Procedia Manufacturing

Volume 5, 2016, Pages 26–40

44th Proceedings of the North American Manufacturing
Research Institution of SME http://www.sme.org/namrc

# Bridging the Gap Between High and Low-Volume Production through Enhancement of Integrative Capabilities

Elisabeth Lervåg Synnes[1]* and Torgeir Welo[1]
[1]*NTNU - Engineering Design and Materials,*
*Richard Birkeland's veg 2B, N-7491 Trondheim Norway*
*Elisler@stud.ntnu.no, torgeir.welo@ntnu.no*

**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 high-volume 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

Selection and peer-review under responsibility of the Scientific Programme Committee of NAMRI/SME

doi:10.1016/j.promfg.2016.08.006

# 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.

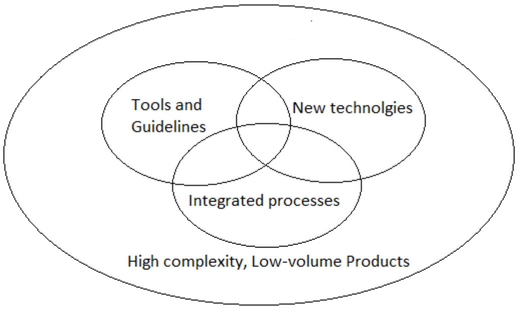

**Figure 1.** Research themes to be investigated within the high-complexity, low-volume context

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, engineering-to-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<br>Interchangeable parts/standardization | Large and complex<br>Customization |
| **Volume** | High | Small batch/ one of a kind |
| **Innovation process** | Product development→ customer demands.<br>Focus on manufacturability | Customer demand→ Product development.<br>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 best-design 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 (PM-TT), 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.

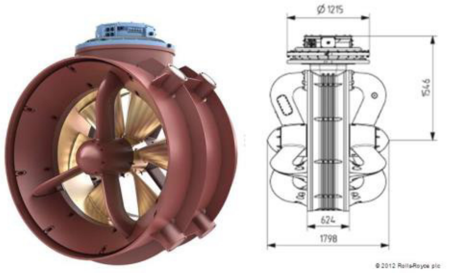

**Figure 2** PM-TT 1600 conventional design built form existing product platform

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. Re-design 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 multi-disciplinary 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-for-automated assembly led to reduced part count, fewer operations and simpler production methods for the PM-TT. The project work have 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 facilitates 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.

# Acknowledgements

We would like to express our thanks to the participants in the Autoflex project for the support and valuable inputs provided to our work. We particularly thank Rolls-Royce Marine for allowing us to get insight into the development process of PM-TT. This work is part of the Autoflex project and has been financed by Rolls Royce Marine and the Research Council Norway, who are both gratefully acknowledged.

# References

Beck, K., Beedle, M., Grenning, J., & Martin, R. e. (2001). *Manifesto for Agile Software Develoment* . Retrieved nov 13, 2015, from http://agilemanifesto.org/

Bhise, V. (2014). *Designing Complex Products with Systems Engineering Processes and Techniques* (1st ed.). Boca Raton: CRC Press .

Blanchet, M., Rinn, T., Von Thaden, G., & De Thieulloy, G. (2014). *Industry 4.0 The new industrial revolution How Europe will succeed.* Munich: Roland Berger Strategy Consultants GMBH.

Boothroyd Dewhurst, I. (2015). *DFMA*. Retrieved oct 1, 2015, from http://www.dfma.com/software/dfma.htm?DFA

Boothroyd, G. (1994). Product design for manufacture and assembly. *Computer-Aided Design, 26*, 505-520.

Boothroyd, G. (1996). *Book review Design for excellence.*

Boothroyd, G., & Alting, L. (1992). Design for Assembly and Disassembly. *CIRP Annals-Manufacturing Technology, 41*(2), 625-636.

Boothroyd, G., & Redford, A. (1968). *Mechanized Assembly. Fundamentals of parts, feeding, orientation, and mechanized assembly* (1st ed.). New York: McGraw-Hill.

Bralla, J. (1996). *Design for excellence* . New-York: McGraw-Hill.

Bralla, J. (1999). *Design for Manufacturability Handbook* (2nd ed.). New-York: MCGrawHill.

Browning, T. (2003). On Customer Value and Improvement in Product Development Processes . *Systems Engineering*, 49-61.

Bullinger, H.-J., Warschat, J., & Fisher, D. (2000). Rapid product development- an overview. *Computers in Industry , 42*, 99-108.

Chesbrough, H. (2003). *Open Innoation The New Imperative for Creating and Profitting from Technology* (1st ed.). Boston, Massachusetts: Harvard Business School Press.

Department of Defense, D. (1998). *DoD Integrated Product and Process Development Handbook.* Washington DC: Office of the under secretary of defense (acqusition and technology.

Duhovnik, J., Zargi, U., Kusar, J., & Starbek, M. (2009). Project-driven Concurrent Product Development . *Concurrent Engineering: Research and Applications , 17*(3), 225-236.

Edwards, K. (2002). Towards more strategic product design for manufacture and assembly: priorities for concurrent engineering. *Materials and Design , 23*, 651-656.

Ericsson, A., & Erixxon, G. (1999). *Controlling Design Variants: Modular Product Platforms* (1st ed.). Michigan: Society of Manufacturing Engineers.

Eskilander, S. (2001). *Design for Automatic Assembly- A Method For Product Design: DFA2* (1st ed.). Stockholm: Dept. of Production Engineering.

Gerwin, D., & Barrowman, N. (2002). An Evaluation of Research on Integrated Product Development . *Management Science , 48*(7), 938-953.

Groover, M. (2014). *Automation, Production Systems, and Computer-Integrated Manufacturing* (3rd ed.). London: Pearson Education Limited .

Haque, B. (2003). Problems in concurrent new product development: an in-depth comparative study of three companies. *Integrated Manufacturing Systems , 14*(3), 191-207.

Hobday, M. (1998). Product complexity, innovation and industrial organisation . *Research Policy , 26*, 689-710.

Hobday, M. (2000). The project-based organisation: an ideal form for managing complex products and systems. *Research Policy, 29*, 871-893.

Hoque, A., Halder, P., Parvez, M., & Szecsi, T. (2013). Integrated manufacturing features and Design-for-manufacture guidelines for reducing product cost under CAD/CAM environment. *Computers & Industrial Engineering, 66*, 988-1003.

Javadi, S. (2015). *Towards Tailoring The Product Introduction Process For Low-Volume Manufacturing Industries* (1st ed.). Västerås, Sweden: Mälardalen University Press Licentiate Theses.

Jina, J., Bhattacharya, A., & Walton, A. (1997). Applying lean principles for high product variety and low volumes: some issues and propositions. *Logistics Information Management , 10*, 5-13.

Jordan, J., & Michel, F. (2000). *Next Generation Manufacturing: Methods and Techniques* (1st ed.). John Wiley & Sons.

Kamrani, A., & Vijayan, A. (2006). A methodology for integrated product development using design and manufacturing templates. *Journal of Manufacturing Technology Management, 17*(5), 656-672.

Kelley, T., & Littman, J. (2005). *The Ten Faces of Innovation: IDEO`s Strategies for Defeating the Devil`s Advocate and Driving Creativity Throughout Your Organization* (1st ed.). United States of America: Doubleday Random House Inc.

Kleven, K. (2012). *Investing for future competitiveness Kleven Maritime- a Norwegian case*. Retrieved sept 29, 2015, from http://www.oecd.org/sti/ind/10%20Kleven%20-%2029Nov12.pdf

Kuo, T.-C., Huang, S., & Zhang, H.-C. (2001). Design for manufacture and design for "X": concepts, applications, and perspectives . *Computers & Industrial Engineering, 41*, 241-260.

Liker, J., & Morgan, J. (2006). The Toyota Way in Services: The Case of Lean Product Development. *Academy of Mangement Perspectives, 20*(2), 5-20.

MacDougall, W. (2014, July). *Industrie 4.0 Smart Manufacturing for the future Germany Trade & Invest.* Retrieved Nov 20, 2015, from http://www.gtai.de/GTAI/Content/EN/Invest/_SharedDocs/Downloads/GTAI/Brochures/Industries/industrie4.0-smart-manufacturing-for-the-future-en.pdf

Miles, B., & Swift, K. (1992). Design for manufacture and assembly. *77*, pp. 221-224. UK: FISITA 92 Institute of Mechanical Enigneers.

Morgan, J., & Liker, J. (2006). *The Toyota Product Development System* (1st ed.). New York: Productivity Press.

O`Driscoll, M. (2002). Design for Manufacture. *Journal of Materials Processing Technology , 122*(2-3), 318-321.

Ottosson, S. (2004). Dynamic product development - DPD. *Technovation, 24*, 207-217.

Pahl, G., Beitz, W., Feldhusen, J., & Grote, K. (2007). *Engineering Design A Systematic Approach* (3rd ed.). London: Springer-Verlag London Limited .

Pan, Z., Polden, J., Larkin, N., Van Duin, S., & Norrish, J. (2012). Recent progress on programming methods for industrial robots. *Robotics and Computer-Integrated Manufacturing , 28*, 87-94.

Persson, M., & Åhlström, P. (2006). Managerial issues in modularising complex products. *Technovation, 26*, 1201-1209.

Prasad, S., Zacharia, T., & Babu, J. (2008). Design for manufacturing (DFM) approach for Productivity Improvement in Medical Equipment Manufacturing . *Inernational Journal of Emerging Technology and Advanced Engineering, 4*(4), 79-85.

Scarr, A., & McKeown, P. (1986). Product Design for Automated Manufacture and Assembly. *CIRP Annals- Manufacturing Technology , 35*(1), 1-5.

Schipper, T., & Swets, M. (2010). *Innovative Lean Development How to Create, Implement and Maintain a Learning Culture Using Fast Learning Cycles* (1st ed.). New York: CRC Press Taylor & Francis Group A Productivity Press Book.

Schuh, G., Potente, T., Varandani, R., Hausberg, C., & Fränken, B. (2014). Collaboration Moves Productivity To The Next Level. The 47th CIRP conferance on Manufacturing Systems Procedia CIRP 17.

Sobek, D., Ward, A., & Liker, J. (1999). Toyota`s Principles of Set-Based Concurrent Engineering. *MITSloan, 40*(2), 67-83.

Sommer, A., Dukovska-Popovska, I., & Steger-Jensen, K. (2014). Barriers towards integrated product development - Challenges from a holistic project management perspecitve . *International Journal of Project Management , 32*, 970-982.

Synnes, E., & Welo, T. (2015). Design for Automated Assembly of Large and Complex Products: Experiences from a Marine Comapny Operating in Norway. Elsevier B.V.

Takeuchi, H., & Nonaka, I. (1986). The new new product development game. *Harvard Business Review*, 137-146.

Tesla motor team. (2014). *Factory upgrade*. Retrieved oct 1st, 2015, from https://www.teslamotors.com/blog/factory-upgrade

Tichem, M. (1997). *A Design Coordination Approach to Design For X.* Delft: ISBN 90-370-0163-7.

Vallhagen, J., Madrid, J., Söderberg, R., & Wärmefjord, K. (2013). An approach for producibility and DFM-methodology in aerospace engine component development . Procedia CIRP 11 2nd International Through-life Engineering Services Conference.

Weyer, S., Schmitt, M., Ohmer, M., & Gorecky, D. (2015). Towards Industry 4.0 - Standardization as the crucial challenge for highly modular, multi-vendor production systems. *IFAC Conferance Paper archive* (pp. 579-584). Elsevier Ltd. .

Willner, O., Powell, D., Duchi, A., & Schönsleben, P. (2014). Globally Distributed Processes: Making the Distinction between Engineer-to-order and Make-to-order. The 47th CIRP Conferance on Manufacturing Systems.

Winner, R., Pennell, J., Bertrand, H., & Slusarczuk, M. (1988). *The role of concurrent engineering in weapons system acquisition.* Virginia : Instituate for defense analyses.