as PD, in the mid-nineties [1, 6-9]. The LPD concept has emerged as companies first optimized manufacturing before identifying design of the product as the next bottleneck; e.g., hard-to-assemble parts and lack of design standardization [10]. Value creation and waste reduction are keys to Lean principles [11], and manufacturing tends to focus on the latter, while the former provides the higher potential in engineering [12].

LPD is a philosophy suitable to improve efficiency in PD. A starting point for LPD was the studies of Clark and Fujimoto [13], who compared American and Japanese auto companies and found striking differences in organization and management. In 2006, Morgan and Liker presented 13 management principles that – right or wrong – can be considered as a foundation for LPD, emphasizing a system's model where all the principles are supportive without being mutually exclusive [2].

The *people* aspect in LPD includes a Chief Engineer system as systems integrator from concept to production launch along with a matrix organization that allows technical specialists to reside in functional units. The *process* aspect focuses on a precise cross-functional integration, including Set-based concurrent engineering (SBCE) and front-loading the development process. The set-based approach, also referred to as the second Toyota paradox, aims to explore multiple options early to avoid costly changes in the later stages [14]. The principle of SBCE matches a set of product design possibilities with a set of manufacturable product designs [3][14]. Finally, the *tools and technology* aspect includes tools, such as Computer Aided Design (CAD) and Computer Aided Engineering (CAE) with a strong focus on standardization and visualization [10]. According to Liker and Morgan [10], only focusing on lean tools will provide limited success; i.e., in line with agile [15], seeing 'people and interactions over tools and process'. Moreover, to succeed in setting LPD into real-world practice, it is insufficient to implement a few tools since Lean requires a cultural transformation into a learning organization [2].

According to a literature review on Lean Engineering by Baines et al. [8], successful implementation of Lean requires organization-wide changes to systems, practices, and behaviours. Lean is said to be as much about creating the right culture, strategy and environment as it is about developing tools and techniques. Hines and his research group at Cardiff University published the Lean Iceberg Model [16]. The tip of the iceberg represents the visible indicators of Lean, such as the processes, tools and techniques. The indicators below the waterline are less visible but remain fundamental for a successful Lean organization. These below-the-waterline indicators include strategy and alignment, leadership, behavior and employee engagement.

3.METHODOLOGY

The research methodology used in this longitudinal research, with the purpose to explore the possibility to use the Lean concept to improve a marine company`s PD system, follows the timeline presented in Figure 1.

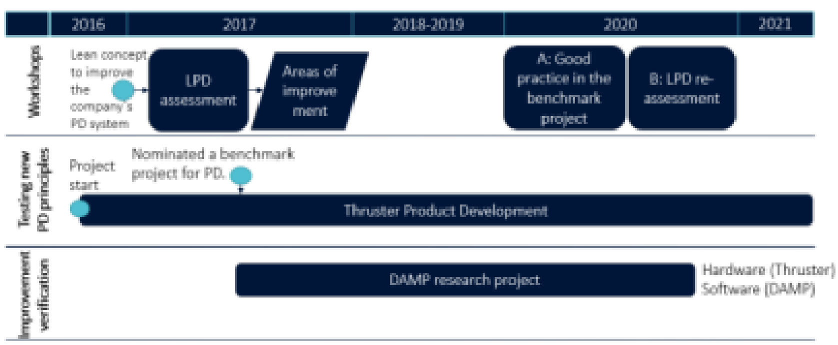

Figure 1 Using the Lean Concept to improve a company's PD system

An LPD assessment workshop with participants from program management, engineering and manufacturing engineering was arranged in 2017. This assessment identified gaps between current and desired future state for PD in the case company. Based on the gaps, three main areas were identified to have particularly high potential for improving the company's PD process:

- Use a set-based design approach in combination with demonstrators to leverage rapid learning and more optimized solutions.
- More seamless integration between functional areas, especially integration of manufacturing early to prevent waste later in the process, e.g., design loopbacks.
- Respect and equality of opinions of all people representing different functions in the project team.

In Nov 2020, two half-day workshops were held with a senior design engineer and a senior manufacturing engineer involved in a company pilot project for new PD principles with the purpose to assess the effect of introducing new PD principles to close LPD capability gaps. The first workshop (A) focused on PD good practice particularly in the front-end of the thruster project and the efforts required to deliver demonstrators of technical solutions and industrialization after 9 months. After assessing and synthesizing data, comparing the three improvement areas against good practices in the thruster project, a second workshop (B) was held to revisit the 2017 assessment and rescore it based on project experiences.

A company in-house research project named Fast Development of new Automated Manufacturing Processes through digital integration and testing (DAMP) demonstrates automated programming solutions, including a digital twin of the product and assembly cell (software) with new thruster modules as the case (hardware). Hence, DAMP is closely related to the PD project and used frequently as a reference in the two workshops. DAMP is demonstrating design practices for automated industrialization outlined for the thruster project. The corresponding author participated in several DAMP project meetings and workshops.

4.RESULTS AND DISCUSSION

In this section, we present the result of the re-assessment of the LPD principles (workshop B), see Table 1. We discuss the results with basis in the improvement areas identified after the initial 2017 assessment and good practice in the PD benchmark project (workshop A). In addition, we focus on standardization as this is a prerequisite for process capabilities in the LPD management system [2]. Design standardization is also an important part of the thruster project value proposition. At the same time the principle *Utilize rigorous Standardization* to reduce variation is identified as a new gap in the re-assessment.

4.1 Front-loading the PD process with demonstrators

The principle Front-loading the PD process is now scored with a smaller capability gap compared to the initial assessment when rated to have an improvement potential. This require allocating relevant resources and taking time to explore design capabilities including manufacturing during concept design. The thruster project aimed for design Right First time (RFT) building demonstrators for industrialization and technical solutions to avoid costly downstream design changes, e.g., to close critical knowledge gaps before detail design is performed. This is referred to as rapid learning cycles, see [17]. Demonstrators give the ability to consider concepts from different perspectives and ensure that relevant competence is involved early in the project. A demonstrator is used to show functionality to internal and external customers. According to company governance, a demonstrator does not confirm if a product is ready for sale and is hence a fast way to test new capabilities. To efficiently explore new solutions, separating the weak from the strong solutions, the following design capabilities are demonstrated early in the thruster project:

- Modular design.
- New machining methods incorporated into design. Utilization of CNC machine capability, design based on manufacturing method instead of tolerance standards.
- New materials and processes for key components.
- Testing and production of core components to control costs.

According to workshop A, the use of demonstrators enabled both cost control and key learning early in the project.

The capability relative to the principle Build a culture to support excellence and relentless improvement is also rated as an improvement in workshop B. Several decades of experience in relevant disciplines are put into the thruster project demonstrating future opportunities. Learning that is not part of the final design solution is captured, e.g., test results are put on the shelf for utilization in other projects if they prove a potential in the next generation of thrusters. At the same time, safe fallbacks exist to meet project timeline, e.g., conventional material solutions for key components are candidates for use while moving down the set-based 'waterfall'.

Table 1 Reassessment of LPD principles 2020

	Lean management principle	Gap current and desired state -17	Comment	2020 Status	Comment
Process	Establish customer-defined value to separate value from waste.	Low	A need to develop competence to fully understand and define customer value.	Improvement	Interaction with yards and customers to map requirements for the thruster project.
	Front load the product development process.	Medium	A risk of being impatient in the concept phase. Focusing on one solution and build a prototype.	Improvement	Resources from relevant disciplines allocated early in the PD project. Technical solutions and industrialization demonstrated. Demonstrators ensure focus and is an efficient way to test solutions.
	Create a leveled product development process flow.	Medium	Main challenge is prioritization of daily production over PD in case of urgency.	Improvement	A product demonstrator was ready for sea water trials after 9 months. Successful planning according to machining priorities and daily production.
	Utilize rigorous standardization to reduce variation.	High	Good at process level. Need improvement at product level. Challenging due to differentiated portfolio and low volume.	New Gap.	Modular design and automated assembly create a new competitive standard for design. Challenge existing design rules and standardization mindset.
People	Develop a 'Chief Engineer System'.	High	Project leader that has several roles in a project. High technical expertise, but sometimes lack capacity to manage project. Rigid processes to ensure control.	Status Que.	Satisfying leadership and decision-making early in the project combining project management with team members high technical expertise. As project evolved, decisions started to be taken outside the project with the result of eliminating risks (innovations) and increasing decision time.
	Organize to balance functional expertise and cross-functional integration.	High	Interfaces between functions are not clear. E.g., Design Engineer doing Manufacturing Engineering work and vice versa.	(Project) Improvement	The project successfully combined technical- and industrialization competence utilizing people from relevant functions. However, to get acceptance from the cross-functional organization, ensuring common focus on customer value, is time consuming. Introducing new design standards.
	Develop towering technical competence in all Engineers.	Medium	The need for more T-shaped people is highlighted.	Status que.	Good in developing specialist competence within functional departments. Need to understand the impact of decisions: ME to understand product functionality and DE to understand manufacturing.
	Fully integrate suppliers into the PD system.	Low	There is a lack of formal process with supplier.	Status que.	Worked closely with the gear wheel supplier for technical solution and system integrator developing manufacturing tools. Components are first machined in-house to understand manufacturing cost.
	Build in learning and continuous improvement.	Medium	Global company with local sub-cultures. Need to encourage knowledge sharing and cooperation (trust).	Status que.	Several decades of experience into the project demonstrating project solutions and future opportunities. E.g., new materials for key components demonstrated but not implemented
	Build a culture to support excellence and relentless improvement.	Medium	Need a cultural change to create awareness and chose the right battles.	Improvement	A project introducing both product and process improvements but also improved collaboration and communication ensuring customer focus in the project, e.g., to make decisions in favour of the overall solution and project requirements.
Tools & Technology	Adapt technology to fit your people and process.	High	A tendency to favor technology over people and process. Required competence and experience to interpret results from new technology.	Status que.	The new thruster project challenge simulation and computational calculations with demonstrators: Combining the strength of practical and theoretical experience and old and new competence. In general, because of manual use of the CAD system, there is a wide range of product variants to maintain: 20 different assembly drawings of the same component used in two different products.
	Align your organization through simple, visual communication.	Low	3D models for visual communication.	Improvement	Demonstrating (both virtually and physically) a new industrialization mindset including modular design and how to design away the need for adjustments with shims in assembly.
	Use powerful tools for standardization and organizational learning.	High	Opportunity to learn from mistakes. Requires effective communication at several levels.	Status que.	Several years of experience in the new thruster PD project. In general, the view is still that the organization can learn more from mistakes and utilize existing in-house competence in projects. Be curious of what 'others' in the organization are doing.

4.2 Early integration of manufacturing competence

Focus on cost optimization in the new thruster project required cross-functional collaboration to understand how a component best can be manufactured. Close to 90% of the parts constituting the test-thruster were manufactured in-house in a few weeks. In-house machining and testing enabled changes to be implemented swiftly and communicated with production. The team *created a leveled PD process flow* with successful planning of manufacturing of test parts according to machine availability and priority in production.

Design RFT (because of front-loading the PD process and early integration of manufacturing competence) is supported by the observation made by a panel member in the PD gated project review held in Aug. 2019: Design for manufacture has been actively completed with Engineering taking production feedback, and making changes real-time to ease production, reduce time and cut costs. Moreover, according to the DAMP project report, cross collaboration is improved compared to earlier projects, e.g., strengthened focus on production in the early design phase. Also, achievements in the DAMP project confirm design RFT, e.g., in accordance with project requirements, the modular thruster design is fit for automated assembly. Automated assembly of a thruster gear module was demonstrated autumn 2019. A demo of the main sequence from digital product model to virtual robot assembly process for the gear module was demonstrated during autumn 2020.

4.3 Equality of opinions in a dedicated project team

According to workshop A the PD benchmark project tore down silos with a team covering the expertise of product function, production, maintenance and service. The team utilized the functional matrix organization when competences were needed, e.g., for computational simulation support. Equality of opinions between functions was present early in the project combining technical competence with industrialization competence to achieve the project vision of significant cost reduction compared to a conventional thruster.

In workshop B, the principle *Organize to balance functional expertise with cross-functional integration* was scored with a smaller capability gap for the project than in the initial assessment. Also initially scored as difficult to change. Although, early involvement of relevant competence to ensure customer focus in the project, the principle is not scored as a general improvement as cross functional integration became a challenge, especially when the project evolved, and more functions and stakeholders were involved. Respondents argued that decision-making outside the project eventually slowed down project progress. To involve and satisfy everyone, using the functional matrix organization to push the project forward, is described as a heavy job generating a lot of non-value-added meetings.

When assessing the *Chief engineer system* principle, it became evident that the type of comprehensive *Chief Engineer authority* described in LPD literature is not present in the company. In Toyota, the Chief Engineer (CE) owns the product while the functional organization owns standards and knowledge [3]. The 2017 assessment pointed at the company CE role as a technical role that currently lacks capacity to do project management, acknowledging the challenge to do both. The Toyota CE role is a superhuman ensuring both decision-making and technical authority in PD. According to workshop B there was a lack of technical project authority to anchor project decisions in the cross-functional organization. The principle was scored as a desired capability with a high gap between current and future state in 2017. Although, a lot of effort to ensure both technical competence lead and project governance, workshop B scored the principle as Status Que, realizing that it is a necessary capability, however, not yet sure how to ensure integration between the project team and the cross-functional organization from start to finish in PD. It is not necessarily the CE system that is the best solution for the company.

Evaluating *People* capabilities, good chemistry between the project members, enthusiasm and project governance were highlighted several times as important factors for project success. This relates to the hidden factors in the iceberg model presented by Hines et al. [16].

4.4 Standardization as the foundation for process capabilities

CNC machines were introduced in the 1970s, but the design method in the case company has not changed accordingly. As an example, company products are very much dependent on adjustments in assembly, thus failing to utilize the full potential of CNC machines. A design practice to succeed with automated assembly is to eliminate the need for adjustments. The new thruster design is the first product concept where the company use the principle of designing according to manufacturing method, including proactive verification with in-process probing and machine calibration, instead of traditional tolerance setting. This design practice requires a new mindset, new drawing information and new understanding of the production system. The method was proven for the new thruster in May 2019, and since then two additional adjustment-free assemblies of the thruster have been completed.

In the initial LPD assessment, it was highlighted that re-use of standard solutions can be a barrier to innovation. Hence, a critical action was to clarify what is assumption, what is verified, what is reuse of knowledge and what needs to be validated to ensure that standardization enables product and process evolution. The benchmark PD project introduce changes in design, process and skills-set standards. Reassessing the principle *Utilize rigorous standardization to reduce variation* in workshop B there is a new gap between company capability and lean capabilities in terms of failing re-using existing design practices. New design practices introduced in the PD project must be further developed and verified before eventually becoming a new company standard and a capability improvement relative to the LPD principle.

In Toyota, design standardization is achieved through common architecture, modularity, reusability and shared components [2]. Respondents acknowledge that the company is not comparable to Toyota in terms of design standardization; however, the modular and standardized thruster design is a step in this direction once reducing the new gap.

There is still also a high capability gap for the principle *Adapt technology to fit your people and process*. This is due to both manual use of the CAD system and the high number of drawings to produce and maintain. New design standards developed in the DAMP project (and thruster project) enable more efficient utilization of technology. A core part of the DAMP research has been to develop software that automate the generation of robot programs. Thruster modules and assembly sequences are digitalized in CAD models to enable a fast and efficient path from the product foundation. To automate with tools requires rigid processes for precise product (and process) information in the PLM system. If adapted as new company standards there is potential to close the capability gap for the LPD principle.

5.CONCLUDING REMARKS

This paper investigates if new design practices outlined for a PD benchmark project close capability gaps relative to LPD principles identified in a workshop held back in 2017. The reassessment identified 6 improvements and 1 capability with increased gap between current and future state compared relative to the initial assessment. The capabilities relative to 6 principles remained unchanged.

Principles that could be managed within the project, such as *Front-load the PD process*, have improved capability because of introducing new PD practices. To close some of the capability gaps initially identified requires changes in the cross-functional organization, which is outside the project control. Similarly, focus on continuous improvement may have improved LPD capabilities during this longitudinal study and hence not a direct result of introducing new PD practices. Still, the new PD practices introduced for the benchmark project are evaluated to have effect on reducing specific capability gaps towards desire future state

The PD practice respect and equality of opinions of all people in the project team contribute to closing the capability gap for the principle *Organize to balance Functional Expertise and cross functional integration* successfully combining functional competences in the project. However, only scored as a project improvement as the matrix organization has strong functional units with stakeholder authority in projects making integration between the project and the wider organization challenging to manage. Similarly, there is a new gap in *utilize rigorous standardization* because of new innovations in the LPD pilot project and hence failing re-using existing design practices.

As new design standards are introduced in the benchmark project it is recommended to do a reassessment when they are accepted by the wider cross-functional organization enabling the next PD project to be more process-driven.

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MAIN PAPER 4

Data-driven product optimization capabilities to enhance sustainability and environmental compliance in a marine manufacturing context

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Abstract: This paper investigates concerns related to product data and digital data flow when aiming to automate company processes. Accurate data is necessary to create value by enabling improved decision-making in product development, including sustainability capabilities. The case analyzed is an engineer-to-order (ETO) company operating in a low-volume marine manufacturing context. A participatory research approach is used to study two projects that are part of the company's digital business transformation, aiming to digitalize information and autogenerate downstream processes. Building on the strengths promised by digitalization requires precise and extensive product and process information. An important facilitation capability is to create a digital thread from design to finished product, including product documentation. This is necessary to establish capabilities both to autogenerate appropriate compliance reporting as part of the product development process and to conduct virtual testing and validation before the physical equipment is acquired, resulting in a manufacturing process that is 'right first time'. In addition, data capabilities guide and enable sound-decision making for improved sustainable practices in the early phase of product development. It is found that the data quality required to utilize tools within the context of Industry 4.0 demands changes to existing product design practices and focus on the three pillars harmonization, integration and automation of data and systems.

Keywords: Industry 4.0; sustainability; manufacturing; data quality; materials management; environmental compliance.

This paper is submitted for publication and is therefore not included.

APPENDIX 2 – Supportive papers

Supportive paper 1

Design for Automated Assembly of large and complex products: Experiences from a marine company operating in Norway

Authors: Elisabeth Lervåg Synnes (main author) and Torgeir Welo.

Published in: Procedia Computer Science 2015.

Abstract: To compete in today's global market companies must continuously improve their products and manufacturing processes. During the past several years, many Norwegian-based companies have outsourced production due to the high operational cost level. The trend is that only the production of complex, knowledge-based products which require advanced engineering, strict quality requirements and high degree of customization remains in Norway. Even for this type of products, more cost-effective product realization methods need to be established in order to strengthen overall competitiveness long term. This paper presents results from an ongoing case study done in a global marine company with operations in Norway, seeking to increase competitive advantage by improving capabilities in automation solutions for manufacturing—despite the fact that the production of large and complex products is usually regarded as particularly difficult to automate in an economical way. This paper aims to research the multifaceted challenge of moving from a manual to an automated assembly process for this type of products when this endeavor involves transferring technology from the early premature phase to full industrial implementation in parallel with the product development process. The results presented in this paper are preliminary as the technology development project is still ongoing. One of the early findings indicates that by re-designing large and complex products for handling with standard robots, the case company was able to automate assembly of its products. Furthermore, having a dedicated team enabled delivering a demonstrator after only two years by applying an *Open Innovation* approach, pulling knowledge from external experts in automation and iteratively integrating this with own organizational capabilities including technology platform, manufacturing strategy, design for manufacturing/assembly and integrated product and process development.

Keywords: Systems Engineering, Integrated Product and Process Development; Organizational Capabilities; Technology Project; Industrialization

1.INTRODUCTION

To compete in a global market, companies must continuously develop new products and manufacturing processes to meet new demands from customers. There is a constant pressure to reduce costs and manufacturing locations are frequently reviewed, especially in global companies. In Norway, many companies have outsourced or relocated production to so-called low-cost countries due to high operational costs. In the short run this can give benefits in terms of lower labour costs, but it does not guarantee competitiveness in the long run. Still the production of complex products that require advanced engineering, strict quality requirements, high degree of customization and are knowledge-based tend to remain in Norway. To stay competitive in the future, more cost-effective manufacturing methods and improved technology are required even for this category of products.

Development of new technology with the introduction of, for example, rapid prototyping, advanced industrial robots, digitalization and advanced control systems may enable competitive manufacturing in which labour costs are reduced to a less significant part of the picture—sometimes less than 5% of the total. This issue is widely recognized and described in the report *Made in Norway* [1], which also refers to actions taken by governments in USA, Germany and Denmark to gain competitive advantage by development of advanced manufacturing technologies. Furthermore, in order for a company to become innovative and capable of developing improved products, towering knowledge of advanced manufacturing technologies and production processes is necessary. If production is outsourced, there is also a risk of losing competence both in manufacturing and engineering in the long run. Regaining the lost competence later is difficult, especially in the technology field with long lead time associated with competence development.

This paper addresses the problem of developing and introducing new technology in a company that is producing products in Norway. The motivation is to gain better understanding of the challenges related to introducing changes in the existing technology platform, focusing on the interplay between product design and production process. The case company, Rolls-Royce Marine (RRM), has a large, differentiated product portfolio in combination with proven capability in both ship design and system integration [2]. RRM has several production facilities located in a relatively small geographical area along the western coastline of Norway, manufacturing large and complex products at low-volume with a high degree of manual labour. This regional area is one of the few complete *maritime clusters* in the world with a vertically integrated value chain. To continuously grow the business and create new jobs, more cost-effective material flow and manufacturing methods are required. Based on this consideration, RRM has identified a need to extend their capabilities in new automation solutions for manufacturing operations, despite the fact that this type of products does not support the usual arguments for automated assembly: Firstly, automation usually requires high volume of standardized parts, whereas RRM products are typically made-to-order or engineered-to-order. Therefore, an automation system in this environment must handle mass-customization of low volumes. Secondly, product size is another factor that adds complexity.

Since RRM has limited automation experience due to its product mix, there was a need to seek competence outside the company. In addition, one could not be sure that automation of such large, complex products would be economically feasible. This resulted in a research project called Autoflex, whose goal was to develop strategies for cost-effective manufacturing of low-volume, complex and heavy products in Norway, using real time adaptive robot control to replace manual operations. A so-called “Permanent Magnet Tunnel Thruster” (TT-PM) was identified to become a suitable case fitting the project description of low volume, large and complex products. The original design of the TT-PM requires a high degree of manual labour operations. Hence, it was early on identified that automation of the existing design would not be cost efficient since it was not initially designed for automated assembly.

This paper addresses how RRM has approached the challenge of delivering a successful solution for automation of the rotor assembly by redesigning the TT-PM, pointing at lessons-learned and the challenges of going forward to industrial implementation. As a starting point, we seek to explore the following topic:

- Integration and implementation of 'new-to-the-company' type technology in product realization projects, leading to (radical) changes in existing practices and capabilities within design, process and technology. More specifically, aiming to identify the multifaceted challenges of moving from a manual to an automated assembly process for large and complex products when this endeavour involves transferring technology from the early (low readiness) phase to full industrial implementation.

This paper is organized as follows: Section 2 presents a conceptual model that we have denoted the *capability pyramid*, along with related theory focusing on the following topics: Integrated Product & Process Development, Design for Manufacturing, Manufacturing Strategies and Technology. Section 3 describes the case study of Automated Assembly of large and complex products in RRM. Section 4 presents Recommendations and Further Work and finally concluding remarks of the paper is presented in Section 5.

2.THEORETICAL BACKGROUND

The four-level hierarchical capability pyramid in Figure 1 depicts a visual representation of the situational description to be investigated in Section 3. Basic theory associated with each level of the pyramid will be presented below. The pyramid aims to describe the identified challenge as to how current capabilities (*Business-as-usual*) in the organization are affected when a project that involves new-to-the-company type of technology is to be introduced. Within each hierarchical level, the current capabilities must be reviewed and adapted to the technology development project—and vice-versa—before the organization arrives at a new technology capability representing the future standard. Also, each level in the pyramid must be seen in connection to each other in order to maximize the capabilities of the organization as a whole; i.e., an integrated system. For example, investing in new manufacturing processes alone will not guarantee improved performance. On the other hand, if one ensures that design is modified to the new manufacturing method and that these two levels are collectively aligned with the company's manufacturing strategy, and that the product and process are integrated and developed concurrently, then the overall capability—as represented by the company's ability to satisfy customer needs—does increase. In Figure 1, the iterative concurrent interactions between levels are represented with arrows. The more effective iteration between the different levels, the more we can optimize the organizations capability as a whole. The height of the pyramid represents the overall outcome of this optimization; if one level fails to enhance its capabilities according to the new technology, the pyramid gets lower and hence the capability becomes suboptimal.

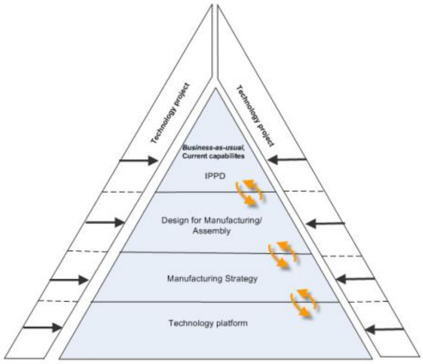

Figure 1 Capability pyramid

2.1 Integrated Product and Process Development (IPPD)

Introduction of a new product can either be done by means of existing manufacturing processes, a modified manufacturing process or it can even require a complete new manufacturing process [3]. Research indicates that up to 85% of the manufacturing costs are locked in by the product design [4, 5]. Hence, to achieve significant cost reductions in manufacturing, it is necessary to consider design and manufacturing in close connection with each other. If design and manufacturing cooperate at an early stage in the NPD (New Product Development) project, trade-offs and compromises can be made between the product and process designs to save both cost and time related to wasteful redesigns [3].

According to Department of Defense Integrated Product and Process Development Handbook [6], "*IPPD is a management technique that integrates all acquisition activities starting with requirements, definition through production, fielding/development and operational support in order to optimize the design, manufacturing, business and supportability processes"*. IPPD is the concurrent, coordinated development of the product and the processes to realize a product in the market place. Further, IPPD emphasizes the use of prototypes both to demonstrate product functionality, and to demonstrate the manufacturing and service processes [7]. It may be claimed that IPPD is essentially based on the same ideas as concurrent engineering; i.e., to shorten lead time and improve quality [8, 9]. If the design is radical, however, it can be difficult to work concurrently since radical innovation is difficult to plan [10]. According to Tempelman et al. [10], definition of the manufacturing process must be done gradually and iteratively as part of the project progress. Further, as IPPD for the most aims to optimize the product and process by iterating over one design solution ('point-based') it is not given that this is the best starting point for an optimal outcome [11].

Sobek et al. [11] popularized the concept of "Set-Based Concurrent Engineering" (SBCE); i.e., considering multiple solutions and then gradually narrowing down the range of options before ending up with one final solution. The paradox of SBCE is that considering a broader range of designs, decisions are delayed compared to other companies, yet the process seems to be faster and more efficient. Hence, investing time up front ('front-loading') to explore solutions both from a design and manufacturing perspective may lead to gains in efficiency and product integration capability later in the process.

2.2 Design for Manufacturing and Assembly

The theory of concurrent development of product and process includes the concepts of Design for Manufacture (DFM) and Design for Assembly (DFA). The idea is to reduce the manufacturing cost such that the design eases manufacture of the parts making up the complete product without compromising quality of the final product. Design for Assembly is a branch on the 'DFM-tree' pioneered by Boothroyd & Dewhurst [12], aiming to achieve the lowest assembly cost. This essentially means achieving an efficient assembly performed by the most suitable assembly system (manual, special-purpose machine or programmable machine assembly).

In the book Mechanized Assembly [13] Geoffrey Boothroyd & A.H Redford studied automatic assembly and recognized that the impact of designs on reducing cost was much more important than the use of mechanized assembly; considerable cost savings can be achieved by a careful consideration of the design of the product and its individual component parts.

To find out that a chosen design does not combine well with earlier decisions can be both time-consuming and complex [10]. However, by considering both manufacture and assembly at an early stage in the design process, there is an opportunity to avoid changes in the design late in the process when the cost of change is high and there is also a risk of delaying the new product in the marketplace. Sometimes DFM can also be rewarding to the design as the choice of manufacturing process can improve the initial design idea [10]. The principles of DFM and DFA have been of great importance in industry. It is well recognized how DFM guidelines have improved quality and reduced cost [14, 15, 16, and 17].

2.3 Manufacutring strategies

The manufacturing strategy should support the company's competitive priorities and support the creation and selection of the organizations future operational capabilities [18, 19]. Successful decisions about automation go in line with what the company aims for in the long term, and the decisions are synchronized with the manufacturing strategy and present capabilities [20]. The Levels of Automation (LoA) concept explains and expresses the continuum of different degrees of task sharing between humans and technology, see [21]. There are several factors to consider in connection with automation of the assembly process; both under and over-automation can have negative influence on competitiveness [18]. Considering automation, each component must be analyzed in terms of shape; how to feed and orient them, material and tolerances, [22]. Up until recently, manual labour has been the preferred production method when components are technically too complicated to assembly or manufacture when the product has a short life cycle and fast market introduction is required, for customized products, and when demand is fluctuating, [23]. Further, HS&E and high risk areas for automation must be considered. Successful decisions regarding automation should be aligned with the company's long term goals, and decisions should be synchronized with the manufacturing strategy and present capabilities, [21].

2.4 Technology

In the early days of the individual companies that today is a part of RRM, products were typically designed by the designer who went down to the manual lathe or milling machine to see how to design the products for easier manufacturing. In the 1970s, Numeric Controlled (NC) machines where introduced and the programmer's role in developing programmes, making jigs and fixtures, etc. increased significantly. Today, there is a shift in that the designer again is gaining more control of the whole process by using simulation tools such as CAD/CAM/FEA, etc. The product geometry and most of the corresponding manufacturing process can be described virtually in computer models, and hence defined simultaneously. Also, programming modules can run simulations and calculate cost. This provides the opportunity to consider several scenarios and to be more confident about predicted behaviour. Further, new technology such as 3D printers and robotics enable more flexible production. The new technology may give a more seamless integration of design, product development and manufacturing, and an improved infrastructure for sharing information. However, according to Jordan et al., today's designers of complex products must consider many issues beyond the technical design challenge, and it can be difficult to develop sufficient understanding to cover all disciplines [24].

For many years, small-volume production has weighted the cost of material and labour less important than what is seen in high volume production (i.e., Toyota in the automobile industry [25]) where it is commonly justified to spend significant resources on tooling and engineering [16]. Assembly robots have been used in the manufacturing of simple products in large volumes. As many as hundred thousands or millions p.a. can be necessary to justify a fully automatic assembly operation with dedicated production equipment. Further, assembly operations are difficult to automate since the human operator is capable of many subtle manipulations, adjustments and compensations for component variation. However, the development of computer-controlled robotics during the last few years makes automatic assembly economically feasible at much lower quantities than in the past. In addition, robots have become less expensive. As robot applications are more used in the high-mix, low-volume segment, the time available to program them is reduced.

3. CASE STUDY: AUTOMATED ASSEMBLY OF PERMANENT MAGNET TUNNEL THRUSTER (TT-PM)

Since some specific results from this study already are available, we have chosen to denote it a case study although the study is still ongoing and therefore may be considered more of a proof-of-concept. In Section 2, a capability pyramid and theories associated with IPPD, Design for Manufacture/Assembly, Manufacturing Strategies and Technology have been presented in brief. These will now be seen in connection with efforts made in an ongoing technology project in RRM, named Autoflex. The aim is to point at the main experiences and some of the challenges implementing 'new-to-the-company' type technology, leading to changes in existing practices and capabilities. RRM wants to extend their capabilities in new automation solutions for assembly of products that are typically made-to-order or engineered-to-order. The goal is to develop a flexible, automated assembly system for products that are large and complex and do usually not call for automated assembly. Here *flexible* means a system that has reconfigurable assembly equipment, one that is scalable to fit a wide range of the product family. Further, *automated* refers to the use of robots with software that are programmed and setup to perform several operations at the same time, while taking into consideration logistics, number of interfaces and work in progress. By *complex* we mean products with a complex functionality built up by hundreds of components/parts.

3.1 Selection of product as demonstrator in the Autoflex project

The Permanent Magnet Tunnel Thruster (TT-PM) is the latest tunnel thrusters design from RRM. Evaluation of technology and development of the first design and sketches started out in the early 2000s. The permanent magnet technology is new to RRM, and in 2013 RRM acquired a company with leading technology of permanent magnetised electrical machines [26]. The PM motor consists of two main parts, stator and rotor, that must be seen in connection with each other. The stator carries a number of electrical coil windings, and the rotor is fitted with strong permanent magnetised magnets. Figure 2 shows the conventional TT-PM 1600 design with a propeller diameter of 1,600 mm and a total thruster weight of more than 7,000 kg.

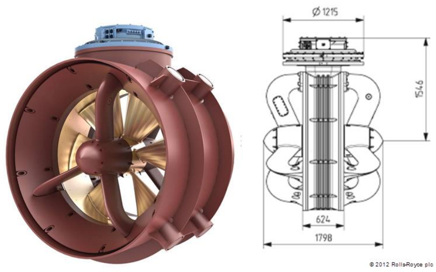

Figure 2 TT-PM 1600 conventional design built from existing technology platform [26]

TT-PM has complex functionality and strict requirements to operating life. To verify reliability of the product, experiences with a non-optimal production process was necessary to avoid introducing too many variables at once. Still this production process required knowledge about both filament winding and magnetization. The prototype/pre-series processes were labour-intensive, and the magnetization process also had challenges related to HS&E. To enable competitive production of the TT-PM in Norway, this called for significantly more effective production methods moving from pre-series to product optimization. RRM also had a vision of automated production of TT-PM using robots, thus making TT-PM a suitable candidate for a demonstrator in the Autoflex project.

3.2 The Autoflex project

Autoflex is a project that started in 2012 with support from the external research community and collaboration with other companies (mainly experts in manufacturing and automation) as a supplement to internal RRM resources. In order to succeed with automation of the TT-PM, it was early identified that this would not be economically feasible without making significant modifications to the existing design.

A small multidisciplinary IPPD team with expertise in functionality, design for automation (external company) and RRM Engineering was assigned to make the design more suitable for automation. The existing design for automated assembly competence was limited within RRM because this capability had not been seen as crucial as complexity and volume of the existing product portfolio do not call for automated assembly. According to Leenders et al. [28] existing knowledge within an organization is often inadequate to succeed with a competitive new advantage, hence requiring high levels of creativity. Seeking competence outside the company and applying an open innovation approach [27] leveraging external resources with design for automation competence have gained the multidisciplinary competence needed. This has been of vital importance to launch a demonstrator within a period of only two years.

To ensure that the re-design was not done at the cost of efficiency and functional compromises, such as noise and vibrations, the following working method has been used: Starting with RRM requirements and related manufacturing set-up as basis, a description of how to re-design and manufacture the components was presented to design-for-automated-assembly experts who subsequently developed the process and decided which tools and equipment to be used. To ensure proposed rotor configurations to be in compliance with functional requirements, design reviews were conducted by RRM experts in permanent magnetised electrical machines. Further, weekly meetings were held to ensure that the team maintained a common understanding as iterations led to further improvements of the design.

When introducing a new product or re-designing an existing one, as the TT-PM, the team will need to make trade-offs both in terms of outcome (time-cost) and desired manufacturing methods versus product functionality [3, 10, 17, 24]. To be able to do optimal trade-offs extensive knowledge of both production process and product functionality is required. As mentioned, it took two years from the first vision of a fully automated production to launching a successful demonstrator of automated rotor assembly with the new design. According to the project manager, this illustrates the potential of developing the design of the product and production/assembly-process in parallel. However, this presumes that a multidisciplinary team has the knowledge required in terms of manufacturing process, product functionality and design for automated assembly. Further, introducing a small team that does 'skunk work' [29] outside business-as-usual has made it possible to be creative and to do more optimal trade-offs. Figure 3 illustrates how future technology projects can be similarly organized by allowing a small team to work outside the existing boundaries of their departments to develop new capabilities. Such a small team has proven to be very efficient once people with the right skills are chosen. A technology project typically serves to stretch the organizations existing capability; the higher the peak (in Figure 3), the more radical the solution. When the technology project is ready for industrialization and ready for handover to the operational part of the organization, the findings in the technology project must be verified with a proof-of-concept demonstrator. Further development from this point requires that balance is established by multiple iterations between the team in charge of the technology project and the team running the commercial business-as-usual project. The final solution is often a compromise between current capability and the ambition level of technology projects, as illustrated in Figure 3.

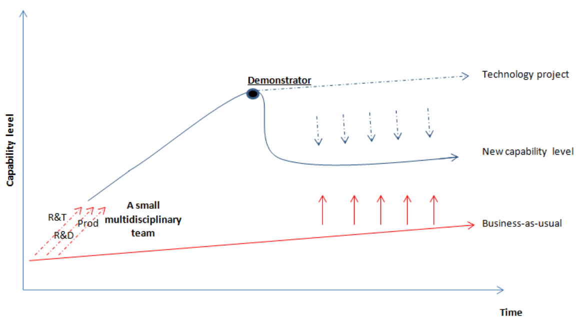

Figure 3 Establishing the organizations new capability level by balancing Technology project with Business-as-usual

Since Autoflex is a technology project, it was not possible to know in advance if automated assembly of RRM products could be done with economical profit and at the same time satisfy functional requirements. A mix of people from RRM—mostly people from manufacturing and a few designers due to time and availability of resources—was also involved in the Autoflex project. It became soon clear that there was some resistance against re-designing the product mainly because the traditional design is built on a set of known principles along with RRM engineers' expertise on complex functional requirements. According to the experience gained in this project, this is one of the main challenges when only a small team is doing the re-design. According to Cheney et al. [30] one reason for resisting change is that the outcome of the proposed changes is uncertain. Therefore, an important next step will be to continuously eliminate uncertainties by using demonstrators to verify the re-design, and thus making it easier to bring the organization to the new capability level.

3.3 Results of re-designing rotor for Automated Assembly

The results to be presented in this section are related to the re-design of the rotor as the stator is still in the research phase and not ready to be demonstrated yet. The project group emphasises the need to see assembly in connection with machining. An example is dimensional accuracy of the last component due to tolerance stack-up upon assembly; this can be avoided by ensuring only one set-up in combination with a dimensional strategy for hard points on the component in machining. New technology and programming methods (combining off-line and on-line programming) allow cost effective deployment of the robotic system, which is described in Linnerud et al. [31]. Also, a flexible control system that eliminates the need for changes when introducing new products has been developed, i.e. there is no need for reprogramming between different components in the component family. Traditionally, the different paths to a product is 'hard coded' into either the PLC or robot control. This makes the solutions less flexible for changes and variations between products. Here this limitation is eliminated by creating a program that is built up with a dynamic set of rules to generate and build patterns to PLC or robot. An example of such a rule is to identify dependencies between components and establish the assembly sequence accordingly.

In the literature, several sources have shown that re-designing for automated assembly has led to cost savings in both material and machining as described in [10, 13]. In this study, one of the main changes was to re-design the components in such a way that they can be handled with standard robots. Table 1 lists some examples of design improvements to make the TT-PM more suited for automated assembly as experienced by the team.

Table 1 Re-design for automated assembly of rotor

Design for automated assembly	Conventional design	Re-design
Parts to be handled by standard robots	Not able to handle large parts with standard robots	Re-design for components to be handled by standard robots
Standardization of screw dimension (less components type to handle, one tool and one feeder)	M16 and M12	M16 replaced with several M12 (smaller bolt head solves space problem).
Bolt holes are re-designed to avoid collision with propeller blades.	Vertical bolt holes. Not enough space for torque wrench	Angular bolts to ease access for mounting tool
Reduce number of parts and operations	Dowel-pins and magnet yokes two separate parts	Dowel pins changed to be machined as part of the magnet yokes.
Simplify entering of yoke		Chamfer on the dowel-pins Force-transducer technology
Fewer feeding systems and types of components	Different design based on how many screws are needed	Standard magnet yoke design with the same amount of bolt holes. However, number of bolts that needs to be mounted varies around the propeller.
Simplify insertion		Larger entering on the dowel-pins
Conical entering to decrease need of accuracy	High demand for precision	The conical section is tighter than the clearance of the dowel pin hole so it will always enter
Reduce the need for precision. Enable use of simpler tool	Not control of component entrance	Expanding dowel-pins in connection with controlled entrance of components (force transducer and tightening in two operations)
Remove cycle-time bottleneck	Filament winding	Encapsulation of magnets
..	..	..

3.4 Set-based approach applied to product development of large and complex products in RRM

Figure 4 is showing the concept of "*Set-based concurrent engineering*" [11] applied on business level to integrate the new technology with the existing product development in RRM; unlike Sobek et al. [11], who applied the concept on product concept level. The figure illustrates the technology project Autoflex represented with the task "Re-design for Automated Assembly of Rotor" (Table 1) on the left side. The right side represents the existing product platform and current capabilities in the company.

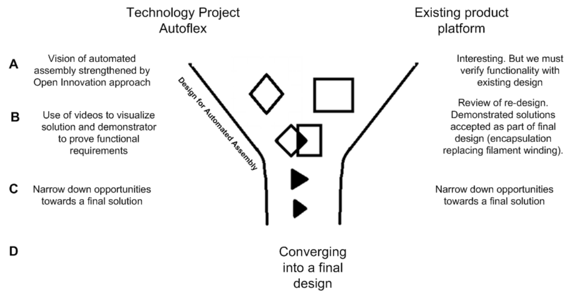

Figure 4 Set-based approach to product development of large and complex products

Sobek et al. [11] emphasize the importance of working with several sets of solutions and then gradually narrowing down ranges of options. In the RRM case, the technology project and the conventional design have been developed in parallel, which essentially means that the latter is a candidate for rejection while moving down the 'waterfall'. In the end, these two solutions will converge into one final solution. To work with two solutions in parallel in the production implementation phase is demanding, yet necessary. Firstly, the strategy serves to verify the complex functionality of the product. Secondly, since the outcome of Autoflex (phase A) was unknown from the beginning, a safe fall back is needed to meet the project time line. Re-designs must prove to fulfil functional requirements before deciding if they can be adapted as a final design, which was the case with encapsulation replacing filament winding (phase B), see Figure 4.

As emphasized by previous IPPD research [7], both demonstrators and videos have been of vital importance to 'sell' the idea/vision of a fully automated assembly of TT-PM internally and to verify how the re-design fulfil functional requirements. So far, this has enabled smooth integration with the existing product platform. In phase C, Figure 4, one continues to develop both solutions as the solutions gradually merge into an industrial solution.

The challenge of going forward includes narrowing down and converging these two solutions into one future design (product and process)—not only for TT-PM but also for future PM products (phase D). This will obviously influence all the levels in the capability pyramid that was presented in Section 2. Communication and iteration within the organization is important to ensure that the organization's capability as a whole is aligned with the final design solution. In Figure 4, the black triangle(s) represents the design as a result of merging the two solutions. How the new static organization will look like depends on which elements of the re-design in Autoflex that will be incorporated as part of the future conventional design, especially since the outcome of the ongoing re-design of stator solution (part D) is unknown at the moment.

4. RECOMMENDATIONS AND FURTHER WORK

As illustrated in Figure 5, the outcome of the Autoflex project will form the basis for future guidelines for automated assembly handed over to support R&T (Research & Technology) and R&D (Research & Design). These design guidelines must be seen in connection with Manufacturing Strategy, Technology platform, as well as existing and future capabilities.

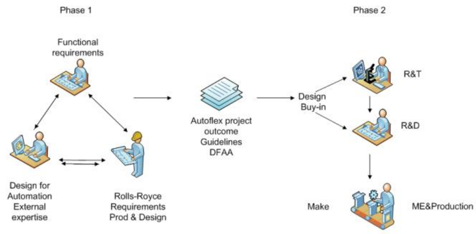

Figure 5 Autoflex guidelines for future capabilities

The successful development (Phase 1) of a rotor assembly demonstrator has shown that the automated assembly of the rotor is feasible. The next challenge (Phase 2) is to incorporate knowledge and best-practices established through the Autoflex project in the design of TT-PM, as well as future PM products and technology/development projects in general. In particular, this will be a challenge for the TT-PM case, where a small team has introduced radically new designs seen in relation to the existing pre-series design. The technology project has given the company insight into what can be achieved, providing a valuable input to resource and technology investments in the future (from Phase 1 to Phase 2). For example, should the design be done for a special type of robot or, alternatively, be made applicable to a general design and rather have the robot adapting to the design?

A strategy for automation and level of automation (LoA) should be in place, as emphasized by Frohm [21], together with a committed ambition level aligned with production, requirements and demands. Examples of such an ambition could be to design all bolt configurations so that they can be mounted with a robot. The next level would be to design the rotors to be assembled by robots, and the higher ambition level of having no manual assembly of PM products. Deciding on the correct level of automation requires knowledge of automation and what is possible and what is not. Gaining the necessary competence of what is possible comes at a price, though. The question is whether or not to pay the price required for gaining the necessary knowledge. In this particular case, it has proven to be beneficial to invite in external competence to support this project and combine internal RRM product expertise with external expertise in automated assembly. This has resulted in an automated rotor assembly that satisfies the criteria's of HSE, reduction in manual work, Lean production and reduced work in progress after only two years.

4.1 Future capabilities in R&T and R&D development

The Autoflex project has enabled vision programming and configuration directly from the CAD model. This provides more flexibility with regards to size and number of parts. To optimize further, one should look for opportunities for the use of common parts, as well as design parts for use of common production tools in the development of the complete TT-PM range. When exploring automated assembly, one should also consider the opportunities for standardization along with product platforms. Introducing robots and automated assembly will not change the existing design process. However, designers must consider guidelines for automated assembly, e.g. knowing which robot to design for. If a flexible production is utilised to make more project specific designs of the rotor, existing working methods will have to change. In general, one will need to focus more on parameterization and design automation. This is possible but requires more advanced use of CAD and other tools as well as the functions that support the capture and re-use of design intent and user intelligence.

5.CONCLUSION

To enable competitive production of the TT-PM in Norway, a technology project named Autoflex was defined to develop more effective production methods—i.e., automate assembly—while moving from pre-series to product optimization. Introducing 'new-to-the-company' type technology in product realization projects is a major challenge since it enforces the company's existing capabilities to change. This is particularly difficult when critical product functionalities must be validated simultaneously as the production technology, which was the case for the new TT-PM design considered herein. Therefore, exploration activities within the technology project have to run in parallel with exploitation activities within the existing product platform, since the outcome of the Autoflex project was uncertain and a fall-back solution was needed to manage risk.

A small IPPD team with the necessary expertise has been assigned to make the design more suitable for automation. Re-designing for automated assembly has led to savings in both material and machining, supporting the findings described in [10, 13]. Applying an open innovation approach [27] by leveraging external resources with towering design-for-automation competence has been of vital importance to achieve a demonstrator within a period of two years only. During this process, weekly meetings were held to ensure that re-design was not done at the cost of efficiency and functional compromises, such as noise and vibrations, for the TT-PM. The combination of the team-members' knowledge and capabilities is what creates new knowledge and insights [28], which proved to be essential to make necessary trade-offs to maintain acceptable risk levels as seen from a business perspective.

The technology project has proven that automated assembly of large and complex products is feasible when effectively combining proven technology and suitable design concepts. From an economical point of view, however, the key is to re-design the product for the manufacturing process employed; examples of such design modifications include part handling with standard robots, enabling tools to get access where needed, standardization of bolt configurations, reduced need for precision by using expanding dowel-pins, and in-process force-transducer technology.

Technology projects typically serve to stretch the organization's existing capability and can thus be considered as *radical* by the rest of the organization. Here, prototypes or demonstrators are important artefacts to verify that results are not achieved at the cost of functional requirements or any other compromises that degrade the value of the product as perceived by the customer. This will also help overcome internal resistance towards change [30]. The resulting outcome of a project is usually a compromise between the existing capability and the ambition level of technology projects, as illustrated by the simple model in Figure 3 above.

By developing new technology in parallel with an existing product platform, complex functional requirements can be verified at the same time as the establishment of an optimal manufacturing process concept for industrial implementation. The process of converging into one final successful design from the sets of different options is largely dependent on inter and intra organizational communication strategies. These must ensure that the organizational capability as a whole is aligned with the requirements of the final design as represented by the needs of the customer as well as intermediate (internal) customers and stakeholders. This process is particularly demanding, yet necessary, and will impact all four hierarchical levels in the capability pyramid model presented in Section 2.

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Supportive paper 2

Bridging the gap between high and low-volume production through enhancement of integrative capabilities

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Abstract: Today—more than earlier—value creation, competitiveness and sustainable growth are dependent on development and utilization of new technology. New technologies enable new ways to develop products and production systems and may improve infrastructure for sharing information. These new technologies bridge the gap between production systems, function and design – and hence between highvolume and low-volume production. For manufacturing companies this represents a true paradigm shift referred to as Industry 4.0. Within this emerging endeavour, organizational learning and social and technical skills become increasingly important to enable faster and leaner operations. In this article, prior art of integrated processes, tools and guidelines for design has been studied. This will be seen in connection with how a company that operates in Norway have succeeded with developing an automated assembly solution for a large and complex product produced in low-volume by re-designing the product and its automated production process in parallel; i.e. a manufacturing context that is usually regarded as difficult to automate in an economical way. As automation knowledge within the company was limited, capabilities have been developed and demonstrated together with selected research partners in a technology project named Autoflex. According to our findings, to sustain competitive within a rapidly changing industry is dependent on, 1) a company's ability to absorb new technologies and provide flexibility within work environment-production system to maximize capacity utilization; 2) processes that facilitates team-work and iterative product and process development; 3) supporting tools such as design guidelines for sharing knowledge between production and product engineering. As a result, companies that succeed in enhancing their integrative capabilities will gain competitive advantage long term.

Keywords: Integrated product and process development, Industry 4.0, Design-guidelines, Case study, Competitive manufacturing

1.INTRODUCTION

1.1 Background

In a rapidly changing industry, companies must constantly introduce new products to survive and adapt their strategies to change. To sustain competitive in a high-cost country, like Norway, companies must establish modus operandi that leverages rapid learning as a means to introduce new products, processes and technologies faster than their competitors. Today, value creation, competitiveness and hence sustainable growth are increasingly dependent on development and utilization of new technology. This changes the premises for global competition and consequently the company's business system. For example, the recent developments within IT, electronics, robotics and additive manufacturing have increased the use of smart robots, smart machines and cyber-physical systems. These technologies may enable more flexible production systems, allowing companies to change and adapt more quickly to changes in customer demands and the market. Furthermore, robots have recently become less expensive and at the same time more 'intelligent', providing improved capabilities to adapt, communicate and interact. This, in combination with the development of more advanced CAM solutions, has made automated assembly financially viable at much lower quantities than in the past. Again, this can lead to productivity leaps for companies and impact cost structures, facility layout, and what skill-sets are required (Blanchet, Rinn, Von Thaden, & De Thieulloy, 2014). For manufacturing companies, this represents a true paradigm shift that is referred to as Industry 4.0 (MacDougall, 2014).

This new industry trend also influences the old regime of outsourcing production to low cost countries—an earlier effort to gain competitive advantage. The new enabling technologies may reduce labour to a less significantly portion of the production cost. This implies that low labour cost alone may no longer be sufficient to ensure competitive advantage long term. Moreover, factors such as quality problems abroad, technology leakage of IP, loss of core activities, high monitoring and coordination costs trigger companies to deploy back-sourcing strategies. Even more importantly, outsourcing often erodes competence development in manufacturing and product engineering, which is almost impossible to regain when teams work decoupled from production. Future-oriented businesses are thus realigning their operations to increase the level of in-house production by investing in advanced production technology. For example, Tesla has built one of the world's most advanced automotive production lines (Tesla motor team, 2014) in high-cost California, and Norway-based Kleven Verft is back sourcing the complex structures of ship hulls by investing in advanced robotics for welding (Kleven, 2012).

1.2 Motivation

In today's hostile market situation, one of the most important precompetitive factors is simply to design a product with the 'right' unit cost. To sustain competitiveness Rolls-Royce Marine (RRM) has identified a need to establish more cost effective product realization methods. In a research project, named Autoflex, RRM together with research partners have demonstrated automated assembly of large and complex products that require close dimensional tolerances. This has been facilitated by combining design-for-automation, state-of-the-art production technologies and assembly simulation strategies. The goal of the project was to achieve cost-effective manufacturing of low volume, complex and heavy products in high-cost countries. The case product, a Permanent Magnet Tunnel Thruster (PM-TT), is the most recent tunnel thruster design from RRM. Re-design of main components has reduced the assembly and manufacturing cost significantly, and hence indicated that automated assembly of this type of products is viable both technically and economically.

The project has truly changed the mind-set of production within RRM. It is now widely recognized that the company by absorbing new technologies can provide the flexibility required within the work environment-production system to improve its competitiveness, and bridge the gap between low-volume and high-volume production. This requires holistic-thinking and rapid innovation processes utilizing integrated *technology, product and process development*; in other words, delivering cost-optimized products based on what the customer wants. Such new design methods must not only consider function, production and service, but also organizational aspects such as quality control, procurement, logistics and control of material flow.

This paper addresses new deployment strategies for integrated technology, product and process development. We seek to summarize the working methods and design principles developed in the Autoflex project. The research involves three main themes in the context of high-complexity, low-volume products; design process knowledge, tools and guidelines used in the design process; and the recent trends in technology development, see Figure 1.

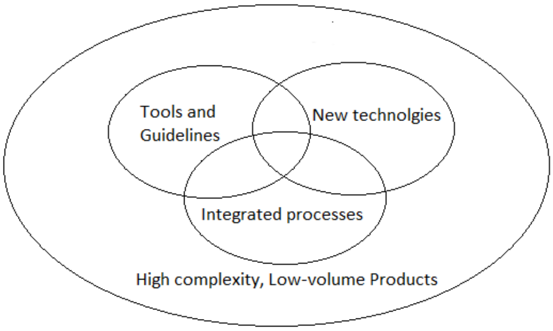

Figure 1. Research themes to be investigated within the high-complexity, low-volume context

This paper seeks to explore the following two research questions:

1. How to ensure systematic utilization of Integrated Product and Process Development (IPPD) to enhance the organization's integrative capabilities in developing a powerful system of people, process and technology?

2. Identify the tools required to facilitate communication between production and product engineering to build knowledge in design-for-automation of large and complex products produced in low volumes?

The reminder of this paper is organized as follows: Section 2 presents recent trends in manufacturing, also referred to as Industry 4.0, which may change the premises for technology, product and process development. Section 3 presents relevant literature on integrated product and process development, including IPPD, Concurrent Engineering, Lean and Agile product development, and finally design guidelines and tools facilitating these processes. Section 4 addresses the two research questions with basis in literature and the Autoflex project. Finally, Section 5 presents concluding remarks.

2.INDUSTRY 4.0

Reports by Roland Berger (Blanchet, Rinn, Von Thaden, & De Thieulloy, 2014) and Germany Trade & Invest (MacDougall, 2014) describe the 4th industrial revolution, where physical objects are seamlessly integrated into information networks. This may result in improved infrastructure for sharing information where design, product development and manufacturing are more closely integrated. In combination with increased digitalization, this may open new ways of designing products and manufacturing systems. An example is 3D-printed parts, which change how a part can be built up and manufactured. The interplay between product design and production may create changes in a company's existing technology platform. The Industry 4.0 concept is representing a paradigm shift in terms of operation and sustainable business. Field devices, machines, production modules and products are comprised as Cyber-physical systems (CPS) that are autonomously exchanging information, triggering action and controlling each other independently (Weyer, Schmitt, Ohmer, & Gorecky, 2015). This facilitates improvement to the industrial processes involved in manufacturing, engineering, material usage and life-cycle management. The manufacturing process will be more transparent, facilitating improved decision-making and learning loops leading to better products.

Companies must invest in R&D to keep phase with technology and be able to offer integrated solutions (Blanchet, Rinn, Von Thaden, & De Thieulloy, 2014). The technology transformation of companies requires not only capital investment, but also investment in acquiring the necessary knowledge (Schuh, Potente, Varandani, Hausberg, & Fränken, 2014). To develop industry leaders within Industry 4.0, the following three success factors are required, according to Blanchet et al. (2014);

- Accelerate innovation by creating and leveraging knowledge from research communities;
- Develop future champions that are able to keep up with technologies, enabling them to offer integrated solutions;
- Establish a dynamic, digital competitive environment that fosters telecommunications and internet usage.

A challenge often faced by companies is launching a new production plant or a new product in an existing factory. Hours of adaption, trials and pre-series are costly and time-consuming. Especially programming of an industrial robot for a specific application can be complex and expensive. Within the Industry 4.0 concept it is possible to create virtual plants and products to prepare the production by simulating and verifying each process virtually (Blanchet, Rinn, Von Thaden, & De Thieulloy, 2014). Further, the development of 3D CAD/PLM software, computer vision, sensor technology and new programming methods may increase the use of robots in the coming years, especially for SMEs where the complexity of programming has been one of the main obstacles blocking them from using industrial robots (Pan, Polden, Larkin, Van Duin, & Norrish, 2012).

3.THEORETICAL BACKGROUND

3.1 High Complexity, Low-volume Products and Production

In this section, we present basic theory related to *integrated technology, product and process development*, including tools and processes. First, we define the terms *high complexity* and *low-volume products*, which are central elements of the context serving as motivation for this research.

According to Hobday (1998; 2000), number of components, depth of knowledge and skills required, degree of customization and other critical product dimensions collectively determine product complexity. Similarly, Bhise (2014, s. xxi) argue that "*the complexity in a product can be attributed to an increase in the number of parts; number of systems needed to accomplish product functions; number of external systems affecting the product; types of technologies associated with the system; number of interfaces among the systems; number of variables associated with the systems and their interfaces; number and types of users and uses and variations in the operating environments and number of disciplines or specialized fields needed to analyse, design, and evaluate various components and systems*". A natural consequence of more complex products is a more complex design process. As the design process is more difficult to execute and control the need for design support increases (Tichem, 1997). Complex products are more common in low-volume than in high-volume production. In mass production, architectures are usually relatively simple and most production tasks can be standardized and automated to achieve cost reduction due to economy of scale. Individual parts are usually with little or no variation, and large quantities are fabricated with short cycle times. On the contrary, engineeringto-order products are manufactured to meet a specific customer need by carrying out unique engineering tasks or significant customization (Willner, Powell, Duchi, & Schönsleben, 2014).

High-volume production is often linked to simple products whereas low-volume production is often linked to customized products. Jina et al. (1997) defined the low-volume production rate as 20-500 units p.a. To simplify and answer the problem statement, we refer to the two extremes high volume, low complexity products and high complexity, low volume products. The typical product introduction in low-volume production include few engineering prototypes, limited and uncertain numbers of pre-series productions and the infeasibility of conventional production ramp-up. Other identified factors include the modification of existing products, the use of existing products instead of the development of entirely new products, and the use of existing production systems with slight modifications for new products (Javadi, 2015). According to Vallhagen et al. (2013), it is more common to focus on functionality of a product than its manufacturability in low-volume production compared to high-volume production industries. Further, in high-volume production there is a higher focus on reducing cycle-time allowing more effort up front for example to develop customized tools. The product's functionality and its characteristics are of less concern compared to the development of custom-engineered products where product performance is critical and the technology is often at the front end (Vallhagen, Madrid, Söderberg, & Wärmefjord, 2013). Table 1 summarises the characteristics of the two production extremes.

Table 1. Characteristics of High-volume and Engineer-to-order production (Hobday, 1998; Vallhagen, Madrid, Söderberg, & Wärmefjord, 2013; Willner, Powell, Duchi, & Schönsleben, 2014)

	High volume manufacturing of low complexity products	**Engineer-to-order manufacturing of high complexity products**
Parts	Small and simple. Interchangeable parts/standardization.	Large and complex. Customization.
Volume	High.	Small batch/ one of a kind.
Innovation process	Product development→ customer demands. Focus on manufacturability.	Customer demand→ Product development. Focus on product function.
Machines	Small. Specialized tools. Fixed.	E.g., a large machining centre. Common tools. Flexible.
Economies of scale	Yes	Fewer parts to share cost.
DFM/DFA	Applicable.	A view often taken is that it is less applicable (Boothroyd, 1994).

3.2 Integrated Product and Process Development (IPPD)

For a company to convert its technology and ideas into new products that meet customer requirements, a product development system that effectively integrates people, processes and technology is needed (Liker & Morgan, 2006; Morgan & Liker, 2006). Integrated product development (IPD) is the overlap of certain activities in the new product development process to improve performance and reduce development time (Gerwin & Barrowman, 2002; Sommer, Dukovska-Popovska, & Steger-Jensen, 2014). This holistic approach to product development was first presented by Takeuchi & Nonaka (1986) and is based on the following six characteristics built-in instability; self-organizing project teams; overlapping development phases; "multi-learning"; subtle control and organizational transfer of learning.

Development of a new product also requires new processes such as manufacturing, logistics and processes to collect and disseminate information gathered (Department of Defense, 1998).

The term Integrated product and process development (IPPD) is defined by the Department of Defense (1998, s. 1) as; "*a management technique that integrate all acquisition activities starting with requirements, definition through production, fielding/development and operational support in order to optimize the design, manufacturing, business and supportability processes*". IPPD emphasizes the use of design tools, such as modelling and simulation, and other commercial best-practices to develop product and process concurrently (Department of Defense, 1998; Jordan & Michel, 2000). IPPD is a broad concept where a multidisciplinary team, including engineers, technical specialists, customers and business and financial analysts, are responsible for delivering a defined product and/or process as driven by the customer's need (Department of Defense, 1998). The interactions within the design process are rapid, highly concurrent, highly interactive and iterative (Jordan & Michel, 2000) emphasizing customer input and creating more manufacturable designs (Gerwin & Barrowman, 2002).

Integrated and parallel development of the product and supporting processes aim to ensure that cost and complex issues are not overlooked in the phases when the cost of making changes is low. For example, manufacturing concerns overlooked in the early phases may create design changes and loopbacks when they surface. It is argued that as much as 85% of the manufacturing cost are locked in by the product design (O`Driscoll, 2002; Boothroyd Dewhurst, 2015). Therefore, it is important that designers receive rapid feedback in the early concept stage where the possibility to influence detailed requirements is high (Vallhagen, Madrid, Söderberg, & Wärmefjord, 2013), either by using manufacturing analysis tools (Boothroyd, 1994) or by using the competence of manufacturing engineers.

According to the Department of Defense (1998) IPPD evolved in industry as an outgrowth of efforts such as Concurrent Engineering (CE). On the other hand, Gerwin and Barrowman (2002) view CE, together with various expressions such as Design for Manufacturing and Quality Function Deployment, as another manifestation of IPD activities. Jordan and Michel (2000) use IPPD as a generic term to convey product realization made by a highly concurrent interactive environment. What all these 'schools' have in common is the aim to avoid costly redesign, unpredicted problems or compromises that degrade the final product (Jordan & Michel, 2000).

3.3 Concurrent Engineering

According to Winner et al. (1988, s. 11) "*Concurrent engineering is a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life-cycle from conception through disposal, including quality, cost, schedule, and user requirements*." Pahl et al. (2007) define CE as *parallel processing of activities* where the product, the manufacturing process and supporting activities are engineered at the same time (Bralla, 1999). This may lead to shorter development time, faster product realization, reduction of product development cost and improved quality.

CE is a dynamic capability in the sense that it can facilitate innovation and enhance performance, but only through its influence on operational capabilities. According to Duhovnik et al. (2009), the success factors of concurrent product development is strategic management on three levels; parallelness of activities, standardization of the process, and integration of product development processes. Haque (2003) argues that CE requires a process-focused organisation.

The challenge associated with CE is that—as the design concept passes between the different groups for assessing feasibility from different perspectives—every change causes new changes, analysis, and hence additional communication demands (Sobek, Ward, & Liker, 1999). The design iterations take time and consume resources, and in many cases, the product design will transfer into a suboptimal solution as the team runs out of time. Further, there is a risk of starting with a design and a process that isn't the best starting point for the final solution. This may lead to iterations over a solution that is non-optimal (point-based), and the time spent late in the process is characterized by find-and-fix it (Sobek, Ward, & Liker, 1999; Morgan & Liker, 2006). If, for example, manufacturing issues are overlooked early in the project, the later it surfaces the more demanding it becomes to fix it. To make most of the time value added, it can be worth investing some extra time early in the process to explore alternatives thoroughly while there is maximum design space concerning both design and manufacturing (Morgan & Liker, 2006). Such front-loading of the product and development process, considering several solutions before narrowing down the opportunities, was termed Set-Based Concurrent Engineering (SBCE) by Sobek et al. (1999). This approach is claimed to lead to more efficiency and improved product integration capability later in the process. The paradox (Morgan & Liker, 2006) of SBCE is that considering a broader range of concepts will delay some decisions, but in return the whole process will be faster and more efficient.

A risk related to concurrent engineering is that not all designers and engineers are team players and teams are more difficult to manage than individuals. Here tools that provide a basis for discussion grounded in quantitative cost data and systematic design evaluation can help ensure that decisions are guided by the knowledge of downstream results—and not the strongest individual (Boothroyd, 1994). Despite the identified cons associated with practicing, traditional CE has gained wide acceptance in both high volume (e.g., automotive) and low-volume (e.g., aerospace) manufacturing (Kamrani & Vijayan, 2006). Today CE represents the industry standard and the preferred product development practice in most manufacturing companies.

3.4 Lean and Agile Product development

Lean is usually associated with production of physical products. However, sources in the literature are also discussing lean in the context of new product development (NPD) (Browning, 2003; Schipper & Swets, 2010; Morgan & Liker, 2006). Morgan and Liker (2006) presents 13 management principles that can be considered a foundation for *Lean product development* (LPD), emphasizing a model where the different principles support each other. To succeed in LPD, however, it is not sufficient to implement a few lean tools; LPD requires a cultural transformation into a learning organization (Liker & Morgan, 2006).

Concurrent engineering (CE) and other IPPD activities emphasize overlapping activities, which may risk executing work based on assumptions and incomplete information (Browning, 2003). In product development (PD) it is important to execute value-creating activities with the correct input information. In PD, becoming "lean" is more associated with increasing value than removing waste, a company focusing solely on performance without considering affordability and time spent is also naïve in a lean perspective. Successful companies must rather find a way to balance and trade-off "faster", "better" and "cheaper".

An important principle in *innovative* lean development (Schipper & Swets, 2010) is the use of rapid learning cycles as a short burst of learning. It may allow the team to maintain a phase while simultaneously narrowing down the number of solution sets until the optimal solution is found. To enable early and cost-efficient evaluation of different alternatives rapid product development (RPD) emphasize the use of prototypes for fast learning (Bullinger, Warschat, & Fisher, 2000). Further, RPD offers the possibility to integrate new technologies, market trends, etc., until the near end of the development process as the concept can be checked and redefined according to the project process (Bullinger, Warschat, & Fisher, 2000). This is in accordance with Set-Based Concurrent Engineering (SBCE), which aims to maintain flexibility late in the development process is important to ensure an attractive final solution.

Prototypes enable rapid learning and minimize mistakes as well as integrate different functions. However, this approach may be problematic for technologically complex products. By combining CAD technologies and Virtual Reality (VR), prototypes can be produced faster and cheaper than before (Bullinger, Warschat, & Fisher, 2000). This is supported by Beck et al. (2001), who argue that lean in this context is commonly associated with agile methods where a company should focus on responding to change instead of following a static plan. According to Ottosson (2004), companies should use an agile approach when they must be innovative, and traditional approaches (IPD, CE) when they merely aim to incrementally improve an existing product. The reason is that CE/IPD has a strong market-need perspective and less focus on bringing innovation forward.

3.5 Design Guidelines, Procedures and Tools

Design guidelines, procedures and evaluation tools are useful means in product development. In the design phase, product requirements for the entire life cycle must be considered (Eskilander, 2001). Kuo et al. (2001) present concepts, applications and perspectives of 'Design for X' emphasizing the full life cycle by addressing design goals and related constraints in the early design stage. While some use the 'X' to represent a process (manufacturing, assembly, maintainability, quality etc.), others refer to DFX as Design for Excellence, (Bralla, 1999; Bralla, 1996; Boothroyd, 1996). The most common concepts are design for manufacturing (DFM) and design for assembly (DFA), which involve simultaneous considerations of design goals and manufacturing constraints (Boothroyd, 1994; Prasad, Zacharia, & Babu, 2008). DFM is a strategy for selection of manufacturing process chain for a part and optimizing the part design for the chosen process chain. DFA aims to optimize assembly operations and the amount of equipment by designing parts for easy feeding, grasping and insertion (Tichem, 1997).

DFX support can be both design guidelines and stand-alone evaluation tools and software programs. Design guidelines for good design practice are derived empirically from past experience. These embody the concurrent engineering philosophy of considering the downstream impact of decisions being made (Edwards, 2002; Prasad, Zacharia, & Babu, 2008; Boothroyd Dewhurst, 2015). The main sources of design guidelines include literature, direct experiences of practising designers and established bestdesign practices in engineering organisations. In literature universal design guidelines that can be applied to nearly any product design situation can be found; e.g. Groover (2014, s. 747). The two last sources are less accessible (Edwards, 2002) and often related to a specific context or process. Evaluation tools and software programs offer systematic procedures for design, providing feedback to the designer based on analyses. As an example, Boothroyd Dewhurst Inc. (2015) offers DFMA software tools, DFA product simplification and DFM concurrent costing. Three well-known methodologies in the area of DFA are the Lucas method (Miles & Swift, 1992), Boothroyd Dewhusrst DFA method and the Hitachi Assembly Evaluation method (Boothroyd & Alting, 1992; Boothroyd, 1994). Hoque et al. (2013) presented the MFL (Manufacturing feature Library)—an intelligent system for manufacturing features in the area of CAD/CAM. Here features are organized hierarchically based on a geometrical and manufacturing process classification system. CAD integrated tools are often applied at the more detailed stages of design, which makes them more suitable for DFM than DFA since DFM consideration require relatively detailed product information (Tichem, 1997). It is believed, however, that recent developments in CAD solutions may reduce this gap. This is in accordance with Boothroyd (1994) who suggested positioning DFA at the concept stages of design to simplify the product structure and economic selection of materials (Boothroyd & Alting, 1992), followed by a more thorough DFM analysis where detailed design of the components should be conducted when processes have been selected.

Most of the first DFA procedures focused on automatic assembly since succeeding with automatic assembly is not feasible without redesigning the product—unlike manual assembly which is always possible (Boothroyd & Alting, 1992). In addition, a product design that facilitates automatic assembly also facilitates more effective manual assembly (Bralla, 1999; Pahl, Beitz, Feldhusen, & Grote, 2007). Since humans are much more adaptive than mechanical units, design for automatic assembly usually requires simplification of the product and more demanding design requirements.

According to Scarr & McKeown (1986), the following design constraints for automated robotic assembly prevail:

- Parts consolidation; is a part candidate for integration or reduction.
- Product variation; as many components as possible should be made common to all product variants.
- Kinematics; industrial robots are single-armed machines.

Constraint number two can be seen in connection with Groover (2014), arguing that in order to utilize robots for assembly a mixture of similar products or modules should be produced in the same cell or assembly line providing the same product configuration but with variations in size, geometry, options etc. One way of creating a flexible product design required to allow product variation, without changing the overall product each time a new variant is introduced, is to establish modular product platforms (Ericsson & Erixxon, 1999). Modularisation offers increased use of standard parts and the possibility of standardized interfaces and components, which enables standardization of manufacturing processes and tooling. Literature on modular design typically describes rather simple products, although the functional interdependencies make modularising complex products more difficult (Persson & Åhlström, 2006).

Eskilander (2001) presents a method for designing products for automatic assembly (DFA2) at both part and product level. DFA2 is a set of structured design rules with a quantitative scoring of the product design combined with qualitative evaluation criteria giving information on design for automated assembly. This approach makes the guidelines more specific as several researchers argue that design guidelines are often too general for any given problem, leaving the translation of the design rule into information with the designer (Boothroyd & Alting, 1992; Eskilander, 2001; Tichem, 1997).

According to Bralla (1999), it will also be useful to apply design guidelines to low-volume production, although the application strategy will vary from those used in high-volume production. The main differences are the importance of cost of tooling, the cost and lead-time for development of the manufacturing process, as well as the selection of production equipment and materials.

4.BRIDGING THE GAP BETWEEN HIGH AND LOW-VOLUME PRODUCTION

4.1 The Autoflex project

The literature review in Section 3 will now be seen in connection with efforts made by RRM to develop new automation solutions for large and complex products with tight dimensional fit-up requirements. RRM has a mixed product portfolio consisting of several large and complex products typically produced in volumes of less than 1,000 units p.a., which comply with low-volume production (Jina, Bhattacharya, & Walton, 1997). The case product, a Permanent Magnet Tunnel Thruster (PMTT), consists of over 100 components, has a propeller diameter of 1,600 mm and a total thruster weight of more than 7,000 kg (see Figure 2). PM-TT has complex functionality and strict requirements to operating conditions. The PM motor consists of two main parts, stator and rotor. The stator carries a number of electrical coil windings, and the rotor is fitted with strong permanent magnetized magnets.

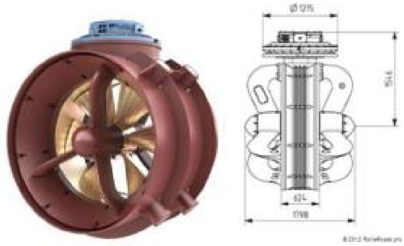

Figure 2. PM-TT 1600 conventional design built from existing product platform

The permanent magnet technology is relatively new to RRM, and the first prototypes were labor intensive. This called for more effective production methods making the PM-TT a suitable demonstrator in the Autoflex project. In order to succeed with automation of the PM-TT, it was early concluded that this would not be economically feasible without making significant modifications to the design. Redesign of the product, and developing the product and automation process in parallel have led to savings in material cost and machining as well as reduction in manual labor.

4.2 Enhancing the organization`s integrative capabilities in creating a powerful system of people, process and technology

The development of an automated solution for the PM-TT required concurrent development of a new technology, a new product design and a new production process, leading to multiple changes in existing practices and capabilities; e.g., the manufacturing system puts some constraints on the product, and vice-versa. Such constraints also represent opportunities for innovation (Schipper & Swets, 2010). In the Autoflex project, manufacturing constraints helped define the gap between the problem and the solution. When automation of the PM-TT was first investigated, the findings indicated increased factory footprint, large robots and significant investments for handling parts due to size. The subsequent efforts to make automated assembly more cost-efficient, triggered re-design and new solutions to problems. For example, a large component was divided into separate modules, leading to the use of standard robots and much less space requirements.

Automation experience was relatively limited within RRM, which made it necessary to employ an open innovation approach (Chesbrough, 2003), adapting knowledge from external partners with more design-for-automated production capability. Combining this with internal expertise, ensured a multidisciplinary competence basis including manufacturing process, product functionality and design-for-automation. Hence, competence development was of vital importance in order to succeed with concurrent development of technology, product and process. One other important factor to enable a working prototype in only 2-year time was involving people with multidisciplinary skillsets (Kelley & Littman, 2005). Such collaboration with the aim to bring innovation fast to market is emphasized by Blanchet et al. (2014) within the Industry 4.0 context.

Sobek et al. (1999) emphasized SBCE on product concept level. In Autoflex, the SBCE concept has been applied on business level (Synnes & Welo, 2015), re-designing the product and integrating verified solutions with an existing product platform. For RRM it has been necessary to develop conventional design in parallel with the design in the Autoflex project to manage risk. This appeared demanding yet necessary, and searching for the optimal solution required several iterations.

Similar to SBCE, lean product development emphasizes investigating the design space early in the process—so-called front-loading. Neither, technology or manufacturing should be driven too far without the other part as this creates investment risks. Trade-offs between function and production must be evaluated early in the design process when the cost of change and the risk of delaying the product in the market place are low. To ensure that re-design for automation fulfilled functional requirements, multiple learning cycles have been used, see (Schipper & Swets, 2010). However, learning cycles can also be costly in the case of complex products since prototypes are often expensive and time consuming. Therefore, simple (low-fidelity) test-samples were commonly used to verify design changes before a more comprehensive prototype was made. Examples include simple samples to test bonding between materials, durability and strength.

In the beginning of the project, process simulation was used to ensure that the team had a common understanding of the project task. Using modeling software for automated manufacturing and assembly enabled simulation of the production process and allowed the designer to take corrective action before the prototype was built and before the design was released for production. An example is the re-design of bolt holes to avoid collision between mounting tool and the product unit. This is in accordance with Bullinger et al. (2000), arguing that the use of simulation and virtual prototypes—especially in the early phases of product development—enable time and cost-efficient decision-making, even for complex products. Also, in low-volume production the number of prototypes has been limited due to cost. The use of simple demonstrators and process simulation bridges to some extent the gap to high-volume production.

4.3 Tools facilitating integrative capabilities for automated production

Boothroyd & Redford (1968) recognized that the impact of designs on cost was much more important than the use of mechanized assembly. Considerable cost savings can be achieved by careful consideration of the product design and its individual components. Boothroyd (1994) argues that no improvement in operation can make a plant fully competitive if the product design is defective. One could, therefore, argue that manufacturability and assembly friendliness are more important than automation when it comes to improving efficiency.

Experiences from Autoflex, however, indicate that relatively small adjustments to product design to facilitate automated assembly with minimum impact on product function can have a huge impact on production and quality cost. For example, design-forautomated assembly led to reduced part count, fewer operations and simpler production methods for the PM-TT. The project work has provided rich data and information for developing guidelines for design for automated manufacturing and assembly, and the first version of these has been developed.

A challenge in low-volume production is tooling and equipment cost. The Autoflex project leveraged competence for designing parts for employing flexible/sharable tooling. Since gripping tools are expensive, smart design of the part is particularly important in low-volume production where there are few products between which investment costs can split. Unlike high-volume production, the production space is limited, and the work environment must be reconfigurable and flexible in the low volume production domain of RRM. Autoflex has shown that by utilizing new technology developments and re-designing the product, this may justify robot investments in low-volume production. One example is using sensors (force-transducer technology and 3D vision), which compensate for tolerance in the gripper (and the robot) and enable assembly with close fit-up requirements. In addition, parameter-controlled programming from CAD makes programming less complex and more operator-friendly. In accordance with Scarr & McKeown (1986), this makes standardization/modularization important, even in the context of low-volume production. An example from PM-TT is standardization of screw dimensions to the need for only one tool and one feeder. Standardization and modularisation may trade-off product functionality, especially for complex products (Persson & Åhlström, 2006).

Design is limited to the way the product is made and what manufacturing can and cannot do have sometimes been 'written in stone' for years in a company. Automated assembly of the PM-TT demanded high precision, which again required dimensionally accurate parts and the need to see machining and assembly in relation to each other. Boothroyd (1994) emphasizes to consider the companion manufacturing cost of a DFA improvement.

The choice of production equipment and software defines the standards for what the designer must think about. The designer must be aware of internal production capabilities as well as those of sub-contractors and materials suppliers. For example, a robot's lifting capacity will constrain the size and weight of both the product and associated production equipment. This will influence trade-offs, such as designing smaller and lighter components or investing in larger robots. The development of design guidelines should therefore not only be based on considering general principles but also the specific production context (Eskilander, 2001). This may be even more relevant for complex products as the reuse of existing production systems for future developments are common (Javadi, 2015). However, as design rules are developed for a specific context, they will become more and more specific for a particular application. To make this become a drawback or an advantage depends heavily on the company's ability to incorporate new technology without being too constrained by its present capabilities.

As the mentality in low-volume production is commonly focused on functionality rather than manufacturability (Vallhagen, Madrid, Söderberg, & Wärmefjord, 2013), guidelines will strengthen the focus on how the part is to be produced. DFA/DFM guidelines is therefore applicable in this context, although they will vary from those in high-volume production, see; (Bralla, 1999).

5.CONCLUDING REMARKS

To sustain competitiveness companies must establish capabilities that enable them to introduce new products, processes and technologies faster than their competitors. Based on a literature review supported by experiences from a case study, we have identified several enabling factors, including:

- A company's ability to absorb new technologies and provide flexibility within work environment-production system to maximize capacity utilization;
- Processes that facilitate team-work and iterative product and process development;
- Supporting tools such as design guidelines for sharing knowledge between production and product engineering.

Development of low-volume products has traditionally focused on product functionality, rather than manufacturability (Vallhagen, Madrid, Söderberg, & Wärmefjord, 2013). However, to sustain competitive within the Industry 4.0 context, there is an additional need to focus more on manufacturability also in low-volume production. High-volume production enables economies of scale, whereas in low-volume production there are less parts between which costs related to development, tooling and production equipment can be shared. Standardization can be an effort to create economies of scale in low-volume production. In addition to general design principles guidelines and tools should therefore be adapted to the specific context, emphasizing standardization of fixed interfaces between production and design.

In Autoflex, the need for involvement and input from different functions (both external and internal), providing the right competence and resources in the conceptual stages of design, was key. This contributed to a leaner product and process development, resulting in a working prototype delivered in only 2 years. In addition, the use of simulation, learning cycles and virtual prototypes enabled a cost-efficient verification of design-for-automation solutions, ensuring that manufacturing did not compromise functional requirements. This also ensured a strong interrelationship between manufacturing and product engineering.

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Supportive paper 3

Enhancing Integrative Capabilities through Lean Product and Process Development

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Abstract: To survive in today's hostile business environment, companies must constantly introduce new products and adapt their strategy to change. Managing product variety may therefore be considered as an important competitive factor. However, this requires resources in terms of people, equipment, inventory and raw material—all of which go against a Lean strategy. Mastering complexity becomes increasingly important in several industries, and companies must find a way to balance between lean and offering product variety. As robots become less expensive and more 'intelligent', in combination with more advanced CAM solutions, automated assembly may become beneficial at much lower quantities than in the past. Also, development of new manufacturing methods may enable new product designs, and vice-versa. In this emerging paradigm shift— also referred to as Industry 4.0—companies must enhance their integrative capabilities and facilitate knowledge sharing between product engineering and production to sustain competitive advantage. This paper discusses organizational capabilities and tools required to enable transformation into Industry 4.0. Literature on Integrated Product and Process Development (IPPD), Concurrent Engineering (CE) and Lean has been studied. This state-of-the-art is seen in connection with efforts made in a research project with the goal to increase competitive advantage by leveraging capabilities in automated manufacturing of large and complex products—a manufacturing context that is regarded as difficult to automate in an economical way. The results show that investing in the latest manufacturing technology alone will not provide the capabilities required. It is also necessary to invest in people skills, knowledge and organizational learning. Process design and design-for-automation must be considered already from the conceptual product design to avoid expensive re-designs and design loops. The use of physical and virtual demonstrators proved to facilitate an efficient and effective design process.

Keywords: Integrated product and process development; Industry 4.0; Continious learning; Smart manufacturing

1.INTRODUCTION

1.1 Background

Today, the global economy is characterized in terms of rapid technological changes, customization and the need for fast time to market. Value creation, competitiveness and hence sustainable growth are dependent on development and utilization of new technology. To survive companies must constantly introduce new products, processes and technologies faster than their competitors do. The pressure on the designer increases as the product life cycle shortens, and the complexity of modern products requires the competency profile of the engineer to be T-shaped (1), emphasizing interdisciplinary skills (2).

To keep phase with customer demands, businesses have had to slim production to bare bones. For many company`s this has involved relocation of production or even outsourcing of capabilities (3). Further, leveraging product variety as a competitive strategy requires more designers and engineers, more components and raw material, more changeovers in production lines, higher inventory levels, more equipment, etc. (4)—all of which go against a lean strategy.

However, forward-looking businesses increase the level of in-house production by investing in advanced production technology, reducing labour to a less significantly portion of the production cost. Such investments in highly automated and IT-driven production are often referred to as Smart Manufacturing, which is a concept that marries information, technology and human strength (3). These new production methods facilitate a lean way of thinking, which changes the premises for competition and consequently the fundamentals for a company's business system.

Advancement in technology often requires changes in the organization to achieve productivity gain (5). This includes both investments in terms of capital and acquiring knowledge (5); i.e., leveraging R&D to keep phase with technology and be able to offer integrated solutions (2).

1.2 Industry 4.0

The Industry 4.0 concept is representing a paradigm shift, where physical objects are seamlessly integrated into information networks (2; 6). This may enable improved infrastructure for sharing information where design, product development and manufacturing are closely integrated. When combined with increased digitalization, the concept may open up radically new ways of designing products and manufacturing systems. The dominant technologies within Industry 4.0 are expected to be IT, electronics and robotics (2), and may facilitate improved manufacturing processes allowing high levels of automation as well as engineering, material usage and life cycle management.

External drivers such as introduction of new materials and technologies influence the way products are designed and exploited. Design is often constrained by the fabrication method such that a new manufacturing technology will create a technology push in design. An example is 3D printed parts, which can enable lighter parts and improved material utilization if the design fully utilizes the opportunities of the processing process.

Traditional automation has not been able to offer the flexibility and agility required for rapid configuration for new product demands (7). However, the development of 3D CAD/PLM software, computer vision, sensor technology and new programming methods may increase the use of robots in the coming years, thus making automatic assembly economically feasible at much lower quantities than in the past.

1.3 Motivation

Rolls-Royce Marine (RRM) has proven capabilities in system integration, ship equipment and design (8). RRM has a varied product portfolio consisting of several large and complex products, typically produced in volumes of less than 1,000 units p.a.. RRM's products are typically customized, engineer-to-order type products. To sustain competitiveness more cost-effective engineering and manufacturing methods are required. As a result, RRM together with research partners has invested in a research project named Autoflex. The intention is to determine capabilities of automated assembly of large and complex products that require close fit-up tolerances. The case is a Permanent Magnet Tunnel Thruster (PM-TT), which is a new product from RRM that fits well into the description above. Competitive production of the PM-TT calls for significantly more effective production methods than those used in the pre-series.

The PM motor consists of two main parts, stator and rotor, which are built up by more than 100 components. The stator carries a number of electrical coil windings, and the rotor is fitted with strong permanent magnetized magnets. It has a propeller diameter of 1,600 mm and a total thruster weight of more than 7,000 kg.

This paper addresses the challenge of developing and introducing new technology in a company that is producing products in a high-cost country, seeking to explore the following topic: How to enhance a company`s integrative capabilities, facilitating changes required to enable an emerging transformation into Industry 4.0? More specifically, the objective is to identify the challenges of product and process development of complex products for a competitive world-market with basis in Norway.

The reminder of this paper is organized as follows: Section 2 presents relevant literature on design development processes. Section 3 addresses the problem in light of the literature presented in Section 2 and with efforts made by RRM to succeed with automated assembly in a high-mix, low volume context. Finally, Section 4 presents concluding remarks.

2.THEORETICAL BACKGROUND

2.1 Product Design Processes

For a company to convert its technology and ideas into new products that meet customer requirements and the strategic goals of the company, a product development system that effectively integrates people, processes and technology is needed (9; 10). Methods that lead to shorter development time, faster product realization, reduction of product development cost and improved quality must be leveraged.

Integrated Product and Process Development (IPPD), Concurrent Engineering (CE) and Lean Product Development all aim to speed up innovation processes using somewhat different approaches. What all these 'schools' have in common is to facilitate design decisions, tackle conflicting goals and avoid costly redesign and unpredicted problems or compromises that degrade the final product (11). While CE has its roots in western product development, Lean has been developed from the Japanese perspective, i.e. the Toyota Production system (12).

Concurrent Engineering

The design and development process can be more efficient by executing working steps in parallel (13). A working method emphasizing this is CE. According to Winner et al. (14) "Concurrent engineering is a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life-cycle from conception through disposal, including quality, cost, schedule, and user requirements." CE puts a huge emphasis on multi-disciplinary teamwork, and has gained high acceptance and represent now the industry standard.

The challenge associated with CE is that—as the design concept passes between the different functional groups for assessing feasibility—every change causes a myriad of changes, analyses, and hence additional communication demands (15). These design iterations take time and resources, and in many cases the product design is transferred into a suboptimal solution as the team typically runs out of time. Further, there is a risk of starting with a design and a process that is not the best starting point for the solution. This may lead to iterations over a solution that is non-optimal (point-based approach) and the time spent late in the process is characterized by find-and-fix it (15; 10).

Front-loading of the product and development process by considering several solutions before narrowing down is termed Set-Based Concurrent Engineering (SBCE), Sobek et al. (15). SBCE is claimed to lead to more efficiency and improved product integration later in the process. Instead of selecting and refining one concept, SBCE consider a broader range of concepts, excluding those solutions that are not sustainable by eliminating alternatives step by step. The paradox (10) is that this will delay some decisions, but in return, the whole process may be faster and more efficient. Moreover, a set-based approach is beneficial when the cost of rework is high (16).

Integrated Product and Process Development (IPPD)

Development of a new product may demand new processes such as manufacturing, logistics and data collection (17). The term IPPD is defined by the Department of Defense (DOD) (17) as; "a management technique that integrate all acquisition activities starting with requirements, definition through production, fielding/development and operational support in order to optimize the design, manufacturing, business and supportability processes". Further, IPPD emphasizes the use of design tools such as modelling and simulation to develop the product and process concurrently (17; 11). IPPD is a broad concept where a multidisciplinary team, also referred as Integrated Product Teams (IPT), is responsible for delivering a defined product and/or process (17). The interactions within the design process are rapid, highly concurrent, interactive and iterative (11), emphasizing customer input and creating more manufactural designs (18). An iterative design strategy is attractive when the quality of the first guess is high, cost of re-work is low and feedback is fast (16).

Lean Product Development

Lean is often associated with production of physical products where the aim is repetitive operations achieving high quality outputs at the minimum cost and time; i.e., maximizing customer value while minimizing waste (19). Lean product development is a total philosophy suitable to improve efficiency in product development with basis in customer value. Several sources in the literature have discussed lean in the new product development (NPD) process (20; 21; 10; 22). Compared to CE and IPPD, lean product development has a strong focus on value and waste (23). However, compared to shop floor lean, becoming "lean" is more associated with increasing value than removing waste in lean NPD (20).

To succeed, however, creating the right culture, strategy and environment is just as important as implementing lean tools and techniques. Lean product development requires a cultural transformation into a learning organization (9). According to Karlsson & Åhlström (22) success requires employing interrelated techniques as elements of a coherent whole.

It is important to initiate and execute value-creating activities with the correct information input. An important principle in innovative lean development (21) is the use of rapid learning cycles as a short burst of learning. Prototypes enable rapid learning and minimize mistakes as well as integrate different functions. However, prototypes used for rapid learning are only feasible when developed quickly and inexpensively. By combining CAx technologies and Virtual Reality (VR), prototypes with high 'functionality' can be produced faster and cheaper than before (24; 16).

2.2 Supporting tools in the product design process

CE, IPPD and lean NPD can enhance a company's dynamic capabilities. However, what actually happens within that process or structure is dependent on the activities and how they are executed. In addition to creating the right culture, there is a need for tools and techniques that support activities. This requires subsystems that are fit for purpose, highly efficient processes are of no use if the people does not possess the skills required (10). Designers must be creative experts, correctly timing the application of tools with input from the right participants in the project (25). This may increasingly withdraw designers from traditional fields of expertise as they must both execute and manage the design process considering viewpoints from several stakeholders. Here, design guidelines, procedures and evaluation tools are useful support. These embody the CE philosophy of considering the downstream impact of decisionmaking (26; 27; 28).

The main sources of design guidelines include the literature, the direct experiences of practising designers and the established design practices in engineering organisations (26). The most common concepts are design for manufacturing (DFM) and design for assembly (DFA), which provides designers with tools to evaluate design-decisions and involve simultaneous considerations of design goals and manufacturing 'constraints' (29; 27).

Eskilander (30) presents a method for designing products for automatic assembly (DFA2) at both part and product level. DFA2 is a set of structured design rules with a quantitative scoring of the product design indicating how "good or bad the design is" combined with qualitative evaluation criteria also giving information on how to design for automated assembly. One way of creating the strategic, flexible product design required to allow product variation without changing the overall product design each time a new variant is introduced, is to establish modular product platforms (31). Modularisation offers increased use of standard parts, and the possibility of standardized interfaces and components, enabling standardization of manufacturing processes and tooling. However, a risk associated with modularisation is compromising product functionality. The key is matching the solution spaces of product and production design (32).

3.DISCUSSION

3.1 The Autoflex project

The literature presented in Section 2 will now be seen in connection with efforts made in a research project named Autoflex. The underlying goal of the project was to achieve cost-effective manufacturing of low volume, complex and heavy products in high cost countries. The case product, PMTT is a large and complex product with tough requirements for tolerance design and strict requirements to operating life. The original design of the PM-TT requires a high degree of manual labour operations and it was early on identified that automation would not be cost efficient without modifications to the existing design.

By combining design-for-automation and state-of-the-art production technologies the project has delivered a physical demonstrator in only two years proving fully automated assembly of the PM-TT rotor. Also a virtual demonstrator of the automated assembly process for PM-TT stator has been developed. The project has introduced new methods and guidelines for engineering and development of large and complex products produced at low volume.

3.2 Enhancing the company`s integrative capabilities

A plant cannot be fully competitive by only improving operations if the design is defective (29). The design solution must not only satisfy the quality and functional requirements of the product, it must also meet certain specifications for fitting the manufacturing process within the company. On the other hand, Koufteros et al., (33) argue that excellence in product development can just as easily be eroded by manufacturing weaknesses.

The key to offer competitive solutions in the market place is considering product, people, process and tools/technology as a total system. In this perspective it is important to invest in knowledge and organizational learning in a strategic perspective. For example, buying a robot is easy compared to leveraging the people skills for incorporating it in the production environment in the most beneficial way for the company.

In the Autoflex project, automation knowledge was leveraged from external experts and combined with internal expertise in products and technology. This ensured a team with multi-disciplinary skills possessing knowledge of the technologies required to develop an automated solution for the PM-TT. Weekly meetings and close dialogue ensured that functional requirements were balanced manufacturing solutions—and vice versa.

When automated assembly of PM-TT first was investigated, the findings indicated increased factory footprint, large robots and significant investments for handling part size. The efforts made to make automated assembly cost-efficient, triggered redesign and new thinking; e.g., a large component of the PMTT was divided into separate modules, which facilitated the use of standard robots with much less space requirements. This is a good example of manufacturing constraints creating a demand for innovation. According to Schipper & Swets (21), defining the gap between the problem and solution identifies where innovation is needed.

Sobek et al. (15) emphasized SBCE on product concept level. In Autoflex, SBCE has been applied on business level, re-designing the product and integrating verified solutions with existing product platform. Since PM-technology is relatively new to RRM and the product has a complex functionality, it was necessary to verify functional requirements with a nonoptimal production process to avoid too many variables at the same time. However, driving technology or manufacturing too far without the other factors creates an investment risk. This is particularly important for complex products since this often requires dealing with a high level of uncertainty and significant investment costs. Developing the conventional design in parallel (set-based approach), was demanding yet necessary, and searching for the optimal solution required several iterations.

To narrow down solutions one can use multiple learning cycles as emphasized by innovative lean development (21). However, learning cycles can be costly when designing complex products since physical prototypes often are expensive and time consuming. In Autoflex, simple demonstrators, both physical and virtual, were used to verify design changes before a final more comprehensive prototype was tested. Simulation of the assembly process based on the CAD model enabled testing before design was released and any expensive equipment was purchased.

The use of simulation enables lean decision-making throughout the development process. The lead time from design to verification of the assembly process can be reduced by virtual manufacturing technologies in combination with automated programming methods from CAD models. A demonstrator of an automated assembly process for the PM-TT stator was programmed and simulated based on the CAD model. It was experienced that the frequency of design iterations increases as one iteration can be performed in a fraction of the time and cost compared to an iteration on a physical prototype.

An animated movie, presenting the project vision, was used when starting up the project to ensure that the multidisciplinary team had a common understanding of the project task. This ensured strategic information input facilitating concurrent activities (20).

Terwiesch et al. (16) argue that neither a set-based nor an iterative approach are superior over the other. What influence trade-off between set-based and iterative strategy is; quality of educated guesses, the engineering change support process and the exchange of information regarding interdependencies between components, and what kind of changes are expected to cause substantial work.

3.3 Guidelines and tools enhancing integrative capabilities

The Autoflex project has changed the mind-set of manufacturing in RRM towards developing the product and the automation process in parallel. One main argument is that relative small changes to the product design can have a huge impact on rational production. Design-for-automated assembly led to simpler product and production methods. A direct result of the re-design is that the automated process time is reduced to a fraction of the time compared to the initial manual process.

When aiming to utilize new manufacturing technologies, as the case in Autoflex, the design of the product, the facility, workstations and equipment are all important. One important experience is that process design, and design-for-automation must be considered already from the concept design to avoid expensive re-designs.

A challenge in low-volume production is that there are fewer parts between which development cost can be distributed. Hence, the cost of material and labor is weighted less important than in high-volume production where significant resources are commonly used on tooling, manufacturability and engineering (34).

In Autoflex, re-designing the product was the key factor to enable cost-effective automated assembly of the PM-TT. For example, design of a part requires designing the gripping tool used in production. If considered early, one can reduce the cost of the tool by designing appropriate geometry and surfaces of the part for gripping. Moreover, modeling the assembly solution at an early stage led to re-design of bolt holes to avoid collision between mounting tool and the product.

The Autoflex project has also brought intelligence into the assembly process. Examples are advanced use of sensors (3D vision and force-feedback) that compensates for tolerance in the gripper (and the robot), enabling assembly with close fit-up requirements.

Automation usually requires high volume of standardized parts. Modularization and standardization require less flexibility in the production system. In Autoflex, this resulted in reduced part count and operations; e.g., by integrating dowel pins as part of component. Another simple example is to have the same amount of bolt holes on a single component, instead of having products with different number of screws. In addition, standardization of screw dimensions allows one tool and one feeder to be used.

Design guidelines can be useful to establish best-practices and a repository of design tools. The project has provided rich data and information for developing guidelines for automated manufacturing. These guidelines can be useful in the further work of developing the complete PM range and help identify interfaces between process and design. Such guidelines would be a good starting point for utilizing the production system and achieve higher volume. Care should be taken in preventing that standardization and modularisation reduce product functionality, especially for complex products (35). Moreover, too much focus on standardization and modularization may be a hindrance to innovations (36).

Design is limited to the way the product is made. However, a company`s ability to absorb new technologies should not be limited by its current capabilities when designing a new product and the production process. The designer must be aware of internal workshop capabilities, as well as the ones of sub-contractors and materials suppliers. For example, the robots lifting capacity will impact the size and weight of both the product and associated production equipment. This will create trade-off issues, such as designing smaller/lighter components or investing in larger robots as in the case of Autoflex. Therefore, the development of design guidelines cannot only be based on general principles found in the literature, such as design principles for automated assembly by Eskilander (30), but also on the specific production context.

4.CONCLUDING REMARKS

To sustain competitive within the emerging industry paradigm shift denominated Industry 4.0, there is an additional need to consider manufacturability also for complex products produced in low-volumes. A lesson taught from the Autoflex project is that investing in the latest technology alone will not provide the capabilities required; it is also necessary to invest in knowledge.

The use of virtual manufacturing and process simulation increases the frequency of design iterations in the development process and may reduce the verification time and cost significantly. Further, this facilitates a leaner product and process development enabling corrective actions to be taken before design release for production and the solution is still on the drawing board.

Based on experience gained in the Autoflex project, we suggest that there are two directional paths for a company to enhance its integrative product development capabilities:

(a) to leverage agile strategies for Integrated Product and Process Development (IPPD);

(b) to frontload resources in early phases when cost of learning is low and the design space is wide, using methods such as SBCE.

In Autoflex, the key was to master both a) and b) to ensure that neither manufacturing nor technology was driven too far without support in the other. Moreover, this working method ensured a strong integration of manufacturing and product engineering. This enabled the company to choose problem solving strategy based on the complexity of the task, the technical characteristics and the problem-solving capabilities of the organization.

Within the Industry 4.0 concept, a company must be able to absorb new technologies that change the premises for competitive production. This implies that a company must strengthen its absorptive capabilities to avoid being boxed in by current capabilities for designing a new product and its belonging processes.

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APPENDIX 3 – Interview guide

SEMI-STRUCTURED INTERVIEW GUIDE

- Research Objective: Map factors that impact how we achieve improved design practice for automated assembly in the context of RRM
    - Experience in the company
    - Obstacles to overcome, and enablers to leverage
- Business objective: Bring improved quality products faster to market at lower cost

ROLES/RESPONSIBILITIES AND BACKGROUND

Main questions	Additional questions	Clarifying questions
Can you please **introduce** yourself?	• What are your **role**/ **responsibilities** in the company?	Focus on roles and responsibilities – risk of spending too much time.
For **how long** have you been working in the company? in the marine industry **in total?**		

CONTEXT SPECIFIC FACTORS

Main questions	Additional questions	Clarifying questions
Do we have clear success criterions defined for development projects in RRM?	If not, what would you have defined as success criterions?	Do we place emphasis on? - **Function/quality,** - **cost** - **time?** Technical success (functional technology) Business success (increased competitiveness, quality)
Do you have experience from projects solving automated production/assembly?	Considerations done? If no, Why have this not been a topic in projects you have been involved in?	
How can we succeed with automated assembly of company types of products?	What should we automate?	**Complexity of automation** • Material constraints • Efficiency of existing operations • Factory footprint
What is the benefit of automated assembly of company products?	• Why is this something that we should focus on?	
• How do you think **Industry 4.0** will affect RRMs opportunity to automate manufacturing?	• How good are we to absorb new technology? • Where do you get input from?	• Trade fairs • Suppliers • Benchmarking (competitors and industries) • Colleagues • Universities • Training and courses

Main questions	Additional questions	Clarifying questions
• Do you think automated assembly in a low-volume setting will impact customer value?	• Standardization vs. customization	
• How does you and your team work to understand customer value?	• Is customer involved during the project?	
• What is the biggest challenge with automated assembly of these type of products?	Are there specific examples from PD projects?	• Economies of scale/volume • Size • Product complexity • Tolerances

PEOPLE

Main questions	Additional questions	Clarifying questions
• How is Knowledge-shared between projects? • Active mechanisms?	• Discussions about automated production? • Internal (site) and external (marine and plc.) • Benchmarking Benchmarking	- How does new employees navigate to find information about previous projects? - Tacit knowledge? - Best practice and lessons learned etc.
How is communication between team members in PD projects?	- Meeting frequency - Formal vs. unformal - Co-location?	How is communication between team members during the PD project?
• What **role** does **manufacturing** take in product development in RRM projects?	• Do you have examples of ME involvement that was best practice? - To what extent can ME influence design?	A specific example of a decision made of ME that had impact on the result.
What is most important for a PD team to produce good results?	Competence • Expertise - T-shaped	What were the background/positions of people working on the project?

TECHNOLOGY BASIS

Main questions	Additional questions	Clarifying questions
How is new process technology and equipment developed?	When is production involved?	
• To what extent do we use and how does digital tools influence design practice for automated production?	• PLM system, plattform for produkt og prosess. • Learning and transfer of digital information How about **knowledge management?**	Existing tools • Team Center • NX • Edgecam
• What opportunities and obstacles/constraints do you see in connection with prototyping, given that production is more automated?	• Simulation/modelling of product and process	• Exploration/clarification of direction • Exploration of requirements • Proof of concept • Production ramp-up

DEVELOPMENT PROCESS

Main question	Additional questions	Clarifying questions
• In projects that we deliver on quality, cost and time. What are we then focusing on?	• If not, what is the main reason?	
• Do we follow RRMs business processes for PD? • To what extent are we using **PILM, IPPR, MCRL** and **TRL**	• If we do not follow the process, what is the reason • What is the main driver for following the process?	
• Are there examples/trends of coherence between result and type of projects?	• Complexity • Novelty • Size	
• How do we capture that a project is in trouble in terms of product cost?	• What is the main driver for cost reduction initiatives for new products?	• What mechanisms comes into play?
• Do functional departments and projects get the **resources** they need when needed	Examples that access to resources (of different reasons) have impacted the opportunity to deliver a PD project?	• Money, cost • Manpower • Department vs. project? • Team-oriented vs. firm driven
• To what extent is **modularization/standardization platforms** defined for products, components and systems and processes	What can be drawn out of modularization/standardization in terms of automated manufacturing, and vice versa.	
• How is information from other functions collected?	• Production • Logistics • Service/after market	Examples of involvement • Methods • Tools • Knowledge-based • Tool catalogues
• In **retrospect,** if you had the chance to do projects over again, **what would typically be the things that you do different? Are there any common denominators?**		

APPENDIX 4 –LPD assessment scorecard

Principle Today and future state scoring between 1-5	**Today**	**Future state**	**Bottleneck to achieve desired future state**
Process			
Establish **customer-defined value**			
Front-load the product development process Er vi sikker på at problemet er riktig definert før vi setter i gang? Utforsker vi flere alternativ før vi låser oss til en løsning?			
A leveled product development process flow *Ressurs-utnyttelse og – tilgang (mann og maskin) i prosjektet, hvor enkelt er det å planlegge prosjekter slik at de kan utføres uten store svingninger i arbeidsmengde?*			
Standardization to reduce variation 1. Product and process 2. Standardized skill sets for engineers.			
People			
Chief engineer master architect «Integrate development from start to finish» 1. Technical expertise 2. Enabler			
Organize to balance functional expertise and cross-functional integration Balanse mellom funksjonell ekspertise innad i spesifikke disipliner (for eks. ME), samtidig som man har en sømløs integrasjon mellom avdelinger som sikrer suksess i hvert enkelt prosjekt. En velfungerende matrise org.			
Develop towering technical competence in all engineers Spesialisert kunnskap om produktet og tilhørende prosesser (*gjerne fra utplassering i produksjon*)			
Supplier involvement in PD			
Focus on learning and continuous improvement			
Build a culture to support excellence and relentless improvement Jobber vi imot tydelig definerte, felles mål			
Tools and technology			
Adapt technology to fit your people and your processes *Teknologi er tilpasset og alltid underordnet til mennesker og prosessene*			
Align your organization through simple, visual communication Enkel kommunikasjon for felles forståelse. Samsvar mellom org mål og individuelle mål			
Use of powerful tools for standardization and organizational learning *Eks A3 report for å kommunisere informasjon*			

APPENDIX 5 – LPD re-assessment result

	Lean management principle	Gap current and desired state -17	Comment	2020 Status	Comment
Process	Establish customer-defined value to separate value from waste.	Low	A need to develop competence to fully understand and define customer value.	Improve ment.	Interaction with yards and customers to map requirements for the thruster project.
	Front load the product development process.	Medium	A risk of being impatient in the concept phase. Focusing on one solution and build a prototype.	Improve ment.	Resources from relevant disciplines allocated early in the PD project. Technical solutions and industrialization demonstrated. Demonstrators ensure focus and is an efficient way to test solutions.
	Create a leveled product development process flow.	Medium	Main challenge is prioritization of daily production over PD in case of urgency.	Improve ment.	A product demonstrator was ready for sea water trials after 9 months. Successful planning according to machining priorities and daily production.
	Utilize rigorous standardization to reduce variation.	High	Good at process level. Need improvement at product level. Challenging due to differentiated portfolio and low volume.	New Gap.	Modular design and automated assembly create a new competitive standard for design. Challenge existing design rules and standardization mindset.
People	Develop a 'Chief Engineer System'.	High	Project leader that has several roles in a project. High technical expertise, but sometimes lack capacity to manage project. Rigid processes to ensure control.	Status Que.	Satisfying leadership and decision-making early in the project combining project management with team members high technical expertise. As project evolved, decisions started to be taken outside the project with the result of eliminating risks (innovations) and increasing decision time.
	Organize to balance functional expertise and cross-functional integration.	High	Interfaces between functions are not clear. E.g., Design Engineer doing Manufacturing Engineering work and vice versa.	(Project) Improve ment.	The project successfully combined technical- and industrialization competence utilizing people from relevant functions. However, to get acceptance from the cross-functional organization, ensuring common focus on customer value, is time consuming. Introducing new design standards.
	Develop towering technical competence in all Engineers.	Medium	The need for more T-shaped people is highlighted.	Status que.	Good in developing specialist competence within functional departments. Need to understand the impact of decisions: ME to understand product functionality and DE to understand manufacturing.
	Fully integrate suppliers into the PD system.	Low	There is a lack of formal process with supplier.	Status que.	Worked closely with the gear wheel supplier for technical solution and system integrator developing manufacturing tools. Components are first machined in-house to understand manufacturing cost.
	Build in learning and continuous improvement.	Medium	Global company with local sub-cultures. Need to encourage knowledge sharing and cooperation (trust).	Status que.	Several decades of experience into the project demonstrating project solutions and future opportunities. E.g., new materials for key components demonstrated but not implemented.
	Build a culture to support excellence and relentless improvement.	Medium	Need a cultural change to create awareness and chose the right battles.	Improve ment.	A project introducing both product and process improvements but also improved collaboration and communication ensuring customer focus in the project, e.g., to make decisions in favour of the overall solution and project requirements.
Tools & Technology	Adapt technology to fit your people and process.	High	A tendency to favor technology over people and process. Required competence and experience to interpret results from new technology.	Status que.	The new thruster project challenge simulation and computational calculations with demonstrators: Combining the strength of practical and theoretical experience and old and new competence. In general, because of manual use of the CAD system, there is a wide range of product variants to maintain: 20 different assembly drawings of the same component used in two different products.
	Align your organization through simple, visual communication.	Low	3D models for visual communication.	Improve ment.	Demonstrating (both virtually and physically) a new industrialization mindset including modular design and how to design away the need for adjustments with shims in assembly.
	Use powerful tools for standardization and organizational learning.	High	Opportunity to learn from mistakes. Requires effective communication at several levels.	Status que.	Several years of experience in the new thruster PD project. In general, the view is still that the organization can learn more from mistakes and utilize existing in-house competence in projects. Be curious of what 'others' in the organization are doing. 12

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