

Assessment and Development of Engineering Design Processes

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Assessment and Development of Engineering Design Processes

A PhD-thesis by Jeppe Bjerrum Ulrikkeholm

PhD-Thesis at the Technical University of Denmark

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DANSK RESUMÉ

Mange ingeniørvirksomheder oplever i disse tider store udfordringer, idet deres kunder i stigende grad efterspørger kundespecifikke produkter til nærvæd samme pris, leveringstid og kvalitet som masseproducerede produkter. For at kunne imødekomme denne udvikling er ingeniørvirksomhederne afhængige af at have effektive engineering design processer, så de kan designe kundespecifikke varianter af deres produkter hurtigere og mere effektivt. Det er imidlertid ikke nogen let opgave at modellere og udvikle sådanne processer. At udføre engineering design er oftest en særdeles iterativ, udefineret og kompleks proces. En overordnet antagelse i dette forskningsprojekt er, at fuld forståelse af engineering design processer kræver forståelse af produktet som designes. Kun gennem indsigt i hvilke produktspecifikationer, som anvendes og produceres i hver enkelt designopgave, kan designprocessen fuldt ud forstås og forbedres.

Med afsæt i denne overordnede antagelse er det primære resultat af forskningsprojektet en operationel 5-faset procedure for vurdering og udvikling af engineering design processer gennem integreret modellering af produkt og proces. Proceduren kaldes IPPM – Integrated Modelling of Product and Process. Ved at sammenflette disciplinerne produkt- og procesmodellering opnås øget indsigt i engineering design processerne. Det bliver klart hvilke produktspecifikationer, der er kritiske for hver aktivitet i processen. Udnyttelse af denne indsigt muliggør konfigurering af processen, således at den passer til produktet, som designes. Herigennem skabes et optimalt procesflow for det specifikke produkt. Denne optimering vil positivt påvirke performance af engineering design processerne og styrke virksomhederne i deres bestræbelser på at imødekomme kundernes stigende krav om individuelt tilpassede produkter.

Foreliggende afhandling er baseret på seks videnskabelige artikler. Tre af artiklerne er skrevet til og præsenteret på videnskabelige konferencer, mens de resterende tre er indsendt til videnskabelige tidsskrifter. Resultaterne fra disse artikler udgør det primære forskningsmæssige bidrag, og hovedkonklusionerne vil blive præsenteret løbende igennem denne afhandling. Endvidere vil resultaterne blive indskrevet i en mere omfattende kontekst, idet såvel den teoretiske som den empiriske baggrund vil blive uddybet. Ydermere gennemgås den videnskabelige tilgang og de metodiske valg i detaljer. Afslutningsvist vil samtlige resultater blive diskuteret grundigt, konklusioner vil blive opsamlet og forslag til fremtidig forskning vil blive fremsat.

Samtlige resultater præsenteret i foreliggende afhandling er opnået i tæt samarbejde med forretningsenheden Marine Low Speed i virksomheden MAN Diesel & Turbo. Forretningsenheden er markedsleder indenfor udvikling og design af kundespecifikke marinetotaktsmotorer.

SUMMARY

Many engineering companies are currently facing a significant challenge as they are experiencing increasing demands from their customers for delivery of customised products that have almost the same delivery time, price and quality as mass-produced products. In order to comply with this development, the engineering companies need to have efficient engineering design processes in place, so they can design customised product variants faster and more efficiently. It is however not an easy task to model and develop such processes. To conduct engineering design is often a highly iterative, ill-defined and complex process, which is not simply understood. A main proposition in this research project is that understanding an engineering design process fully requires understanding of the product being engineered. Only by understanding what product features are used and produced in every engineering design task the process can be fully understood and eventually improved.

Taking its starting point in this proposition, the outcome of the research is an operational 5-phased procedure for assessing and developing engineering design processes through integrated modelling of product and process, designated IPPM – Integrated Modelling of Product and Process. By merging the areas of product and process modelling, additional insight into the engineering design processes is acquired. It becomes evident what product features and specifications are crucial for every step in the process. Utilising this insight enables configuring the process to specifically suit the product being engineered, thereby creating an optimal process flow for specific product in question. This optimisation is positively influencing the performance of the engineering design processes and supports the companies in complying with the increasing customer demands for customised products.

The thesis at hand is based on six scientific articles. Three of the articles are written and presented at scientific conferences whereas the remaining three are submitted to scientific journals. The results of the six papers constitute the main contribution of the research, and the main conclusions will be presented throughout this thesis. In addition to this, the results are placed in a more holistic context as the theoretical and empirical backgrounds of the project are elaborated. Furthermore the research design and scientific approaches are described in details, and eventually the results are discussed, overall conclusions are made and future research is proposed.

The results produced throughout the research project are developed in close collaboration with the Marine Low Speed business unit within the company MAN Diesel & Turbo. The business unit is the world market leader in developing and designing customer specific two-stroke marine diesel engines.

PREFACE

This dissertation is submitted to DTU Management Engineering, Technical University of Denmark, in fulfilment of the requirements for acquiring the PhD-degree. The project is an industrial PhD-project carried out in collaboration between the Technical University of Denmark and MAN Diesel & Turbo. The work has been supervised by Professor Lars Hvam and Senior Manager Hans Oxvang Mortensen. The dissertation consists of a recapitulation of the research study and a collection of six research papers prepared during the period from October 2010 to January 2014. Generally, British spelling rules are used in this thesis. Papers P1 and P5 are submitted under the name 'Jeppe Bjerrum Nielsen', whereas papers P2, P3, P4 and P6 are submitted under the name 'Jeppe Bjerrum Ulrikkeholm'.

Jeppe Bjerrum Ulrikkeholm, Kgs. Lyngby, January 2014

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I would also like to thank my PhD-colleagues at the Section of Operations Management at the Technical University of Denmark. Martin Bonev, Gabor Herczeg, Pelle Jørgensen, Christian Sørup, Thordis Oddsdottir, Anders Kudsk and Fatemeh Rahimi. The process of conducting a PhD-project is at times frustrating and you occasionally feel somewhat isolated. Having you guys around was comforting and I appreciate the time we spent together at the office, at conferences, social events, etc.

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Besides being a PhD-student I am also a husband and a father - a very fortunate one. Thank you to my loving wife Mette and gorgeous son Gustav. Your support, your comfort, your smiles and your hugs constantly reminded me of how lucky I am. I honestly don't know how I would have gotten through my PhD, without you guys around.

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CHAPTER 1 – INTRODUCTION

Chapter 1 serves as a general introduction to the research project. It starts out by briefly describing the overall problem as well as the main objective that is to be addressed throughout the thesis. The chapter then introduces the background for the projects in terms of the empirical and theoretical foundations. The motivational basis for engaging in the project is described alongside with delimitation and scoping of the research. Eventually, the chapter is concluded by presenting key definitions and terminology used consistently throughout the thesis.

1.1 ENGINEERING THE CUSTOMER SPECIFIC PRODUCT

Much has happened since the golden days of standardisation, when Henry Ford stated that any customer could have a car painted any colour he or she wanted, as long as it was black (Ford & Crowther, 1922). This attitude basically made the Model T obtainable for a vast amount of consumers, as the standardisation of the product allowed massive cost reductions making the vehicle affordable for the common man. These days however, many companies are experiencing increasing demands from their customers for the delivery of customised products that have almost the same delivery time, price and quality as mass-produced products (Hvam et al., 2008). Now we actually customise our cars, our clothing, our furniture and our cell phones to mention a few commodities. The development clearly suggests that we as consumers experience the customisation as value-adding. The originator behind the concept of mass customisation, Joseph Pine, articulates this by saying that what will make us happy as consumers is to spend our time and money on satisfying the desire for authenticity (Pine, 2004).

Marine diesel engines can not be described as an average consumer commodity. However, the market for marine diesel engines is experiencing a similar development in the demand for customised products. More and more variance is required by the market, which increases the pressure on providers of such products. This research project is focusing on the consequences of this development and how to deal with it.

For engineering design companies the development towards increasing demands for customised goods amplifies the need for having efficient engineering design processes in place, so the companies can design customised product variants faster and more efficiently. Engineering design processes are however often very complex, and can therefore be difficult to model and develop. A basic proposition in the research at hand is that understanding an engineering design process fully requires understanding of the product being engineered. By integrating a model of the product features used in the engineering design process and clarify in which steps of the process the features are used, additional understanding of what actually takes place within the engineering design process will be acquired. This insight can then be utilised to develop the processes enabling optimal process flow. It is important to emphasise that focus within this thesis is on processes related to designing variants of existing products rather than the design of new products. The reasons behind this focus will be elaborated continually throughout the thesis.

Existing approaches for modelling engineering design processes are however quite general in scope (Eckert & Clarkson, 2005). The reason for this may lie in the fact that the scope of design is vast and engineers design everything from screwdrivers to aircrafts (Ulrich & Eppinger, 2003). Only at a very abstract level can the engineering design process of such different products be the same. Therefore, design methodology has typically looked at what is general in engineering design processes, ignoring factors such as how the product itself affects the process. As stated above, a fundamental idea behind this research project is that without understanding the link between the engineering design process and the product being engineered it becomes difficult to understand and address the complexity inherent in the engineering design processes. The aim of the research is therefore to develop a procedure for

assessing and developing engineering design processes through integrated modelling of product and process.

1.2 PROJECT BACKGROUND

The research project at hand is an industrial PhD-project carried out in collaboration between the Marine Low Speed business unit of MAN Diesel & Turbo and the Section of Operations Management at The Technical University of Denmark. Being an industrial PhD-project implies that the PhD-candidate is formally employed within the company rather than at the university. The candidate is however still subject to the same knowledge dissemination obligations and ECTS-course requirements as traditional university-based PhDs. The project is co-funded by MAN Diesel & Turbo and the Danish Ministry of Science, Innovation and Higher Education. The research was initiated in October 2010 and it was completed in early January 2014.

SETTING THE EMPIRICAL STAGE

As stated above the empirical stage is set by the Marine Low Speed business unit of MAN Diesel & Turbo. The business unit develops and designs customer specific two-stroke marine diesel engines, and they are world market leader with a market share above 85 %. The company perception is that the massive market share is realised by delivering high quality products, but also by complying with all customer requests regardless of how unique they might be. This strategy has resulted in a steep increase in number of variants offered to the market.

Recently the company has experienced increasing problems keeping delivery deadlines and retaining the usual high level of quality and this development is partly attributed to the significant development in variance. Figure 1 is based on data from year 2000 until 2010, which was the year when the research project was initiated. It shows the percentage development in number of variants offered to the market alongside the development in workforce related to developing and designing these variants.

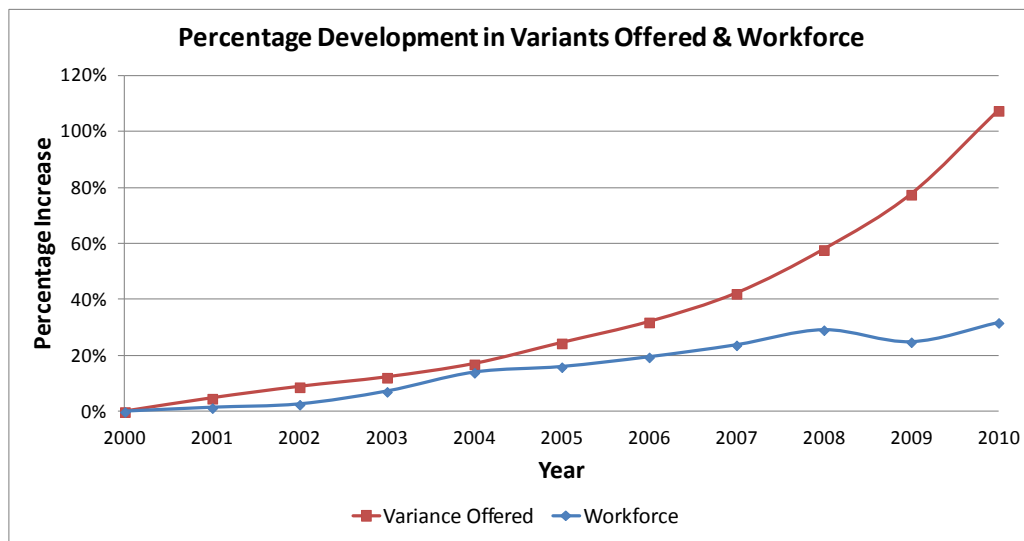


FIGURE 1: PERCENTAGE DEVELOPMENT IN VARIANTS OFFERED & WORKFORCE

The plot is exhibiting a quite clear divergence in the development of the two parameters. Where the variance offered to the market has more than doubled from year 2000 until 2010, the workforce has only been increased by approximately 30 %. When undergoing such a development and at the same time experiencing lead time and quality issues, one way of complying with this could be to reduce the product program. However, as the belief is that the 85 % market share can be attributed to the extensive product portfolio and the willingness to accede to the unique customer requests, reducing the product program is not considered an option. Rather, the company wishes to thoroughly examine their engineering design processes in order to optimise the performance of the internal processes as much as possible. The industrial PhD-project at hand is part of this overall initiative.

The case company as well as the empirical setting of the research project is described in further detail in Chapter 3.

FRAMING THE THESIS THEORETICALLY

The research project at hand can be described from a theoretical point of view as having a **context**, a **core** and a **supplement**, see Figure 2.

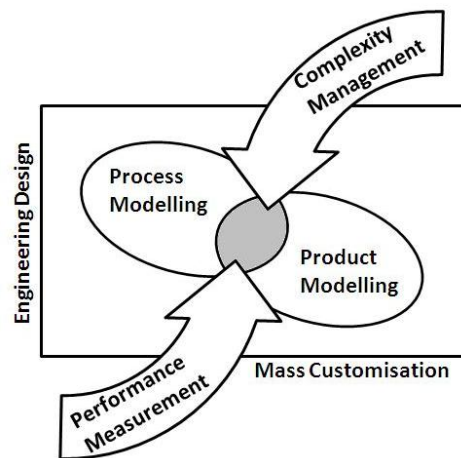


FIGURE 2: FRAMING THE THESIS THEORETICALLY

The **context** is spanned by theories within Engineering Design and Mass Customisation. Engineering design can be described as the application of scientific and engineering knowledge to the solution of a technical problem in form of a new product (Pahl et al., 2007). Mass customisation means producing goods and services to best meet individual customer needs with near mass production efficiency (Zhang & Tseng, 2007). As the case company is designing and developing customer specific diesel engines, these theories are providing the theoretical **context** for the project.

The **core** of the project is however focused on development of engineering design processes. And as a basic proposition within the research is that product knowledge should be included in the modelling of the engineering design processes, theories within Product and Process Modelling constitute the theoretical **core**. Modelling products and processes is basically about achieving a higher understanding

of the product and process, which enables the modeller to make better decisions on potential changes within the product or process.

Finally theories within Performance Measurement as well as Complexity Management can be described as **supplementing** the core. Performance Measurement supports quantifying the effectiveness of actions within processes (Neely et al., 2005) and Complexity Management focuses on among other things evaluating the suitable level of variance a company should offer its customers (Tanner, 2009). The theory of Performance Measurement thereby **supplements** the research in assessing existing engineering design processes, and Complexity Management **supplements** by revealing the impact of increasing product variety on engineering design process performance.

In unison the theories described above constitute the theoretical foundation of the research project. All theories will be elaborated in Chapter 2.

MOTIVATIONAL BASIS

It has for some years been a desire at the author's research group within the Section of Operations Management to investigate the basic proposition that understanding an engineering design process fully requires understanding of the product being engineered. With this understanding, additional insight is expected to be acquired which can be utilised to develop the engineering design processes and improve their performance.

Investigating this proposition does however require significant time allocated to the analyses and it requires a suitable empirical context to investigate within with free access to data. The Marine Low Speed business unit provided exactly this empirical context when launching the industrial PhD-project. The company did however not just start the project in order to contribute to testing of a rather theoretical proposition. They also had clear interests in improving the performance of their engineering design processes. This gave the research project a dual purpose of contributing to existing process modelling theories while addressing a real-life problem of managerial significance. This dual purpose served as a great motivation for the author.

OVERALL RESEARCH PROBLEM

Based on the outlined empirical and theoretical context the following overall research problem is formulated:

How to assess and develop engineering design processes through integrated modelling of product and process?

As stated under motivation the research objective is dual. It aims at providing a theoretical contribution to process modelling theories with a specific focus on the development of complex engineering design processes. But it also aims at solving a specific empirical problem experienced by the case company. The overall research problem is elaborated in detail and split up into four research questions in Chapter 4.

DELIMITATION

The primary scope of the research is to develop a procedure for assessing and developing engineering design processes. It is focusing on how to operationally model the engineering design processes in order to acquire a higher understanding of what actually takes place within the individual process steps. This insight is then to be utilised in revealing task interdependencies, which supports developing and rescheduling the tasks within the process flow.

Due to constraints on time and resources of the actors involved, it has not been possible to fully implement and test the procedure on a wide scale within this project. A detailed cost/benefit analysis has therefore not been possible to conduct. These issues will be elaborated and discussed in detail in Chapter 6.

1.3 DEFINITIONS & WORDING

As described earlier in this chapter the overall objective of the research project is to develop an Operational procedure for Assessing and Developing Engineering Design Processes through integrated modelling of product and process. This paragraph aims at elaborating what is specifically meant by the wordings of this overall objective within this thesis.

When using the term Engineering Design in this thesis it is defined as the application of scientific and engineering knowledge to the solution of a technical problem in form of a new product that meets some specific customer needs (Pahl et al., 2007). The Engineering Design Processes are then a series of complex knowledge-intensive activities requiring significant expertise, that in unison aims at realising the product in question.

When stating one objective as Assessing engineering design processes it is defined as determining the performance of the processes in question in terms of parameters such as cost, lead time, quality, etc. The other objective of Developing the processes means rescheduling the activities and taking task interdependencies into account, in such a way that the most optimal process flow is realised in terms of the performance parameters included in the assessment of the processes.

It is also explicitly stated that the procedure for developing the engineering design processes should be Operational. Phrasing it this way underlines the empirical ambitions of the research. It is not only the objective to contribute to theory, but also to formulate an approach of managerial significance, which can be applied in addressing real-life process problems in engineering design companies.

The engineering design processes in focus are later further concretised to be processes related to creating variants of existing products rather than related to the development of new products. These processes are known as Specification Processes, where existing knowledge is utilised to specify and

adapt existing components in a more routine manner (Schwarze, 1996). This can also be described as Engineering Change Processes, which are occupied with alterations made to parts, drawings or software that have already been released during the product design process (Jarratt et al., 2011).

1.4 SUMMARY

The purpose of Chapter 1 has been to provide the reader with an overall introduction to the research project. The project is initially framed by describing the empirical and theoretical context in which it is placed. The aim is presented as contributing to the theories within process and product modelling in the empirical setting of an engineering design company developing customer specific products. The dual purpose of contributing to theory while solving an actual managerial problem is highlighted as a particular motivational factor. Furthermore, the reader is introduced to the overall scoping and delimitation of the project. It is important to underline that the main contribution is to develop a procedure for assessing and developing engineering design processes and how to operationally model products and processes in an integrated manner. The research does not provide a conclusive cost/benefit analysis of applying the procedure itself. However, the applicability and evaluation of the procedure will continually be addressed throughout the thesis. The chapter is finally concluded by presenting key definitions and terminology used throughout the thesis.

CHAPTER 2 – THEORETICAL FOUNDATION

Having a solid theoretical foundation is a crucial precondition for any research project. During the course of this study several theories have been applied, and the most pivotal will be introduced in this chapter. The direct research contribution of the research at hand lies within the fields of Product and Process Modelling, which is why theory within these areas obviously plays a major role. The context in which the contribution is developed is however equally important to understand. As the case company is an engineering design company designing customer specific products, theories within the areas of Mass Customisation and Engineering Design are included. These theories support framing of the research project and underline the context in which the research contribution is developed and tested. Finally theory on Complexity Management and Performance Measurement will be briefly introduced as they supplement the body of theory in question.

2.1 MASS CUSTOMISATION

In the world of today's competitive business there is an increasing demand for customised products, driving companies to constantly expand their offered product variety, often with the effect of introducing more complexity into the product families (Pine, 1993). Many companies are thereby experiencing increasing demands from their customers for the delivery of customised products that have almost the same delivery time, price and quality as mass-produced products (Hvam et al., 2008). One way of complying with this is by engaging in mass customisation. Mass customisation basically means producing goods and services to best meet individual customer needs with near mass production efficiency (Zhang & Tseng, 2007; Bettig & Gershenson, 2010). The objective is to combine the efficiency of mass production with the differentiation possibilities of customisation (Tseng & Piller, 2003).

A central principle of mass customisation is that the product range being offered should be modular so customised products can be realised by combining the modules in different ways (Hvam et al., 2008). Often this combination of modules is supported by a configuration system used to support the tasks involved in the customer-oriented business processes related to specification of the products, also called the specification process. The concepts of modularity and the specification process will be described briefly below.

MODULARISATION

Product modularity is closely related to the term product architecture as well as to mass customisation. (Worren et al., 2002) defines a modular architecture as a special form of product design in which loose coupling is achieved through standardised component interfaces, which enables the production of a large number of end items. In short, product modularity can be defined as the use of standardised and interchangeable components or units that enable configuration of a wide variety of end products (Schilling, 2000).

In order to introduce modularity it is crucial to understand the architecture of the product that is to be modularised. The architecture describes the structure and composition of a product and getting a clear understanding of the architecture enables the decomposition of the product into modules (Harlou, 2006).

THE SPECIFICATION PROCESS

Companies engaging in mass customisation need to give special attention to the business processes related to adapting products to suit the customers' needs and to create specifications which form the basis for subsequent activities involving production, assembly, delivery and servicing (Hvam et al., 2008). These are also known as the specification processes.

A specification is defined by (Hvam, 1999) as a description which can unambiguously transfer needs or intentions from one group of people to another. This can be many different things such as design drawings, part lists, assembly specifications, production plans, etc.

You can talk of different kinds of specifications processes such as engineer-to-order, modify-to-order or configure-to-order (Hvam et al., 2008). Engineer-to-order is common for companies producing very complex products, and it is called the creative specification process. In such companies many resources are put into the design and specification of each individual product. Modify-to-order is also referred to as the flexible specification process, where existing products are modified in order to comply with specific customer requests. The configure-to-order specification process is most often supported by a configuration system containing fixed rules for how existing standard modules are to be combined to meet the demands from the customers.

It is important to underline the differences between the specification process and the product development process. Using the definitions formulated by (Schwarze, 1996) a product development process is about generating knowledge and designing new components in a creative process. The specification process however is characterised by having lower degrees of freedom and by utilising existing knowledge to specify and adapt existing components in a more routine manner.

ONE-OF-A-KIND

One type of company that might benefit from moving towards mass customisation is so-called one-of-a-kind companies that design or produce large complex products such as marine diesel engines, cement factories, etc. Companies of this type face a considerable challenge in achieving efficiency in the task of designing the individual product in detail, so it suits the customers' needs (Hvam et al., 2008). For one-of-a-kind companies to achieve greater efficiency in customer tailoring, (Hvam et al. 2008) advise separating the tasks of product development, where various parts of the product are developed from scratch from the tasks of designing a part of a product in detail so it matches the individual customer's need. This point refers back to the difference between the specification process and the product development process described above.

HOW THEORY OF MASS CUSTOMISATION CONTRIBUTES TO THIS RESEARCH

The theory of mass customisation supports understanding of the empirical context in which the case company is situated. The company is experiencing increasing demands for customised products and they attempt to comply with this development by utilising their modular product range and continually improve their specification processes so they perform as optimal as possible. As a main outcome of the research at hand is a procedure for development of engineering design processes the theories of specification processes aided in framing the application area of the procedure. This aspect is addressed in more detail in Chapter 5 and more specifically in the paper P4.

2.2 ENGINEERING DESIGN

The concept of engineering design is rooted within product development. Product development can be described as the set of activities beginning with the perception of a market opportunity and ending in the production, sale and delivery of a product. The role of engineering design is then to define the physical form of the product to best meet customer needs (Ulrich & Eppinger, 2003). Engineering design is about applying scientific and engineering knowledge to the solution of a technical problem in form of

a new product (Pahl et al., 2007). Design projects are often unique, infrequent and associated with considerable uncertainty related to aspects such as the time required to develop solutions, the performance level of the proposed solutions and the time and money required to verify performance (Eckert & Clarkson, 2005).

Designing basically involves people, in form of a design team, with the appropriate expertise. They are then undertaking a process, which can be described as a sequence of activities arranged into phases and steps, to define a product (Eckert & Clarkson, 2005). For the members of the design team, it is knowledge that links everything together and enables them to take the actions and to make the decisions that direct the process and determine its outcome (Pahl et al., 2007).

ENGINEERING DESIGN PROCESSES

Taking the above into consideration, engineering design processes can therefore be characterised as knowledge-intensive activities. Each step in the process involves members of the design team identifying the knowledge that defines a particular sub-task and then using their expertise to process that knowledge into a state that defines the selected sub-solution (Eckert & Clarkson, 2005). Engineering design processes are thereby significantly different from business administration processes. Business administration processes are usually simple, well-defined and repetitive whereas engineering design processes are characterised by being ill-defined, iterative and complex (Maier & Störrle, 2011). The distinct characteristics of engineering design processes arise from the complex nature of the product itself, the complexity of the process and the difficulty of capturing this in any kind of model. These factors are highly interdependent, and it can be very difficult to distinguish the cause and effect relationships between them. Due to these characteristics of the engineering design process the individual process steps within the overall process therefore easily end up being black boxes when applying conventional process mapping techniques, as they are not able to deal with and express this complexity in a suitable way.

Several scholars such as (Fixson, 2004), (Eckert & Clarkson, 2005) and (Albers & Braun, 2011) acknowledge that these factors are highly interdependent. However, no structured modelling approach is explicitly aimed at understanding this link between the engineering design process and the product being engineered. Most process modelling approaches today are too general in scope (Eckert & Clarkson, 2005). The reason for this may lie in the fact that the scope of design is vast and engineers design everything from screwdrivers to aircrafts (Ulrich & Eppinger, 2003). Only at a very abstract level can the engineering design process of such different products be the same.

ENGINEERING CHANGE

Academic design literature such as (Pahl et al., 2007) and (Ulrich & Eppinger, 2003) has traditionally had a strong focus on the development of new products. The modification of existing products has however been given an increased focus during recent years by (Jarratt et al., 2011), (Veldman & Alblas, 2012) and (Pasqual & Weck, 2012) to mention some, and the significance of the term engineering change has eventually been quite recognised. (Jarratt et al., 2011) defines engineering change as alterations made to parts, drawings or software that have already been released during the product design process. A

change may encompass any modifications to the form, fit and/or function of the product as a whole or in a part, and may alter the interactions and dependencies of the constituent elements of the product.

However, most of the recent published literature on engineering change is focusing on the change propagations that occur within the product when changes are made (Koh et al. 2012) and (Yang & Duan, 2012). But the success or failure of any design process depends crucially on finishing on time and to budget. To achieve this, a successful engineering design process can be just as important as a high-quality product (Eckert & Clarkson, 2005). The objective of the research at hand is therefore to expand the focus to embrace the change propagations between product alterations and the engineering design process dealing with this change.

HOW THEORY OF ENGINEERING DESIGN CONTRIBUTES TO THIS RESEARCH

Similarly to the theory of mass customisation, the theory related to engineering design supports framing the research project. The primary collaboration partner is a company performing extensive engineering design. The project at hand is rooted within the engineering departments of the company focusing on designing variants of existing products in accordance with customer requests. This focus thereby entitles the inclusion of theory within engineering design and also within engineering change. As the main contribution of the project is a procedure for assessment and development of the engineering design processes, the project has a heavy focus on the process side and more specifically on the issues related to modelling of processes.

2.3 PRODUCT MODELLING

Many companies face significant challenges when trying to get an overview of their entire product portfolio. Using product modelling techniques can be a mean to acquire this. Furthermore it can support relevant stakeholders in obtaining an overview of the variance within the individual product families. A product family might include thousands of variants, and describing all these individual variants is quite an extensive task. However, the overview is essential as the existence of each individual variant might need to be considered when making decisions regarding the product family (Harlou, 2006). So, by modelling your product range you will achieve a better understanding of the product, the variance within it and improve your abilities to control the complexity that exists within it.

In general, product modelling can be interpreted as the logical accumulation of all relevant information concerning a given product range. But to do so you need a tool, such as the Product Variant Master, which is chosen as the primary product modelling tool in this research project.

THE PRODUCT VARIANT MASTER

The Product Variant Master (PVM) is a well-described tool for performing product modelling and visualisation (Hvam, 2001; Hvam & Jensen, 2007). The tool supports describing the complete product assortment in an efficient manner to all stakeholders. It provides an overview of the product range offered by a company and illustrate how the products can vary. More specifically it shows the different parts that comprise a product, the relationship between the parts, the variations available of each part,

the amount of each part needed to construct a final product, the attributes of all parts and finally the rules of how parts are related. The tool has its basis in system theory, multi-structuring theory and object oriented modelling, and simply put, it can be said that a PVM contains a description of the company's product range and the associated knowledge (Harlou, 2006).

A simple example of how a Product Variant Master could look like can be found in Figure 3, which will be used as an illustrative example for the exposition of the PVM-technique.

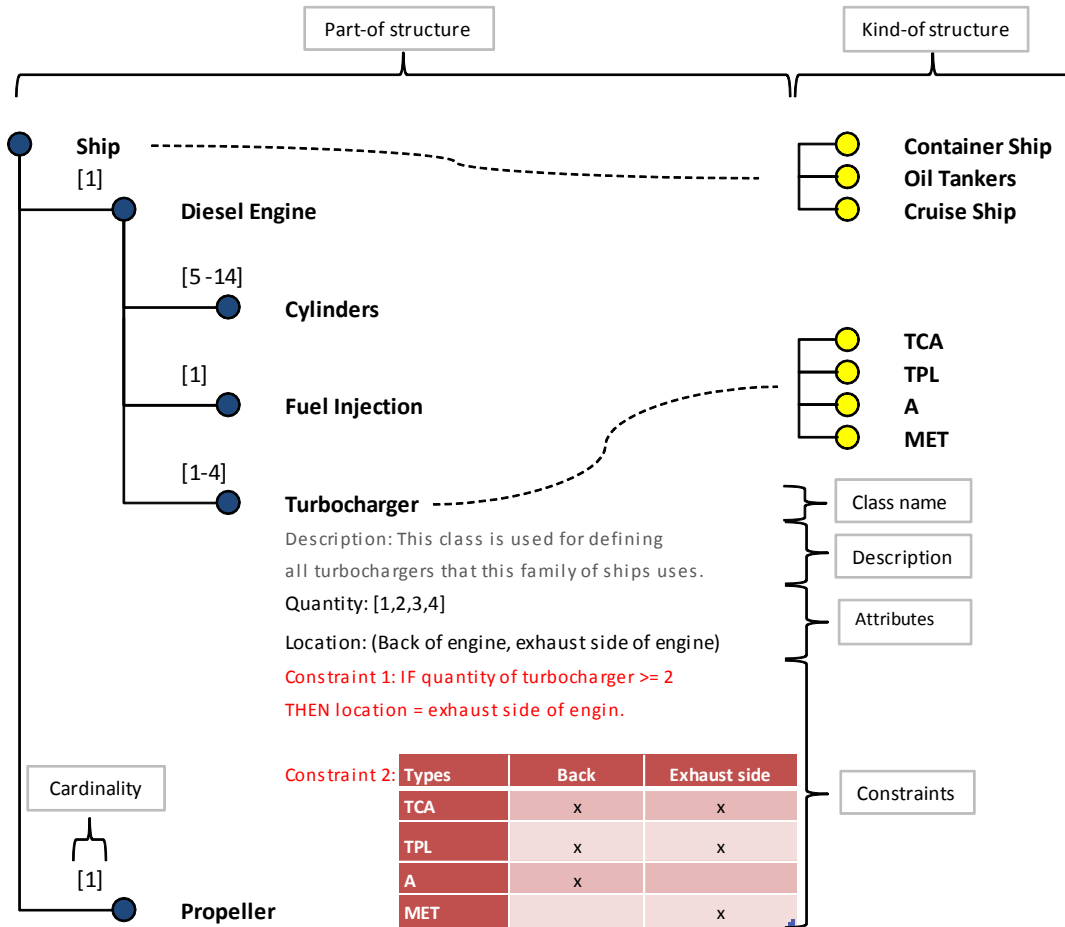


FIGURE 3: THE PRODUCT VARIANT MASTER

The PVM consists of two overall parts. The left hand side of the model describes the product's generic structure, and is called the 'part-of-structure'. It contains the modules, components and parts, generally referred to as classes, which appear in the entire product family. For example, as can be seen in Figure 3, a ship consists of the parts: diesel engine, propeller, etc. The engine then again consists of additional parts: cylinders, a fuel injection system and turbocharger. Each part of a product that is depicted on the PVM is called a class. A class is defined as a group of objects with the same structure or function (Hvam et al., 2008). In addition, the number (cardinality) of each class needed to construct a final product is specified, e.g. one fuel injection and one to four turbochargers are needed to construct an engine.

Classes in the 'part-of'-structure can be related to each other with what is called an aggregation structure in object oriented modelling, by combining the nodes in the PVM. These relations then describe the hierarchy between classes so to speak. For instance in the relation between the classes 'Diesel Engine' and 'Turbocharger', the 'Diesel Engine' comprises the super-class to the sub-class 'Turbocharger'.

All classes furthermore have descriptive parameters called attributes, which define the variation within the class. For instance, using the example from Figure 3 again, a turbocharger can either be placed on the back side of an engine or on the exhaust side of an engine. By combining this notation-form with the notion of super-classes and sub-classes, it becomes possible to describe the product on many levels from main component all the way down to detailed properties of the product-parts.

A PVM normally contains many classes and attributes, which are related in different ways. These relations are illustrated on a PVM with constraints. Consider for example Constraint 1 in Figure 3. If the quantity of turbochargers to be included is 2 or higher then the location-attribute needs to be 'exhaust side of engine'.

The right hand side of the PVM is called the 'kind-of'-structure, and it describes how the individual classes and parts can appear in several variants. For example, according to Figure 3, there are four types of turbochargers available: TCA, TPL, A and MET. Constraints can also be related to these 'kind-of'-variants, consider for example Constraint 2, which describes the relationship between the type of turbocharger and the location-attribute. The 'kind-of'-structure is analogous to the generalisation/specialisation structure within object oriented modelling (Hvam et al., 2008).

HOW THEORY OF PRODUCT MODELLING CONTRIBUTES TO THIS RESEARCH

The Product Variant Master has been used in many different contexts, such as for developing product configuration systems (Hvam, 1999; Hvam & Pape, 2006; Mortensen et al., 2011), establishing product architectures (Mortensen et al., 2008; Mortensen et al., 2010) and to clean up product families (Haug et al., 2010). In this research project the aim is to adapt the PVM so it can be used in a new context: As a tool for improving engineering design processes through integrated modelling of product and process.

A specific strength of the PVM-modelling technique for the research at hand is that it can describe a product on several levels, from very abstract to very detailed by making use of aggregation structures and the attribute notation. A central scope of the project is to develop a modelling tool that can support identifying interdependencies between engineering design tasks. And analyses will show that analysing interdependencies between components only reveals parts of the overall picture. By being able to model the product on attribute level as well allows a detailed mapping of interdependencies between product features of different components. This will prove to add significant value to the outcome of this project, which is illustrated and elaborated in especially paper P3.

2.4 PROCESS MODELLING

Simply put a business process can be described as a set of linked activities or tasks that utilise some kind of input(s) and transfer them into a product or service for either an external or internal customer. The transformation taking place in the process should ideally add value for the end-customer (Hammer & Champy, 1993). Most business processes are cross-functional, spanning the "white space" between the boxes on the organisation chart (Rummler & Brache, 2012).

Business processes are often mapped out and visualised. This is called process modelling or process mapping. Many types of tools, including flowcharts, notation languages and methods are used to map out business processes. The tools and methods that were utilised in this thesis will be presented in the following sub-sections.

BUSINESS PROCESS MODELLING NOTATION, BPMN

The most well-known tool for modelling processes is probably the Business Process Modelling Notation, BPMN. BPMN is a flowchart tool used to create graphical models of business processes, where each step in the process is represented by a distinct symbol. The symbols are then linked together with arrows indicating the process flow direction. The aim of BPMN is to provide businesses with the capability to understand and communicate their internal business procedures using a standard notation that is straightforward and fairly easy to use. By using the BPMN-tool, an overview of a process can be depicted, showing the chronological order of activities performed, who is responsible for each activity and where responsibility is handed over. Furthermore it clarifies which communication is occurring between different departments and external stakeholders (White, 2004).

In the research project at hand, the BPMN-notation will be utilised for acquiring initial process understanding of the processes being analysed.

INTEGRATED DEFINITION, IDEF

The IDEF-method is another widely used process mapping tool. IDEF is not just a single model but a family of 16 different modelling structures. However, in this thesis it is only IDEF0 which is put into use, and therefore only IDEF0 is addressed here. The IDEF0 was originally intended to model the functional behaviour of engineering systems. And yet it is now being applied to a wide variety of business processes.

There are two main modelling components in an IDEF0 model. The first is functions, defined as either activities or processes, which are represented by a box. The second component is data and objects that relate to the functions, which are represented by arrows, see Figure 4 (IDEF, 1993).

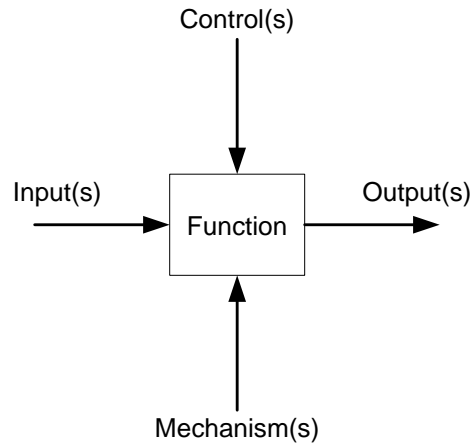


FIGURE 4: IDEF0-NOTATION

Inside each IDEF0-box is a name, describing what happens in the function. Arrows on the diagram do not represent flow as in traditional flowcharts but rather data and objects related to the functions to be performed. Each function is constrained by the data and objects made available in that function. The specific side of a box that an arrow interfaces with reflects the arrow's role. Arrows entering the left side of a box are inputs. Inputs are used or consumed by the function to produce outputs. Outputs are the data or objects produced in the function and they are represented by arrows leaving the right side of a box. Arrows entering the box on the top are controls. Controls detail the conditions required for the function to produce correct outputs; e.g. policies and standard working practices. Arrows entering the bottom side of a box are mechanisms. Mechanisms represent the means that support the execution of the function, e.g. equipment and people (IDEF, 1993). IDEF0 furthermore has a strong hierarchical structure which can be used for decomposing activities within the process into more detailed sub- or component-activities (O'Donovan et al., 2005).

DESIGN STRUCTURE MATRIX, DSM

The third and last modelling approach presented here is the Design Structure Matrix, DSM. This tool is especially suitable for engineering design projects, which involves specification of many interdependent variables which together define a product, how it is made and how it behaves (Steward, 1981). The DSM is a matrix structure representation that captures the sequence and the technical relationships among different design tasks in a project. By using the modelling technique it becomes possible to find alternative sequences of the tasks and streamline the inter-task coordination (Eppinger et al., 1994). It can be considered an information exchange model that puts emphasis on the relations between complex tasks in order to determine a sensible sequence for the tasks being modelled (Yassine, 2004). One of the DSM-method's strengths is that it can deal with complex engineering design projects that have complicated interdependencies among their activities.

The DSM is a square matrix with rows and columns representing a complete list of elements (activities, tasks or phases) being performed in a system (process). Marks in the matrix show the relationship between the elements. The output information from one activity becomes the input information for another activity. There are three basic types of relationships among elements: parallel (independent or

concurrent), sequential (dependent) and coupled (interdependent). Parallel means that two activities are independent of each other and therefore no information exchange is required between the activities. Sequential means that one activity has to be performed before another activity can start because the design parameters of one element are built on information about the outcome of another element's parameters. Coupled means that activities are intertwined, and one activity can therefore not be completed without first knowing certain parameters of another activity. At the same time the second activity cannot be completed before knowing the parameters of the first activity. Therefore the activities have to share information and cooperate.

In a Design Structure Matrix when reading across a specific row, the marks in the matrix indicate all of the activities whose output information is required to perform the activity corresponding to that row. For example, row I in the left hand side of Figure 5 indicates that activity I needs some kind of information from activities C, F and J before it can be completed.

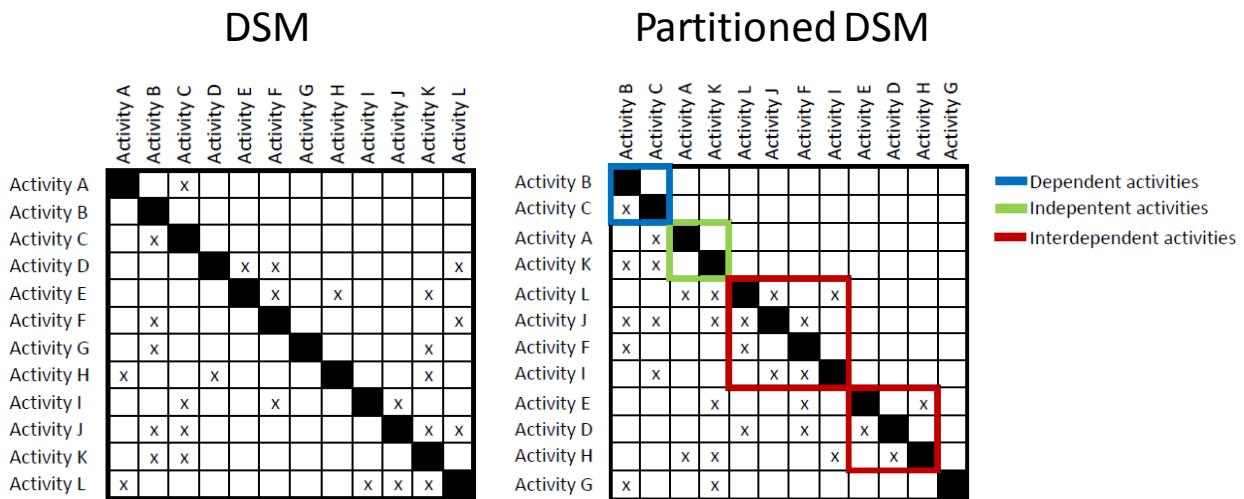


FIGURE 5: THE DESIGN STRUCTURE MATRIX

All marks in a matrix below the diagonal (the lower triangular of the DSM) represent that information is conveyed to downstream activities. Marks above the diagonal indicate that an upstream activity is dependent on the input from a downstream activity. If an activity is dependent on inputs created downstream then that activity must make an assumption about the input it needs from the downstream activity. For example, activity A in the left hand side of Figure 5 must make assumptions about the input created by activity C (note that the order in which the activities are performed is the order in which they are listed in the matrix, A to L). Then after activity C finishes, activity A may have to be reworked if the assumption was incorrect. One central strength of the DSM-method is that it clearly highlights if activities have possible flawed inputs and therefore the activities might have to be reworked, which have significant impacts on cost and scheduling. That is why the aim of the DSM-method is to reorganise the sequence of activities, by rearranging the rows and columns in the DSM, so as many activities as possible are below or close to the diagonal, thereby reducing their impact. Rearranging activities can be

done with a simple algorithm called partitioning. The right hand side of Figure 5 shows the partitioned DSM. Note that activity C is now rescheduled so it is placed before activity A.

However, sometimes after a DSM is partitioned, certain marks cannot be brought below the diagonal without forcing one or more other marks above it. This indicates that activities are coupled (interdependent). An example of this is activities E, D and H in Figure 5. When activities have been found to be coupled they can be arranged to be carried out concurrently and exchange preliminary information frequently. If coupled activities are functionally based, a solution may be to combine activities into a single activity and assigning it to a cross-functional team (O'Donovan et al., 2005). However, if that is not possible then upfront planning is key to saving time and resources. Iteration plans can then be established, determining what tasks should start an iteration process based on estimates of missing information (Yassine, 2004).

ACTIVITY DETAIL SHEETS

In order to get a better understanding of what is actually talking place within the individual activities in a process, the process modeller can benefit from applying a predetermined and fixed information sheet as interview template with process actors. (Madison, 2005) has developed the Activity Detail Sheet for such purposes. Activity Detail Sheets are in short a structured way to acquire information in interviews with employees about a specific activity in relation to aspects such as inputs/outputs, tasks to be completed, etc. These can therefore play a role in the knowledge acquisition when modelling current work processes. Basically an Activity Detail Sheet represents all the information a person must know to successfully complete an activity.

HOW THEORY OF PROCESS MODELLING CONTRIBUTES TO THIS RESEARCH

As a main contribution of the research project is a procedure for assessing and developing engineering design processes it is only natural to include existing literature on process modelling. The Business Process Modelling Notation contributes to getting an overview of existing processes, in terms of aspects such as what activities are carried out and by whom. The IDEF0-modelling technique and the Activity Detail Sheets support acquiring deeper understanding of the individual tasks within the process in a structured manner. Finally the Design Structure Matrix supports the handling of interdependencies between tasks and re-sequencing of tasks to create an optimal flow.

2.5 COMPLEXITY MANAGEMENT

Complexity management typically has a strong focus on the management of product variants. It focuses on describing the variety of and within the products or services a company offer its customers. In general, too much variety will be a burden both for the customers and the company, while too little variety will decrease the competitive advantage it can be to offer variety (Tanner, 2009). It is often very difficult to find the right level of complexity and many companies suffer from the fear of having too little. (Wilson et al., 2010) argue that variety in products offering customers something they are willing to pay for is good complexity. Bad complexity is however variety that customer will not pay for, or pay enough for. Many firms are convinced that they maximise the fit between product offerings and

customer desires when they increase their product variety, and that this allows them to maintain or even increase their market share. This might be the case, but at the same time companies often experience lower performance of its internal operations when product variety increases significantly (Salvador et al., 2002).

When creating variants of an existing product you achieve greater differentiation compared to your competitors. This might result in growth in sales but at the same time it will increase the product portfolio complexity as it is necessary to manage another product variant. It is therefore a balance, and the task of finding an optimal level of product complexity is difficult. (Closs et al., 2008) argue that the optimal level of complexity in a product portfolio can be described as achieved when the combination of diminishing sales return and increasing costs due to complexity are taken equally into account.

Focusing on costs and on the product as the only source of complexity is however somewhat narrow. Increasing complexity within a product portfolio is likely to induce complexity into the processes dealing with the products. Adopting a wider perspective on complexity is suggested by other scholars such as (Albers & Braun, 2011) who emphasise the need for researching the complex relationship that exists between product and process. (Lindemann et al., 2009) also introduce the term structural complexity management, which places a holistic perspective on the mutual complexity that exists between the market, product, process and organisation. Accordingly (Wilson et al., 2010) also plead that three types complexity exist within product, process and organisation, and that all three dimensions should be addressed in order to fully understand the complexity inherent in the company.

HOW THEORY OF COMPLEXITY MANAGEMENT CONTRIBUTES TO THIS RESEARCH

The theory of complexity management is relevant to address when considering cases dealing with increasing levels of product portfolio variance. Complexity management supports identifying whenever the complexity is becoming too high, and also in deciding what can be considered good and bad complexity. Furthermore, the theory acknowledges that product and process complexity are interrelated and that addressing these individually will only partly solve the problem. This standpoint supports the basic proposition of the research at hand, when claiming that full understanding of engineering design processes requires understanding of the product being engineered.

2.6 PERFORMANCE MEASUREMENT

Performance measurement can be defined as the process of quantifying the efficiency of actions, while a performance measure can be defined as a metric used to quantify the efficiency of an action (Neely et al., 2005). There are numerous reasons for using performance measurement, but common for all is that individual feelings and perceptions should be replaced with facts. Without performance measures, managers cannot really understand how their business work, the problems within them, and whether their attempts to improve performance is working as planned (Kaydos, 1999). Performance measurement can therefore be seen as an important precondition for making improvements. (Harbour, 1997) even claims that you cannot improve what you cannot or do not measure.

Measuring performance provides managers and front-line employees with valuable insight that can enable the actors to identify potential improvement initiatives. It can support better understanding of existing business processes, enable improved quality and productivity as well as better planning and forecasting (Kaydos, 1999).

Making use of performance measurement has great potential. Investigations carried out by (Davenport & Harris, 2007) showed that a consistent use of analytics and performance measurement have a great impact on business and financial performance. High performers are 5 times more likely to use analytics strategically compared to low performers.

HOW THEORY OF PERFORMANCE MEASUREMENT CONTRIBUTES TO THIS RESEARCH

A central aim of the research at hand is being able to assess and diagnose existing engineering design processes. Application of performance measurement contributes to reaching this objective. Assessing the current state is however not the final objective. The current state is to be improved and as stated by (Harbour, 1997) this can only be done by first understanding the conditions of the current state. These ideas are to be incorporated in the procedure for assessing and developing engineering design processes which this research project aims to formulate.

2.7 SUMMARY

Theories with major significance for the research project have been introduced throughout this chapter. Theories on mass customisation and engineering design constitute the context in which research is carried out as the case company is an engineering design company designing customer specific products. The specific theoretical contribution that the research aims at producing is however within the areas of product and process modelling, why significant emphasis is placed on these theories. Finally, theories on complexity management and performance measurement have been introduced as they play a minor but decisive role in the research at hand.

CHAPTER 3 – EMPIRICAL FOUNDATION

The primary collaboration partner of the research at hand is the Marine Low Speed business unit of MAN Diesel & Turbo. This chapter briefly introduces the company and their business model. The market is described and the strategy for how the company attempts to cope with the market developments is introduced. The strategy does however pose some challenges for Marine Low Speed. These challenges are introduced as they illustrate the background for initiating this research project.

3.1 CASE COMPANY INTRODUCTION

MAN Diesel & Turbo is part of the MAN-Group, an international company that has existed for more than 250 years and has departments all over the world, with headquarters located in Germany. The MAN-Group is one of Europe's leading industrial players in transport-related engineering, with a revenue of approximately €16.5 billion. As a supplier of trucks, buses, diesel engines, turbomachinery, and special gear units, MAN employs approximately 52.500 people worldwide.

MAN Diesel & Turbo is the world market leader for large diesel engines for use in ships and power stations, and is one of the three leading suppliers of turbo machines. The company employs around 12.500 persons and has representatives in over 150 countries. The head office is situated in Augsburg, Germany.

MAN Diesel & Turbo has a history of more than 100 years when it comes to design and development of diesel engines. In the years between 1893 and 1897 Rudolf Diesel and MAN-engineers developed the first diesel engine in Augsburg. This was the beginning of a long period where MAN Diesel & Turbo had a leading role in the development of diesel engines and the company still plays a decisive role in the industry. In 1898 Rudolf Diesel granted the Danish company Burmeister & Wain (hereafter abbreviated B&W) an exclusive manufacturing right for the diesel engine in Denmark. B&W started as a small mechanical workshop in a backyard in Copenhagen. A year after receiving their license B&W had produced their first engine and the company later expanded to being both an engine and ship builder. In 1911 B&W built the world's first ever diesel-powered ship. Through first and second World War and the subsequent decades B&W steadily grew. B&W's reputation increased in the following years but in the 1960's and 1970's the company got hit by a tougher international competition triggered by the growing globalisation. This led to that B&W in 1980 was taken over by the German company MAN and this marked the birth of MAN Diesel & Turbo.

MAN Diesel & Turbo has six business units, one of which is the Marine Low Speed (MLS) unit with headquarters located in Copenhagen Denmark. The Marine Low Speed business unit is the primary collaboration partner of this research study. This unit is responsible for designing and developing large customer specific marine two-stroke diesel engines to propel large container ships, oil tankers and other vessels. The Marine Low Speed unit has a large product range with engines that vary in power output, size and features. Engines can range from small 8 ton, 450 kW engines to large 2.820 ton, 97.300 kW engines. Two engines are rarely completely alike as the customers often have specific requests that call for some customisation of the engines. In order to comply with the unique requests for customised engines, the company is using a modular based product platform, which allows for reuse of modules across specific orders and engines.

MARINE LOW SPEED BUSINESS MODEL

The Marine Low Speed unit develops and designs two-stroke marine engines and therefore produces specifications for engines, e.g. drawings, bill of materials and other product related specifications. However, MLS does not produce the engines themselves. They operate using a so-called licensee

business format. A licensee needs to fulfil MLS's quality expectations in order to be accepted as a producer of their design. Figure 6 shows the most common process for design, production and delivery of MLS-engines.

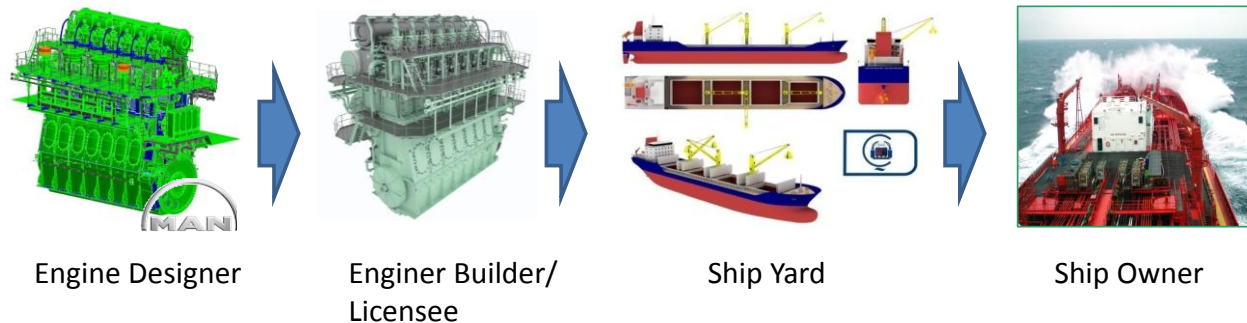


FIGURE 6: THE PROCESS FROM DESIGN TO DELIVERY OF ENGINE

When a ship owner wishes to build a new ship, it is most common that he puts in an order at a ship yard. The ship owner lists up all specifications for how the ship should be, including engine requirements. The ship yard then contacts the engine builder or licensee and puts in an order for an engine on behalf of the ship owner. Then, the license engine builder orders an engine design at e.g. MLS, after which the engine design company designs an engine in accordance with the given specifications. The design is delivered to the licensee who builds the engine, delivers it to the ship builder, who then mounts it in the ship. Finally, when the ship is completed, the ship yard delivers it to the ship owner. Therefore, the end-user of the engine design is actually the ship owner, but MLS do consider their licensees or engine builders as their direct customers.

The relation between MLS and engine builders producing MAN Diesel & Turbo engines is very close. That is because the engine builder produce the whole engine based on MLS-designs, and if the engine does not fulfil the end-customers expectations, MLS and the engine builders are together responsible for the shortcomings. MLS therefore makes a licensee agreement with the engine builders. The licensee agreement includes a degree of quality and production control from MLS's side.

THE MARKET

There are currently only three available providers of design for two-stroke marine diesel engines. MLS is definitely the biggest provider as they have a massive 85 % market share in terms of engines produced. Their biggest competitor is the Finnish company Wärtsilä which has around 12 % of the market share, while the Japanese company Mitsubishi has only 3 %. The market share of around 85 % has been quite stable for some years, which is mainly due to customer loyalty and conservatism of the customers. A ship owner that has always done business with MLS with a good experience is most likely going to do business again with MLS, when the demand for a new engine arises. However, at the time of writing some state-owned Chinese companies are rumoured to attempt to enter the otherwise very conservative market.

Customers in this market field are also limited, as there are only around 20 licensees in the world that have the know-how and resources available to produce such large engines. It is also very rare that new licensees enter this market. Most of the engine builders are located in East Asia, i.e. in South-Korea, Japan and China.

Although the amount of competitors and customers are fairly stable, the business for two-stroke marine diesel engines has in recent years however changed considerably in terms of the level of customisation required by ship owners. The engine designers are experiencing increasing demands for customised engines forcing the design providers to increase the variance offered to the market in order to comply with the development. Furthermore, the business environment is ever changing due to legislation changes, mainly environmental legislation which is being given continually increased attention by legislation authorities. With increased technical know-how and health and environmental awareness comes stricter legislation. This development obviously poses significant challenges for the company. Regardless of this development the customer expectations do however remain the same: on-time delivery, high degree of optimization of the engine while meeting ship owner requirements and adequate documents with as few errors and deficiencies as possible.

THE COMPANY STRATEGY

The vision of Marine Low Speed is to be the number 1 designer and licensor of two-stroke diesel engines, known for its loyal, reliable and prompt support. And by number 1 the company is mainly referring to the market share as their primary objective. The aim is to win every single order and to maintain or even increase the current market share of 85 %. In order to fulfil this goal of winning every order the company will continue to deliver customer specific, high quality products on time, even if it requires significant development and engineering work. Marine Low Speed Engineering thereby wants to offer and maintain a product program that contains competitive engine types for all relevant applications.

3.2 EMPIRICAL SETTING

Having a strategy of complying with every unique customer request in a market experiencing increasing demands for customisation and stricter environmental legislation poses a significant challenge for Marine Low Speed. The consequence has been a steep increase in the number of very customer specific product variants offered by the company. This is clearly reflected in the product program, which has more than doubled in the period from 2000-2010 and the tendency is continuing, as illustrated in Figure 7.

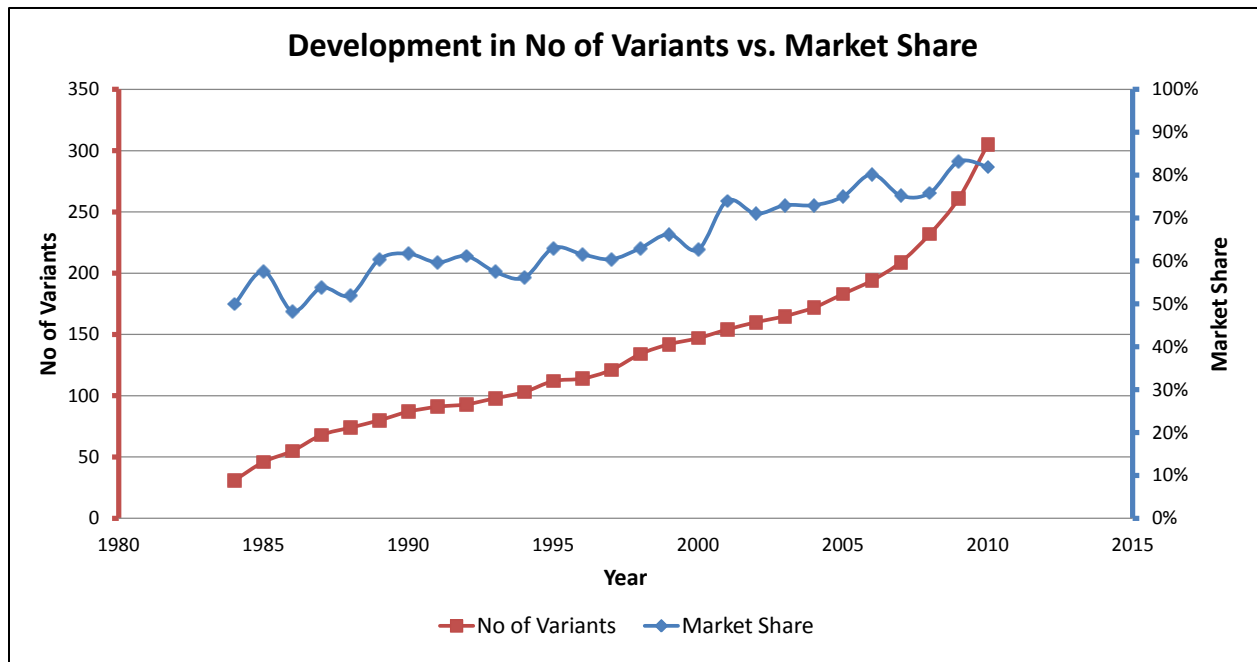


FIGURE 7: DEVELOPMENT IN NUMBER OF VARIANTS OFFERED & MARKET SHARE

The company position is that the best way to satisfy the customer is to offer the most technically advanced solution, and to comply with the customers' request without trying to sway the customers towards choosing a product variant that is more frequently designed. The company fears that if an alternative variant is suggested to the customer, the customer will instead address a competitor and place the order there. And by considering the market share development illustrated by the blue line in Figure 7, it is also quite difficult to argue against the strategy of winning the market by increasing variance, as the plot strongly suggests that it actually is a successful strategy. The number of variants offered may have been increased significantly, but market share has simultaneously increased to more than 80 percent. It is therefore not considered an option not to comply with the customers' requests regardless of the development and engineering efforts needed to fulfil the requirements put up by the customer.

The development illustrated in Figure 7 has without doubt resulted in increased pressure on the engineering and R&D-departments within MLS with several occurrences of delivery and quality issues in consequence. The departments do thereby not seem to have the resources needed to fulfil the objectives without it affecting the delivery and quality performance. As reducing the product program is not considered an option, the aim is to scrutinise the existing engineering design processes and enhance the performance of the engineering departments if possible. Several initiatives have been initiated in order to anticipate these challenges, among them this research project.

3.3 SUMMARY

The main collaboration partner of the research at hand is the Marine Low Speed business unit of MAN Diesel & Turbo. The business unit as well as its place within the overall MAN-group is introduced briefly

in this chapter. Marine Low Speed is the market leader within the two-stroke marine diesel engine business, and they intend to remain as such. However, as described above, several challenges need to be overcome in order to continually ensure the position as market leader. Customers require increasing levels of customisation while legislation authorities are formulating ever stricter emission regulations causing the company to put a lot of effort into redesigning and developing the engines offered. This needs to be done while keeping the performance related to quality and delivery intact, as this is key to maintaining customer loyalty.

The current empirical setting of the company is also introduced as it illustrates the background for this research project. How is a company that intentionally continue to increase the product variance offered to the market, to deal with the challenges that goes with this increase? And what is the magnitude and character of these challenges? These are some of the empirical questions which the research at hand attempts to answer.

CHAPTER 4 – RESEARCH DESIGN

This chapter introduces the research design of the study at hand. Initially the overall research problem is described and the main objectives of the research are identified. When having described the objectives it is also relevant to consider the stakeholders involved in the project as they might have different objectives. Main stakeholders and their interests are therefore described and discussed in detail. This is followed by an introduction to the four research questions of the study each relating to different phases of the overall project. The methodological approach applied in order to answer the research questions is then described followed by the scientific limitations of the chosen methodology. The chapter is rounded off by introducing the expected outcome of the research project.

4.1 RESEARCH PROBLEM

The empirical reality faced by the case company is increasing demands from customers for delivery of customised products. This development causes the company to enhance the offered product variance which again results in increased pressure on the engineering departments with several occurrences of delivery and quality issues in consequence. A main initiative launched by the company is to comply with this development by continually developing their engineering design processes. To develop complex engineering design processes is however not a straightforward task. The literature review reveals that engineering design processes are iterative, ill-defined and complex and therefore hard to model and develop with existing modelling approaches. Merging the areas of process and product modelling is presumed to provide additional insight into the engineering design processes and the objective is to investigate how integrating a product model into the process modelling can enable an optimisation of the engineering design processes. This empirical and theoretical starting point has led to following overall research problem:

How to assess and develop engineering design processes through integrated modelling of product and process?

This research problem will be addressed by formulating a procedure for assessment and development of engineering design processes. The procedure will contain an operational modelling technique for performing integrated modelling of products and processes as well as an approach for how to assess the existing engineering design processes and determine their performance. It will especially be investigated how increasing levels of variance affects the performance of the engineering design processes.

The objective of the research is dual. It aims at providing a theoretical contribution to process modelling theories with a specific focus on the development of complex engineering design processes. But it also aims at solving a specific empirical problem experienced by the case company.

4.2 STAKEHOLDERS

The research at hand has three main stakeholders being the scientific community, managers in engineering companies and engineers doing engineering design. The stakeholders' interests are to some extent overlapping but they do also deviate from each other in certain aspects. The three stakeholders will be described below alongside with their main interests in this project.

SCIENTIFIC COMMUNITY

The main interest seen from a scientific perspective is to add knowledge to existing literature, but also to obtain more empirical insight into the difficulties of addressing engineering design processes. Specifically, this study aims at contributing to existing process modelling theories within the context of engineering design. By addressing literature within the area of both product and process modelling a new collective perspective is added on disciplines that are usually seen as separate activities.

The contribution to the scientific community is made through six scientific papers. Three papers submitted and presented at scientific conferences and three papers submitted to scientific journals. The conferences have been quite different in terms of scope and focus. One conference had focus on how to comply with increasing demands for customised products (MCPC), one conference within operations management (EurOMA) and one conference within engineering design (ICED). These different themes each represent central areas within the research behind this thesis, and illustrate the span covered by the research. Presenting the research at the conferences supported the author in developing the ideas and adapting the procedure based on the immediate feedback from attending scholars. The journal papers are submitted to journals within engineering design as these were deemed most suitable. All papers have been or are currently being validated by professional reviewers supporting the validity of the findings produced in the study.

The publication strategy for the research has been to start with conferences in order to test and refine the research ideas and then incorporate the feedback obtained in an elaboration of the results. The elaborated and further enriched papers were then submitted to scientific journals.

ENGINEERING DESIGN COMPANIES

The other main stakeholder in this research is engineering design companies. Being an industrial PhD-project, this research has from the very beginning had a substantial focus on creating value for the practitioners involved. Early in the research process a gap in literature addressing product and process modelling was identified, but it was pivotal that the gap was addressed in a way that created value for the case company. The design of the research project with the PhD-candidate employed in the company rather than at the university has however created some significant challenges. Too much focus on a theoretical gap has not been of considerable interest for the company whereas this aspect was crucial from a scientific point of view. The parties involved therefore needed to put a lot of effort into identifying a common denominator without diluting the project. By making the contribution as operational as possible while keeping attention on how to develop existing theory, the author believe a valuable compromise and contribution for all parties have been achieved.

The stakeholder description of engineering design companies will be sub-divided into managers, designers and process modellers as their interests differ to some extent.

MANAGERS IN ENGINEERING DESIGN COMPANIES

The empirical context for this research is that the engineering departments experience increasing demands for customised products with short lead time and in high quality. This has resulted in a high pressure on the engineering departments in question with significant challenges for the managers when assigning and setting deadlines for the engineering design tasks. In order to carry out this job optimally the manager needs a clear overview of all interdependencies between engineering design tasks. Otherwise tasks might be scheduled inappropriately according to each other causing bottlenecks to occur. The main interest of the managers has therefore been to acquire a decision support tool for

setting deadlines and distributing the engineering tasks. This decision support tool therefore needs to be an output of applying the procedure to be developed.

DESIGNERS IN ENGINEERING DESIGN COMPANIES

The designers within the company are also key stakeholders for the application of the procedure, as they possess the detailed knowledge needed on both the engineering design processes and the product being engineered. It therefore requires substantial resources from this stakeholder when applying the procedure. This circumstance proved to cause difficulties in the empirical context of the project as the designers were under a lot of pressure for keeping up with deadlines while ensuring design in high quality. The benefit for the stakeholder should obviously be that their tasks, after application of the procedure, are better coordinated and scheduled, so non value adding re-work and loops in the engineering design process are avoided.

PROCESS MODELLERS IN ENGINEERING DESIGN COMPANIES

The third stakeholder in engineering design companies is the process modeller, who can be described as the main user and co-ordinator of the application of the procedure to be developed. The process modeller needs to map existing processes, gather substantial amounts of information on product and process and to conduct several interviews with designers. It is therefore important that the procedure to be developed supports the process modeller in acquiring this information, and in general the procedure should be made as structured and operational as possible. In this research project the role of the process modeller is carried out by the author.

4.3 RESEARCH QUESTIONS

The purpose of the overall research problem formulated in paragraph 4.1 is to frame this research. It sets up the context by stating that the subject area is within engineering design of customer specific products. It also states that the overall objective is to develop a procedure for assessing and developing engineering design processes. Finally it adds the mean through which the objective seeks to be realised by stating that integrating the product and the process modelling tasks is expected to provide the insight needed. The research problem is still however quite wide. So in order to make the objectives more concrete, four sub-questions have been formulated. The formulation of these research questions has been an iterative process based on both theoretical and empirical insights gained along the way.

Research question 1 (RQ1) has the focus of developing a modelling approach for how to perform integrated modelling of product and process. The second research question (RQ2) embraces RQ1 but also goes further, as it incorporates the modelling approach into a more comprehensive procedure for how to assess and develop engineering design processes. The third question (RQ3) follows the first two by addressing when to actually apply the procedure and the modelling approach developed, and how to create maximum value of applying them. Finally, the last research question (RQ4) goes one step back and put further focus on the aspect related to assessing the performance of existing engineering design processes.

RESEARCH QUESTION 1 – MODELLING PRODUCTS & PROCESSES IN AN INTEGRATED WAY

A central proposition of this research was from the very beginning that including product features in the modelling of engineering design processes would provide valuable insight and enable a better understanding of the processes in question. Different modelling approaches were therefore studied and evaluated and it became clear that no modelling approach actively support integration of product knowledge into the process modelling. The first research question is therefore:

How to operationally model products and processes in an integrated way?

It is a criterion for success to make the modelling approach as operational as possible due to the significant empirical objective of this research. Making the approach too theoretical and comprehensive would reduce the value significantly for the practitioners involved in the project. To model complex engineering products such as marine diesel engines is however an exhaustive task. It is therefore important to identify an appropriate level of detail to include in the modelling task. If too little detail is included the analyses might be worthless. But on the other hand, too much detail could also cause the process modeller to drown in detail.

RESEARCH QUESTION 2 – THE PROCEDURE

Answering RQ1 is a significant step in the process of achieving the overall objective of this research project. However, modelling the products and processes in an integrated way is only a mean for reaching the higher objective of actually assessing, developing and improving engineering design processes. The modelling approach developed is therefore to be integrated into a more comprehensive procedure.

How to systematically assess and develop engineering design processes?

In order to develop an engineering design process it is necessary to have a thorough understanding of the existing process. The procedure therefore needs to feature diagnosing and assessment of existing processes. Understanding the existing process then supports the process modeller in targeting his or her efforts when developing the process.

RESEARCH QUESTION 3 – APPLICABILITY AND EVALUATION OF PROCEDURE

After having formulated a modelling approach and a procedure for developing engineering design processes it is valuable to consider suitable fields and contexts of application and evaluate how to obtain as much value as possible when applying the procedure. The third research question is therefore as follows:

What characteristics are decisive when assessing the suitability of the procedure and how to create maximum value of applying it?

Very few, if any, modelling approaches and procedures for process development should be considered universal, and the procedure developed in this research is no exception. In order to test the applicability and evaluate how to create maximum value of applying the procedure, case studies holding different characteristics are to be conducted. The outcome of answering this research question will firstly be a list of case characteristics that should be in place before applying the procedure and secondly recommendations for how to conduct the analysis.

RESEARCH QUESTION 4 – ASSESSING THE PERFORMANCE OF ENGINEERING DESIGN PROCESSES

In order to develop engineering design processes it is crucial to actual understand and diagnose the existing processes. Research question 4 is related to this aspect and thereby takes on step back as it aims to asses the performance of engineering design processes. The stakeholders involved had from the very beginning a desire to acquire a better understanding of this performance. And more specifically it was an objective to obtain insight into how increasing product portfolio variance affects the engineering performance. The fourth and final research question for the study at hand is therefore:

How do increases in product variance affect engineering performance in terms of cost, lead time, on time delivery and quality?

The research related to this research question stands somewhat out compared to the other research questions. Whereas the first three research questions will be investigated in a qualitative manner, research question 4 is to be addressed in a more quantitative manner. However, answering research question 4 will provide valuable insight into how to assess existing engineering design processes, which is a clear objective from the overall research problem formulated in paragraph 4.1.

4.4 RESEARCH METHODOLOGY

In order to ensure consistency in the research carried out it is highly relevant to define the scientific assumptions as it guides the choice of research methods. The nature of the subject and the paradigm the researcher relates to are critical parameters for any research study. The way in which the research approaches science determines how the data should be obtained, and just as important, how the data should be understood.

PHILOSOPHY OF SCIENCE

The functional properties of a diesel engine are well known, as it builds on principles more than a hundred years old. You could therefore argue that it is possible to describe the world of designing such diesel engines objectively and therefore apply a positivistic approach to this research. However it is quite clear that the process of designing specific parts for such engines differs significantly across the individual designers. Furthermore, when the author as a researcher attempt to document how the individual designers work the author is likely to perform some interpretation of the situation. It is therefore fair to assume that reality is not independent of the individual, which is a basic assumption of the constructivist paradigm (Croom, 2009). But to claim that all knowledge is relative would be

inaccurate. The chosen scientific approach of this research project is therefore considered to be critical realism.

CRITICAL REALISM

Critical realism claims that there are independent realities that can be understood, as opposed to social constructivism, which claims that all knowledge is relative (Danermark et al., 2002). But critical realism also emphasises that the described reality is imperfect. This is opposed to the positivist point of view, which maintains that reality is limited and can be described by objective facts. It therefore breaks away from both the constructivist perception that “all knowledge is relative” as well as the positivistic perception that “all knowledge is limited to what can be quantified” (Jespersen, 2005). In critical realism, the social variables are a precondition, and it is assumed that it is impossible to quantify these completely. To specifically quantify a certain phenomenon demands total control of all physical and social variables, as in a closed laboratory, which is impossible when dealing with large complex organisations such as MAN Diesel & Turbo in practice. When developing a procedure for assessment and development of engineering design processes, the outcome will beyond doubt be affected by the designers involved in the process as well as by the author self.

Critical realism first of all makes the ontological assumption that there is a reality but that it is usually difficult to apprehend. It distinguishes between the real world, the actual events that are created by the real world and the empirical events which we can actually capture and record (Easton, 2010). Or in other words, reality has an objective existence but we do not have full access to reality (Danermark, 2002). From a critical realist perspective, the goal of science is then to try to transform scientific theories of the independent reality into deeper knowledge of reality.

When conducting research and ascribing to critical realism the findings are most often attempted validated by testing the results in different settings, which is termed ‘retroduction’ (Easton, 2010). This is in this study addressed by research question 3 where the applicability and evaluation of the suggested procedure is to be tested in different cases.

When taking the standpoints from critical realism in conducting research it is not uncommon to apply several research methodologies to enhance the reliability of the findings (Walters & Young, 2005). By mixing methods and continuously testing the objectives of the research the author can increase the probability of giving valid recommendations. This study applies the methodologies action research and case studies in a combined manner to achieve this.

EXPLORATORY RESEARCH

No structured procedure for developing engineering design processes through integrated modelling of product and process has been identified, which characterises the research at hand as exploratory research, with focus on theory development rather than theory testing. Exploratory research is conducted into a research problem or issue when there are very few or no earlier studies to which we can refer for information about the issue or problem. The approach is usually very open and concentrates on gathering a wide range of data and impressions. As such exploratory research rarely

provides conclusive answers to problems and issues, but gives guidance on what future research, if any, should be conducted. A central aim is therefore to assess which existing theories and concepts can be applied to the problem or whether new ones should be developed (Collis & Hussey, 2003). In this research this becomes evident as several modelling approaches are studied, tested and evaluated. Fragments from different theories are selected, adapted and merged into a new approach. The theory development study occurs through an iterative research process, where the findings are continually evaluated and the process of acquiring further results is adapted with the inclusion of the obtained experience (Karlsson, 2009).

ACTION RESEARCH

The aim of this research is to go deep into the engineering design processes within the Marine Low Speed business unit of MAN Diesel & Turbo, attempt to bring about change concerning how the work is organised and to monitor the results. Such a focus on change and with the researcher deeply involved in the process acting as a change agent makes action research the proper choice of methodology. A basic idea of action research is to experiment in the field rather than in a laboratory, which makes it well suited to work with practitioners and managers in large organisations. Action research is at one and the same time the investigation of action, implementation of investigation through action and the transformation of research into action, and is frequently used in intra-organisational problems (Kagan et al., 2008).

(Coughlan & Coughlan, 2002) list three pre-requisites for doing action research:

1. The project needs to be a real issue, which means it must be of both research and managerial significance.
2. The action researcher has to gain access to the organisation in which the project is founded.
3. There needs to be a contract ensuring the involvement of key members of the organisation who recognise the value of the action research approach and are willing to have the action researcher working with them in relation to real-life problems, joint-meaning construction and workable solutions.

Only by ensuring these pre-requisites can a successful action research study be conducted.

Action research is carried out in a cyclical manner comprised of a pre-step and four basic steps, see Figure 8 (Coughlan & Brannick, 2005).

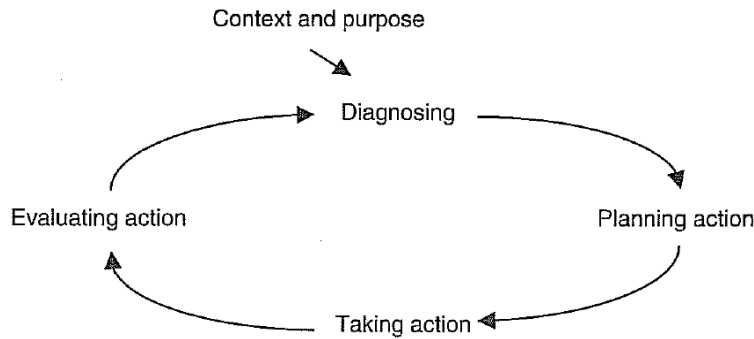


FIGURE 8: THE ACTION RESEARCH CYCLE

The action research cycle starts with an understanding of the context of the project. Then collaborative venture of diagnosing occurs with naming the issue that are to be addressed. After the diagnosing comes the planning of action. Here it is decided what needs to be changed, how commitment is built and how resistance is managed. Then action is taken by making the desired changes in collaboration with key members of the organisation. Finally the action is evaluated and reflections on the outcomes of actions are made before the next cycle of planning and action is initiated. Ascribing to such a cyclical approach is very suitable when developing new theory while contributing to managerial practice as it allows for refinement of the approach based on the accumulated experience from earlier loops.

SINGLE CASE RESEARCH

As the research study is conducted as an industrial PhD-project with the author employed in the case company, it sets some limitations on the source of data. All papers and analyses are conducted using the Marine Low Speed business unit within MAN Diesel & Turbo as empirical case, making the study a single case study. Several cases are investigated within Marine Low Speed, but the company context is the same for all cases. As the research is carried out as a single case study, it can affect the validity, reliability and generalising potential of the outcome of the study. Context-dependent knowledge gives this type of science a basic limitation when generalising the conclusions made on the basis of a single experiment (Smith, 2006). However (Gummesson, 1991) contends it is possible to generalise from a very few cases, or even a single case, if the analysis has captured the characteristics of the phenomena being studied.

4.5 DATA COLLECTION

In reaching the objectives of the research study at hand both qualitative and quantitative data is gathered and analysed. The first three research questions are answered through mainly qualitative data whereas the fourth question related to engineering performance is addressed by usage of quantitative data.

QUALITATIVE DATA

Answering research question 1 through 3 requires substantial insights into how several designers work and how they organise different design task. Acquiring this insight calls for a comprehensive collection of qualitative data to be obtained through mainly interviews and workshops.

INTERVIEWS

Interviews really comprised the cornerstone of the data collection in this research study, as interviews are very well suited for gathering complex knowledge from experts. The main source of data is unstructured and semi-structured interviews with the designers who provide insight into both processes and products. It is a deliberate choice not to use structured interviews as it is desirable to allow the interviews to develop by itself. A central objective is to document the complex tacit knowledge used when performing certain engineering design tasks. Due to the nature of this knowledge it is difficult to stick to a prefabricated interview-sheet, also because the researcher might not understand how the individual designer approaches his or her tasks in advance. Making use of controlled interviews might therefore not provide the same insight, as it is crucial that the interviews with the designers are allowed to extend beyond the initial knowledge of the researcher, which is a characteristic of semi-structured interviews (Ulin et al., 2005).

Using interviews in single case studies is well suited as it allows the researcher to perform in-depth investigations as well as follow-up discussions in order to ensure that the information captured is as valid as possible.

WORKSHOPS

Smaller workshops are also to be conducted in the process of acquiring the qualitative data needed for answering research question 1, 2 and 3. A critical aim in the study is to identify and address interdependencies between different designers' tasks. Getting these people in the same room enhances the possibilities of identifying these and facilitates a collective learning process across the organisation. It will thereby also serve as a validation of the information acquired through the individual interviews.

QUANTITATIVE DATA

Quantitative data is needed for answering research question 4 focusing on engineering design performance. Massive amounts of data from the company's PLM and ERP-systems as well as internal company databases are therefore extracted and analysed. The objective is to acquire insight into the performance of the engineering design processes primarily related to cost, lead time, on time delivery and quality.

4.6 LIMITATIONS AND CONSTRAINTS OF RESEARCH

As stated earlier, the project is carried out as a single case study. This can affect the reliability, validity and generalising potential of the study and the limitations and constraints of the research therefore need to be addressed. Context-dependent knowledge, where social factors are significant, gives this type of science a basic limitation when generalising the conclusions made on the basis of a single experiment (Smith, 2006). However, according to (Gummesson, 1991) it is possible to generalise from a very few cases, or even a single case, if the analysis has captured the interactions and characteristics of the phenomena being studied. The use of a single case study will often put the researcher in a position

of trust with the subjects of the study. This is likely to lead to a development of relationship with the subjects, which is assumed to benefit the collection of data by increasing the volume or specifics.

This paragraph will introduce the concepts of reliability, validity and generalising potential as well as criteria for how to evaluate action research. The evaluation of these related to the research project will be described and discussed in further detail in Chapter 6.

RELIABILITY & VALIDITY

Reliability is concerned with the findings of the research and whether anyone would get the same results as you if they were to repeat the research (Collis & Hussey, 2003). This is quite unlikely in the research at hand due to acknowledgement of the influence of social factors both from the subjects being studied and also the researcher self. However, the requirements for reliability are usually interpreted somewhat differently when talking about qualitative research. Qualitative research traditionally focuses more on validity, which concerns the extent to which the research findings accurately represent what is really happening in the situation (Collis & Hussey, 2003). And this tendency often gets even stronger when considering single case studies (Voss et al., 2002).

GENERALISING POTENTIAL

When constructing a model or a new procedure based on a single case study it is relevant to consider and evaluate the applicability of the findings in a broader context. Would it be valuable to apply the same procedure in another context and would one obtain the same outcome? A clear limitation of this research is that the findings are based on data from one company only. One therefore needs to be cautious when concluding whether the findings can be generalised. If similar tendencies can be found in other companies, the external validity of the findings will be improved considerably and the generalising potential will be higher. Further discussion on the matter of generalising potential as well as validity and reliability can be found in Chapter 6.

EVALUATING ACTION RESEARCH

When assessing the quality of an action research study (Levin, 2003) argues that the contribution to scientific discourse is not a matter of sticking to the rigour-relevance polarity but of focusing on vital arguments relating to participation, real-life problems, joint-meaning construction and workable situations. These aspects will all be addressed throughout this study. Joint-meaning construction and participation will be attempted included through frequent interviews, workshops and feedback information. To continually improve the engineering design processes with the objectives of lowering the resource consumption and lead time while improving the quality of the work carried out is indubitably a real-life problem. The challenge of the study is then to provide workable solutions that create value for the company while contributing to the existing body of theory.

Finally, when presenting the limitations of the research conducted it is once again stressed, that the primary scope of the research is to develop a procedure for assessing and developing engineering design

processes. It is not within the scope to conduct a detailed cost/benefit analysis of applying the procedure. This issue is discussed in further details in Chapters 6 and 8.

4.7 EXPECTED OUTCOME

When having ascribed to action research it is critical to consider how to fulfil the dual objective of producing results of both managerial and theoretical significance. To the knowledge of the author no current methods for redesigning and developing engineering design processes do take into account the product features to be used in every process step. It is therefore anticipated that this research could provide a contribution to process development theories. Generating theory through action research is situation specific and incremental (Coughlan & Coughlan, 2002). This is also the case with the research at hand. However, the belief is that a significant step from particular to general can be taken with this research, as the case company represents a typical engineering company. The managerial contribution will focus on providing a structured approach for process modellers and managers to analyse and organise engineering design activities in a more optimal way and thereby increase the efficiency, reduce lead time, improve ability to deliver on-time and improve the quality of the engineering work carried out.

4.8 SUMMARY

The overall research problem of the study at hand is to investigate how to assess and develop engineering design processes through integrated modelling of product and process. This chapter basically describes how the author intends to do this. Firstly the overall problem is introduced alongside with the main objectives of the study. The project is deeply rooted within the case company which makes the research objective dual. Value needs to be created both on theoretical and empirical level in order to make the project a success. The main stakeholders and their different interests in the project are therefore introduced and discussed. Afterwards, the overall research problem is decomposed into four sub-questions designated RQ1, RQ2, RQ3 and RQ4. The first two research questions put main emphasis on formulating a procedure for assessing and developing engineering design processes through integrated modelling of product and process. The third research question assesses the application of this procedure and aims at investigating how to create maximum value of applying the procedure. The fourth and final research questions focus on examining the impact of increases in product variance on engineering design performance.

Paragraph 4.4 introduces the research methodology of the study. The scientific approach is described as critical realism which claims that reality has an objective existence, but we as researchers do not have full access to it. The methodologies applied are action research and single case study which combined are considered appropriate for realising the objectives of the research study. Action research has focus on addressing real-life problems while contributing to theory which is consistent with the overall objective of creating both theoretical and empirical value with the research. The sources of data are then described briefly followed by a discussion of the scientific limitations and constraints of the research. The significance of obtaining high validity is emphasised as being particularly important due to the qualitative nature of the research study. Finally, the expected outcome of the study is described

briefly, once again underlining the dual objective of creating value on theoretical as well as on empirical level.

CHAPTER 5 – ANALYTICAL PROCEDURE

Chapter 5 is a condensed description of the results produced throughout the research project. Three journal papers and three conference papers were written, and they each comprise central building blocks in achieving the overall objectives of the research project. Four papers focused on the formulation of a procedure for assessing and developing engineering design processes through integrated modelling of product and process. The remaining two papers centred on assessing the performance engineering design processes. This chapter presents the main results and contributions of the papers.

5.1 DEVELOPING ENGINEERING DESIGN PROCESSES THROUGH INTEGRATED MODELLING OF PRODUCT AND PROCESS

An overall ambition of the project is to develop an operational procedure for assessing and developing engineering design processes. This ambition has resulted in the formulation of a 5-phased procedure designated IPPM, Integrated Product and Process Modelling.

Engineering design processes are often ill-defined, iterative and complex, and can therefore be difficult to model and develop. A basic proposition in the research at hand is that understanding an engineering design process fully requires understanding of the product being engineered. By integrating a model of the product features used in the engineering design process and clarify in which steps of the process the features are used, additional understanding of what actually takes place within the engineering design process will be acquired.

The IPPM-procedure facilitates assessing, modelling and developing engineering design processes in a structured and systematic way. The procedure supports mapping and diagnosing of an existing process and it creates insight into the complex activities within a process that are usually unanalysed when applying most known process modelling approaches. By utilising the insight gained through the IPPM-procedure, processes can be specifically configured to suit the product being engineered. This allows better planning and scheduling of the engineering activities in a more optimal way and thereby increases the efficiency, reduces lead time, improves ability to deliver on-time and improves the quality of the engineering work carried out.

The first article P1 describes the very initial attempts of formulating a modelling approach for performing integrated modelling of product and process. P2 and P3 are highly interrelated and they contain a refined elaboration of the concepts introduced in P1 alongside a more comprehensive procedure for assessing and developing engineering design processes. P4 presents an accumulation of the experiences gained throughout the application of the IPPM-procedure and introduces a list of characteristics identified as having significant impact on the applicability of IPPM. The paper also evaluates how to maximize the value of applying the procedure and serves as a natural compilation of the insight gained throughout the case studies conducted.

All results based on papers 1 through 4 are related to the research questions RQ1, RQ2 and RQ3. Focus is on developing and evaluating the modelling technique as well as the procedure for assessing and developing engineering design processes.

P1 – THE MODELLING TECHNIQUE

Title: Developing Engineering Processes through Integrated Modelling of Product and Process.

This paper was written throughout the initial phases of the PhD, and it describes the first attempt of performing integrated modelling of product and process. It presents an early and limited version of the overall procedure for developing engineering design processes. The basic idea was to construct a model

of the product being engineered and to integrate this with a model of the engineering design process, and finally utilise the insight gained to develop the processes in question.

The empirical case was based on the introduction of new emission technology at the Marine Low Speed business unit. The company had developed the emission technology on prototype level, but it had not yet been adapted to comply with the entire product range. To organise the work around designing this solution in full scale across the entire engine program was a considerable challenge. The company therefore faced the task of developing a complete set of engineering design processes for specifying their products including the new emission technology.

The scope for the paper was therefore to develop and apply the modelling technique with the aim of developing a new set of engineering design processes. As this paper represents the first attempt of performing integrated modelling of product and process, the main focus is on developing and operationalising the modelling technique, and it thereby primarily relates to research question 1.

MODELLING APPROACH

The overall approach was first to model the product in question applying the well-established Product Variant Master modelling technique. Next step was then to interview designers involved in the specification of the product and to describe their tasks related to this specification. Finally, the ambition was to link the product features identified in the PVM to the individual tasks thereby obtaining an understanding of how the product and more importantly how the different tasks were interconnected.

The starting point and a central aspect to be researched was therefore how to operationally model the emission product and the engineering design processes. It quickly became evident that complexity was a central issue to deal with when modelling the product. The emission system alone without the interfacing components consisted of more than 500 drawings and specifications. To model and assess the potential process implications of each of these parts would be very time consuming and probably only add limited value. It was therefore crucial to identify the relevant product features that were decisive for the engineering design process.

The individual designers did however have difficulties in assessing which features were decisive, as their main focus was on their specific tasks and not on the interdependencies between tasks. The size and complexity of the product model therefore kept increasing, and it was difficult to assess when the appropriate level of detail was included in the product model. The outcome of this process was a Product Variant Master describing the emission system.

The next step was to identify and analyse the central engineering activities through which specification of the product should take place. Focus was put on the complex engineering activities where the crucial product features determined in the PVM were specified. By clarifying which product features and specifications are used as well as produced, the content of the different tasks became more transparent. The identification and characterisation of the engineering design activities were carried out through interviews with the relevant product experts. It did however quickly become clear that it was necessary

to come up with a formalised template for conducting these interviews, so it could represent the knowledge in a suitable manner. The Task Clarification Card, also called TCC, was therefore developed, see Figure 9.

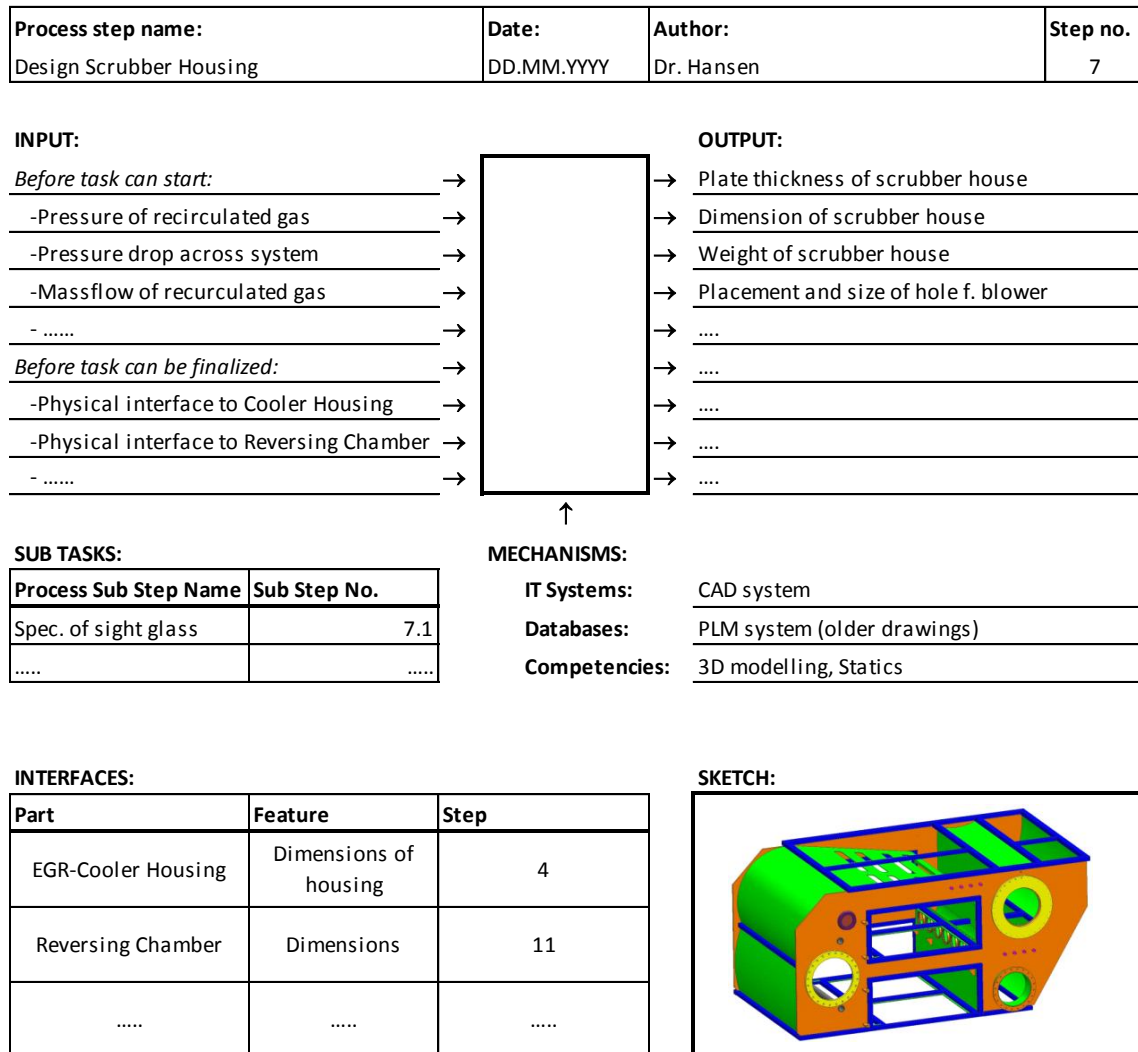


FIGURE 9: THE TASK CLARIFICATION CARD

As the name suggests the purpose of the Task Clarification Card is to clarify what engineering activities actually take place within the individual task. The cards are basically used for identifying what product features are used (Input) and produced (Output) in every significant engineering design task. They also support a characterisation of the activities carried out during the specification process allowing for a deeper understanding of what competencies and tools are needed, as well as which sub activities comprise the overall design task. The introduction of the Task Clarification Card is inspired by the usage of so-called CRC-cards that are used within the area of product modelling, where each major product component is described in a predefined template (Hvam et al., 2003; Haug et al., 2010). A more thorough exposition of the Task Clarification Cards can be found in P1. Introducing the TCCs should not be seen as an attempt to make strict controlled interviews. It was still the intention to make the interviews very

open and allow them to develop. The cards should rather be seen as a mean for storing and structuring the minimum amount of information needed in order to carry out the analysis.

After having produced Task Clarification Cards for all engineering design tasks to be present in the specification process, the idea was now to link the insight gained from modelling the product, captured in the PVM, with the engineering design processes represented in the TCCs. An elaboration of the PVM-representation was needed in order to enable the linkages between the product and the process. The outcome was the introduction of the PVM in a revised form, called the Cross Referenced PVM, which is able to express task interdependencies caused by product features used in several process steps. Figure 10 contains a subset of the Cross Referenced PVM developed in the specific case.

	EGR-system	Used in Step:	
		Input	Output
	Performance Specification		
	Performance requirements for overall system		
	• Massflow of recirculated gas	5,6,7	2
	• Pressure of recirculated gas	3,5,7	2
	• Pressure drop across system	4,6,7	2, 5
	• Temperature of recirculated gas		2
	•		
	EGR-Cooler		
	For cooling of the EGR-gas		
	• Dimensions of housing	7	4
	•		
	Pre Scrubber		
	For removal of SO ₂ in the exhaust gas		
	•		
	Scrubber Housing		
	Contains the Scrubber Unit		
	• Plate thickness of scrubber house		7
	• Dimensions of scrubber house		7
	• Weight of scrubber house		7
	•		
	•		
	Water Treatment System		
	For cleaning the scrubber water in the system.		
	•		

FIGURE 10: THE CROSS REFERENCED PVM

Every time a product feature appeared as an input or output in the Task Clarification Cards, it was noted in the Cross Referenced PVM next to the product features in designated input and output-columns. In

other words it is used for compiling the information of every product feature throughout the complete specification process. These cross references identified between the PVM and process steps provide valuable information on how to organise and sequence the engineering design tasks.

However, it became evident that it was very difficult to handle the high number of interdependencies between product features in the input and output columns of the Cross Referenced PVM. A conclusion was therefore that some additional supporting tool was needed for this task.

CONTRIBUTION

The main theoretical contribution of P1 is a first attempt of formulating an operational modelling technique for performing integrated modelling of product and process as addressed by RQ1. Known modelling techniques were taken into use, others were modified and several were merged into a new approach. More specifically the theoretical contributions are considered to be the Task Clarification Cards and the Cross Referenced PVM. These supported the task of getting a deeper understanding of what activities took place within the engineering design process and how the design tasks were interconnected through specific product features.

The empirical contribution was supporting the actors to be involved in this future specification process for the emission technology. The product itself was at an early development phase so no formal engineering design processes for creating customer specific variants of the product with the new emission technology was established. The research behind this paper supported the initial development of these processes.

EXPERIENCE GAINED

This first attempt of developing an operational modelling tool for doing integrated modelling of product and process provided some valuable experience for future case studies. It was realised that when both the process and the product are very complex and the amount of cross references are substantial, it is necessary to come up with a computational tool that can aid in revealing potential adverse dependencies.

It also became evident that it is challenging to find the right level of detail to include in the analysis. If too little detail is included, critical process dependencies caused by certain product features might be missed. However, if too much detail is included, the modelling task will explode and carrying out the analysis would require disproportionate large resources reducing the value of the analysis. Complexity is thus a critical issue that needs to be dealt with when performing integrated modelling of product and process. This especially becomes evident when considering complex products such as marine diesel engines. It is therefore crucial to focus on the product features that are decisive for the engineering design process. These have to be identified through interviews with the product experts who possess a thorough understanding of the complexity of the product.

The characteristics of the case furthermore gave some insight into where applying the developed modelling technique with the aim of developing engineering design processes is appropriate. The case for the paper was characterised by a product being in its very early development stage and an engineering design process that was not operationally defined. These case characteristics led to several challenges. Creating a model of a product that is not fixed is problematic, as the modelling task needs to be extended for as long as the product is being developed. The solution space was simply too open. The insights acquired on this matter is elaborated in P4, which summarises the experiences gained through three case studies of developing engineering design processes.

P2 & P3 – DEVELOPING THE PROCEDURE

P2 Title: Including Product Features in the Development of Engineering Design Processes

P3 Title: Assessing and Developing Engineering Design Processes

The following paragraph describes two papers in one setting as they were written in direct continuation of each other, one being a conference paper and the other an elaborated journal paper. The focus is on improving the integrated product and process modelling technique, but also on formulating a more holistic procedure for assessing and developing engineering design processes, designated IPPM – Integrated Modelling of Product and Process. The papers thereby address both research question 1 and 2.

The analysis is also based on empirical data collected in collaboration with the Marine Low Speed business unit. The unit of analysis is a subset of the order process within the company. Based on an order from a customer it is analysed how a specific engineering department designs a solution fulfilling the specific customer request. The department in question was experiencing increasing lead times and efficiency problems due to lack of overview over dependencies between engineering design tasks. Too often bottlenecks were identified which were caused by dependencies not taken into account when internal deadlines were set for the different engineering design tasks. The empirical objective for the study was to map these interdependencies so they could be taken into account when setting deadlines for the engineering design tasks.

THE IPPM-PROCEDURE

Whereas P1 focused mainly on the modelling technique, P2 and P3 have a wider scope. The objective is to formulate a complete procedure for how to assess and develop engineering design processes. The outcome is following 5-phased procedure called IPPM, see Figure 11.

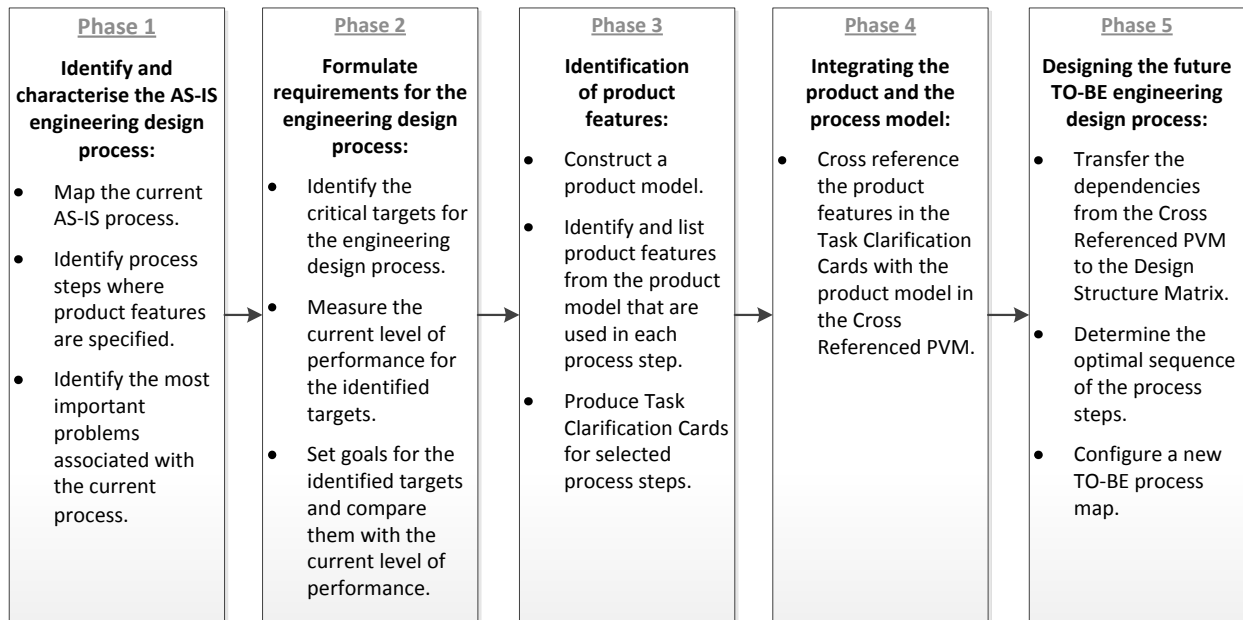


FIGURE 11: THE IPPM-PROCEDURE

PHASE 1 – IDENTIFY & CHARACTERISE AS-IS PROCESS

In order to develop engineering design processes, it is necessary to acquire an understanding of the existing process. The first step is therefore to map out the AS-IS process and identify the process steps where product information is being processed and product features and specifications are produced. This can be done using numerous process mapping tools. In the papers the Business Process Modelling Notation was chosen as it is deemed suitable for the task at hand. At this stage we are interested in getting an overview of the existing process applying a widespread, easy-to-use and intuitive mapping tool. The tool does not need to provide an in-depth understanding of the process yet. The purpose of phase 1 is mainly to get an overview of the process. The detailed insight into the individual process steps will be acquired in phase 3. Process steps that are identified as tasks where product features are specified are highlighted as they are of particular interest.

After having mapped the existing process it can be evaluated by identifying the most critical problems associated with the process. This will provide insight into which problems need to be addressed in the development of a new and improved process. Examples of problems could be too many bottlenecks, too many transfers of responsibility, too many loops, etc.

PHASE 2 – REQUIREMENTS FOR NEW PROCESS

After having identified and characterised the existing engineering design process, the next step is to make clear what requirements are to be placed on the process. A starting point for the requirements is the company's current strategy plan and their commercial targets, such as profitability, product strategy, delivery time, etc. Based on this it is identified which targets are critical if the company is to meet its overall targets. Typical measures for a company's specification process could be lead time for producing specifications, on time delivery for specifications, resource consumption for producing specifications and quality of specifications. This should not be seen as a complete list. Other measures

might be more relevant, and it has to be assessed when analysing the current AS-IS process, which measures are most important to address.

When targets are identified, the next step is to carry out a series of measurements to determine the current level of performance for the selected targets. Finally, future quantitative goals are set for the identified targets. Then the current level of performance and the target goals can be compared and the largest gaps can be identified. This will indicate where the greatest potential for improving the engineering design process will be.

PHASE 3 – IDENTIFY PRODUCT FEATURES

Phases 3 to 5 are closely interconnected as these are the phases in which the actual integrated modelling of product and process takes place. Figure 12 illustrates how the phases are interrelated and the figure will be used as reference for the rest of this paragraph.

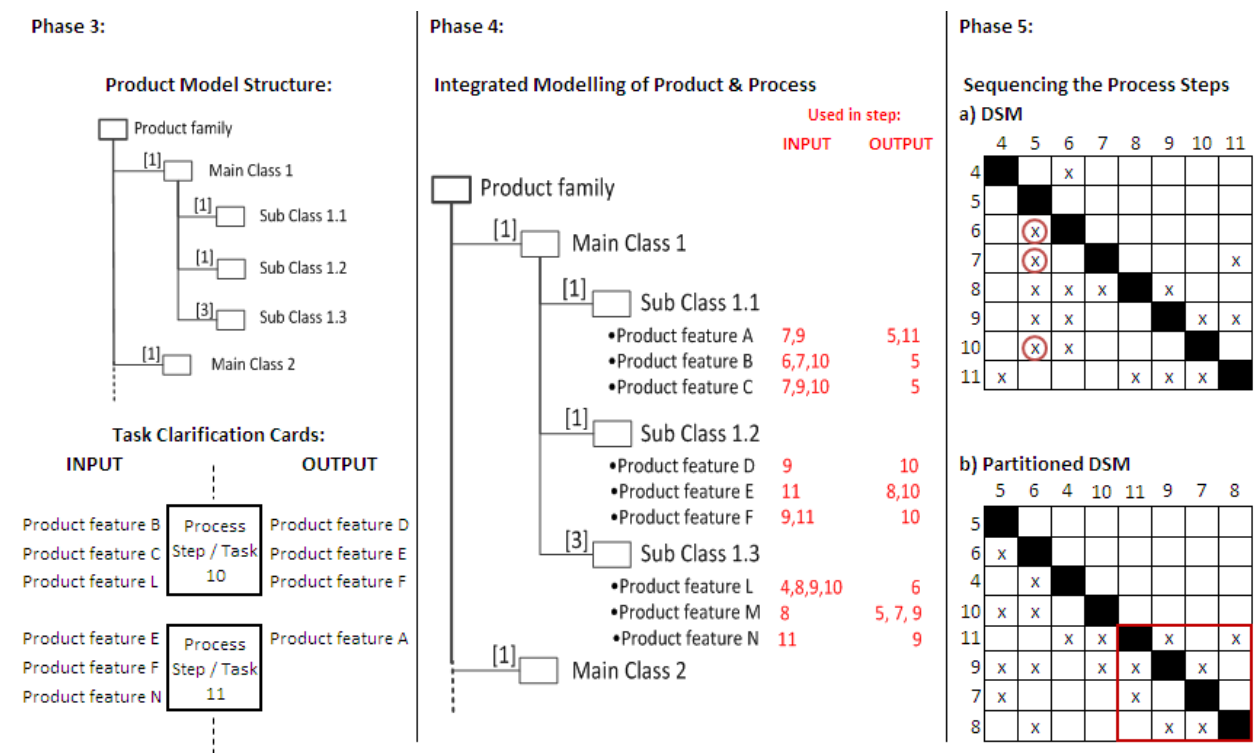


FIGURE 12: PHASE 3, 4 AND 5 OF IPPM

As stated earlier the basic proposition of this study is that understanding the product being engineered will provide additional understanding and insight into what actually takes place within the engineering design process. In phase 3 the first objective is therefore to construct a product model. As in P1 the author applied the Product Variant Master as product modelling tool. The main reason for choosing this tool is that it is straightforward to understand and to put in to use, while describing the product family in an efficient manner to all relevant stakeholders. The main focus of the product model at this point is to document the structure of the product, see upper left side of Figure 12. Normally, when applying the

Product Variant Master technique it is also part of the task to identify all features and constraints of the product. However, this is neither necessary nor practical when modelling complicated products for the purpose of integrating the model with an engineering design process. Complicated products can consist of hundreds even thousands of product features. To assess the potential process implications of every product feature can therefore be very complex, time consuming and only add limited value. P1 confirmed this matter. It is therefore vital to identify the relevant product features that are decisive for the engineering design process and not waste time on less significant product features.

As realised in the study behind P1, identifying the right level of product detail to include in the PVM is one of the most critical issues that must be addressed when applying the IPPM-procedure. Too much information will only lead to a time consuming process where the goal of IPPM can potentially be lost in the amount of product detail. However, not enough detail can almost defeat the purpose of the IPPM-procedure as critical product relations may be missed. Identifying the relevant product features is mainly done through interviews with product experts, as they are the most likely to be able to identify which product features are critical to the process. In order to support these interviews and document the knowledge provided by the designers the Task Clarification Card introduced in P1 was applied.

One addition was made to the TCCs based on the experience gained in P1. As part of the input declaration the source of the input should now also be stated. The reasons for this will be elaborated below. The basic idea is to conduct interviews with the employees who perform tasks identified as having process implications in the AS-IS diagram from phase 1, using the TCCs as interview templates. For each interview the scope is to fill in all the information except the output column. In stead, after having conducted all interviews, the output columns are filled out tracing back the stated inputs using the source information. This way only product features having an impact on the engineering design process are included, ensuring a suitable level of detail. This is done as earlier studies, P1, resulted in an information overload in the output columns of the Task Clarification Cards. Back then the designers stated every nut and bolt which they specified as outputs. However, these had no significance for the engineering design process and only added unnecessary complexity to the modelling task. The explicit declaration of the source of the product features is crucial for getting an overview of the interdependencies between the tasks.

Revealing interdependencies is however not the only benefit of the TCCs. The engineering design process for complicated products is very complex and there is a need to share information as well as to communicate it among the parties involved in the process. The Task Clarification Cards confirm such information and the cards thereby serve as a knowledge management tool, supporting knowledge sharing and preservation. The TCCs can furthermore be considered as design manuals for how to perform tasks, serving as a check list which can be used by the design engineers when carrying out the individual tasks. This is especially valuable when aiding new designers to assimilate and digest design, as new designers often face significant challenges in fully comprehending complex design activities.

PHASE 4 – INTEGRATING THE PRODUCT AND THE PROCESS MODEL

In phase 4 the integration of the product features and the process steps takes place. The scope is to clarify where all product features are defined or modified. This is done by cross referencing the product features on the Task Clarification Cards with the product model from phase 3 applying the Cross Referenced PVM introduced in P1. This is illustrated earlier in Figure 10.

The cross references between the product model and the process steps provide valuable information on how to organise the sequence of the engineering design tasks. The IPPM-procedure also identifies the process steps that do not convey any new information i.e. do not produce specifications. These process steps indicate that they might be non-value adding and therefore they should possibly be eliminated to improve the process flow.

PHASE 5 – DESIGNING THE TO-BE PROCESS

The 5th and final phase is about designing the new improved engineering design process based on the insight acquired through the previous phases. The Cross Referenced PVM-tool introduced in phase 4 clearly displays the dependency relationships of the process steps. Nevertheless, engineering design processes are often complex, with numerous process steps. Thus, the interdependencies in such processes are often complex and intertwined, making the job of reorganising the process steps in an optimal order too difficult to do without some kind of algorithm. The author chose the Design Structure Matrix as a tool for dealing with this complexity. The DSM-modelling approach is a well-established tool suitable for handling interdependencies between elements, for instance between engineering design tasks. By using a simple algorithm, the DSM supports re-organising of elements based on their relationship dependencies, which is also called partitioning of the DSM. The Design Structure Matrix is evaluated to be an ideal modelling tool to utilise in conjunction with the Cross Referenced PVM-tool

The information from the Cross Referenced PVM is therefore transferred to the DSM with the output column in the Cross Referenced PVM controlling the columns in the DSM while the input column controls the rows. After the DSM is filled it is partitioned. The partitioning reveals the optimal sequence for the process steps based on minimising feedback loops in the process. Using the information displayed in a partitioned DSM, a new TO-BE process map can be configured for the engineering design process.

In the Marine Low Speed case this resulted in a large 104 x 104 master matrix containing all engineering tasks producing specifications and their mutual interdependencies. However, when partitioned the matrix revealed a substantial amount of interdependent coupled tasks. If only information on the dependencies between the different design tasks was available, this would be the final result. One would then have to deal with the coupled tasks in an iterative manner and try to set suitable deadlines for these. But the detailed information acquired in the Task Clarification Cards can be of further use. The cards obviously contain information on how tasks are related but also information on which specifications and product features that actually create the interdependencies between the engineering tasks.

By transferring the cluster of coupled tasks from the DSM and exploding these tasks into specifications stated in the TCCs, it becomes possible to make a new DSM containing specification dependencies rather than task dependencies. By partitioning the specification DSM in the case at hand, it was revealed that a few critical specifications really caused the major clustering of the engineering tasks. An exemplification of the procedure is illustrated in Figure 13.

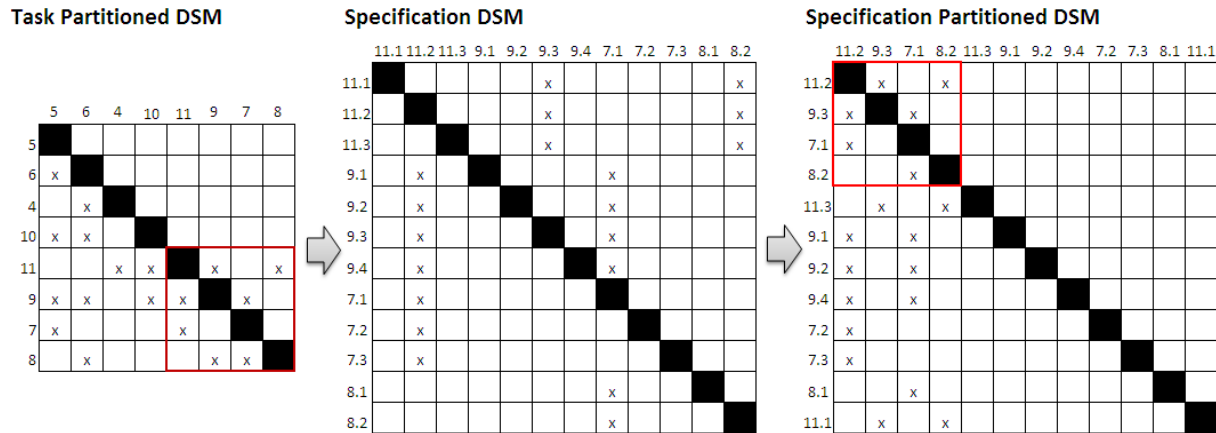


FIGURE 13: FROM TASK DSM TO SPECIFICATION DSM

The example above shows that four tasks (7, 8, 9 and 11) are coupled. However, when addressing the specifications of these four tasks in a separate DSM it becomes clear, that it is only one specification from each task that creates the interdependencies (7.1, 8.2, 9.3 and 11.2). Therefore the designers responsible for these tasks should, if possible, determine these key specifications as early as possible, as this will induce a less coupled workflow.

In summary, the five phases reveal a detailed understanding of the single activities in a process, which then can be utilised to reorganise the sequence of process steps in an engineering design process. By applying the insight gained by the IPPM, an engineering process can be redesigned leading to an improved overall process flow.

CONTRIBUTION

The theoretical contribution of P2 and P3 is partly an elaboration of the contribution from P1. An attempt to formulate an operational modelling tool for performing integrated modelling of product and process. The papers thereby address research question 1. But the contribution is also a more holistic 5-phased procedure for how to assess and develop engineering design processes in a structured and systematic way as addressed by RQ2. The procedure supports mapping and diagnosing of an existing process and it creates insight into the complex activities within a process that are usually unanalysed in most known process modelling approaches. By utilising the insight gained through the IPPM-procedure, processes can be specifically configured to suit the product being engineered, thereby creating an optimal process flow for that specific product.

The empirical objective in the specific case was to create a master DSM containing information on all engineering design tasks and their mutual product feature dependencies. For every incoming order the

group leaders should then subtract the subset of tasks relevant for the specific order from the master DSM. The reduced DSM should then be partitioned and if needed an additional specification based DSM should be made and partitioned. This will provide the group leader with a valuable decision support tool for setting deadlines and distributing the engineering design tasks.

EXPERIENCE GAINED

In order to deal with the large amount of interdependencies between tasks and product features the author introduced the Design Structure Matrix as part of the overall procedure for assessing and developing engineering design processes. Furthermore, experience from P1 showed that identifying the right level of detail to include is crucial. Too much will make the analysis overwhelming while too little will make it worthless. By adding the source information for input product features in the Task Clarification Cards only process-decisive information was included in the analysis, increasing the value of the output.

The case for P2 and P3 was a subset of the order process for how a design department engineered solutions fulfilling specific customer requests. It was focusing on creating variants of existing products with only minor modifications. The product being engineered was therefore rather fixed and the engineering design processes were very well-established. These characteristics proved to be very suitable for applying the IPPM-procedure.

P4 – APPLICABILITY AND EVALUATION OF PROCEDURE

P4 Title: Applicability and Evaluation of IPPM – Integrated Product and Process Modelling

This paragraph describes the fourth and final paper related to the development of the IPPM-procedure. In the period 2011-2012 the procedure was applied three times by the author on rather different engineering design cases. The cases differed significantly in terms of for instance number of actors involved in the engineering design process, the maturity level of the product being engineered and the level of detail included in the analysis. The results from these three case studies provided valuable insight into the applicability of IPPM, and enabled the author to list what characteristics that should be in place in order to get maximum value from applying IPPM. This paper therefore addressed the content of research question 3.

IDENTIFYING AND EVALUATING DECISIVE CHARACTERISTICS FOR THE APPLICATION OF IPPM

Based on the experiences gained in the three case studies, the following seven characteristics was identified as being especially relevant to consider when applying IPPM, see Table 1.

Characteristic	Description
Actors Involved	How many people are involved in the engineering design process? The more people the higher is the need for coordination.
Cross-Disciplinary	Does the engineering design process spread over several departments and different disciplines? The more cross-disciplinary and cross-functional, the more challenging is the mutual task coordination.
Level of Detail Included	What level of detail is included in the modelling of the product and process? Too much will make the analysis overwhelming while too little will make it worthless.
Maturity Level of Product	What is the maturity level of the product being modelled? Is it prototype or variant creation of well-known products? The more open the solution space is, the more difficult is it to model the product.
Resource Consumption	What is the resource consumption for specifying the product in question? The more resources, the more interesting is it to investigate whether improvements can be made.
Frequency	What is the frequency of the engineering design process? Processes occurring more frequently might possess a higher improvement potential in total.
Process Nature	Is the process dynamic or static in nature? Dynamic processes can be hard to map as they evolve over time.

TABLE 1: DECISIVE CHARACTERISTICS FOR THE APPLICATION OF IPPM

In order to illustrate the significance and influence of these characteristics, the three cases are briefly presented below and evaluated according to the stated characteristics.

CASE 1 – DROWNING IN DETAIL

The first case revolved around an ongoing customisation of a specific main component within the engine, called the hydraulic power supply (HPS). Customers often wanted the component adapted and optimised for their specific needs causing a small group of designers to continually adapt the component. The engineering design process exhibited no critical problems. However, the actors involved had a wish to get the process scrutinised in order to establish whether the process flow could be improved.

The hydraulic power supply is a component that has been included in engine design for many years at MLS. The technology is quite fixed and the engineering work carried out can therefore be characterised as variant creation of existing products. The team designing the HPS consisted of four persons, all possessing a rather detailed understanding of all the components involved, even though they had separate areas of responsibility related to specifying the HPS. This meant that whenever coordination was necessary, every single actor most often knew exactly who to address to ensure a successful coordination. The engineering design process could therefore not be characterised as cross-disciplinary. In order to attempt to uncover knowledge that was not apparent to all actors involved, a product model containing very detailed product knowledge was constructed.

As the design team was rather small, and since they were also responsible for the design of several other components, the resource consumption for designing the HPS was by and large relatively low. The frequency on the other hand was quite high as approximately 75 % of the engines ordered needed to

have a hydraulic power supply specified. The engineering design process was very fixed and static and was conducted by and large the same way every time.

What was especially time consuming in the application of IPPM in case 1 was the high level of detail included in the product modelling. Every nut and bolt was carefully included only with the outcome that it was realised that the value of including them was very limited. In case a designer made alterations on very detailed and specific part-level it rarely affected the design tasks of the other designers. And if it did, the team only consisted of four people so the coordination was straightforward and quite uncomplicated. The somewhat discouraging conclusion of applying IPPM in case 1 was therefore that the effort put into the analysis by far exceeded the yield gained.

CASE 2 – NEW TECHNOLOGY DEVELOPMENT

The second case was the introduction of new emission technology to be incorporated into all engines described in detail in P1. The company had developed the emission technology on prototype level but it had not yet been adapted to comply with the entire product range. The designers therefore faced the task of developing a complete set of engineering design processes for specifying their products including the new emission technology. The product being in an early development phase meant that no formal engineering design processes for creating customer specific variants of the product with the new emission technology were established. The actors to be involved in this future specification process therefore had a need to acquire an overview of interdependencies between different design tasks.

As the product was on prototype level and still quite immature, the engineering design processes were still very dynamic. There were a lot of iterative loops of redesigning and rethinking solutions, which required many resources from the staff involved. One thing the designers were much occupied with was to create an emission system that could cover several engines with the same design. This way they could reduce the engineering efforts needed and keep the frequency of designing the emission system low. The engineering design team to be involved in designing the emission technology as part of the overall products consisted of 8 people, scattered across different departments and engineering disciplines. The need for coordination between designers was therefore somewhat higher compared to case 1.

As a lesson learned from case 1 was to be careful when choosing the level of detail to include, the author was cautious when establishing the product model. The designers were encouraged only to include what they considered to be relevant product features when filling in the Task Clarification Cards. To model a product being still on prototype level was however difficult as fundamental design changes and reprioritisations occurred frequently. This resulted in constant revisions of the product model as well as the Task Clarification Cards. Thereby the modelling task never really came to an end and the benefits of applying the IPPM-procedure could not be fully harvested.

CASE 3 – CREATING VARIANTS IN LARGE DESIGN TEAM

The third case was an analysis of a subset of the order process within the company described in papers P2 and P3. Based on an order from a customer it was analysed how a specific engineering department designed a solution fulfilling the customer request. The engineering design tasks to be performed within

the department were highly interdependent and also dependent on engineering work carried out in other departments. The overall process was therefore characterised as being cross-disciplinary. The department in question was experiencing increasing lead time and efficiency problems due to lack of overview over dependencies between engineering design tasks both within and outside their own department. Too often bottlenecks were identified which were caused by dependencies not taken into account when internal deadlines were set for the different engineering design tasks.

The design team, consisting of 11 people, was occupied with adapting existing engine components in accordance with specific customer requests. They were not involved in fundamental redesign of the product but rather on creating variants of well-known components. The frequency of the process was high as it was conducted every time the company received an order. The process nature was therefore also quite static even though it differed exactly which components were to be customised for the individual order. The resource consumption was high also due to the fact that the scope of the engineering design process was wider. Whereas case 1 and 2 focused on specific components, case 3 included many components to be specified by the department in question.

As earlier applications of IPPM caused substantial problems related to the level of detail to include in the analysis, the author put effort into minimising the level of detail. In stead of asking the designers to inform both inputs and outputs from their individual design tasks when filling in the Task Clarification Cards, they were only to provide information on which inputs were needed to conduct the task. This way, only product features that were decisive for the engineering design process were included, keeping the level of detail low without losing valuable information.

By applying the IPPM in case 3 the author was actually able to thoroughly model the product and process in an integrated way creating valuable insight into product feature dependencies between the engineering design tasks. By utilising this insight it will be possible to develop the engineering design process and improve the performance of the department in question.

SUMMARY

In summary, the application of the IPPM-procedure was conducted on three cases which exhibited quite different characteristics. Table 2 restates the characteristics identified as especially crucial for the application of IPPM and summarises how the three cases relate to those characteristics.

Case	Actors Involved	Cross-Disciplinary	Level of Detail Included	Maturity Level of Product	Resource Consumption	Frequency	Process Nature
1	4	No	High	Variant Creation	Medium	Medium	Very Static
2	8	Yes	Medium	Prototype Level	High	Low	Dynamic
3	11	Yes	Low	Variant Creation	High	High	Quite Static

TABLE 2: CHARACTERISTICS OF CASE STUDIES CONDUCTED

In terms of outcome of applying the IPPM it was clear that case 3 was the most appropriate case. Case 1 drowned in detailed product modelling, providing only limited value in a process setting that was quite simple and easy to cope with. Considering a product on a low maturity level was the main reason for the problems experienced in case 2. But case 3 seemed to possess a more appropriate mix of characteristics making the application of IPPM suitable and provided valuable insight.

CONTRIBUTION

Based on the case studies conducted it has been possible to identify seven characteristics that have significant impact on the applicability of IPPM: Actors involved in process, whether the process is cross-disciplinary, level of detail included in analysis, maturity level of product, resource consumption within process, frequency of process and the nature of the process. In order to create maximum value when applying IPPM it is crucial to make sure the process is worthwhile putting effort into optimising. This is ensured if the frequency as well as resource consumption is high. Also, it is essential that the coordination challenges are substantial, which is indicated by a high number of actors as well as whether the engineering design tasks in question spread over several disciplines and departments. Furthermore, the process modeller should make sure that the maturity level of the product is rather high. Products on prototype level are hard to model as they continually develop causing the modelling task to extend significantly. Similarly, one should only address processes that are rather static. If the process flow is too unsettled, the process modelling task can be too tedious. Finally, it is very important to find an appropriate level of detail to include in the modelling task. Process modellers should be careful to capture what is decisive but also be cautious of not including too much detail as this might cause the analysis to drown in irrelevant information.

The main contribution of P4 is an applicability study of when to utilise the IPPM-procedure and how to create as much value as possible when applying it. The paper thereby aims at answering research question 3. Applying IPPM requires significant efforts when mapping both the product and process under investigation. And to conduct interviews with several designers for all engineering design tasks within an overall process is beyond doubt a time-consuming activity. Because of that, it is important that process modellers do some thorough considerations before applying the IPPM-procedure. By doing a preliminary assessment of an engineering design process with regards to the characteristics identified in Table 1, the process modeller can firstly assess whether IPPM is an appropriate choice and secondly significantly enhance the output of applying IPPM.

5.2 ASSESSING THE PERFORMANCE OF ENGINEERING DESIGN

As stated initially in Chapter 5, a main objective of the overall project has been to formulate an operational procedure for developing engineering design processes through integrated modelling of product and process. Another significant objective having focus from the very beginning of the project was related to determining the performance of engineering design. This objective was partly integrated in phase 2 of the overall analytical procedure, but it was also pursued more separately and in depth in the articles P5 and P6.

The research carried out has focused on the significance of variance and more specifically the implications of increasing variance on the performance of engineering design. Increases in variance are important for many reasons. It supports companies in attracting new customers and in creating differentiation from competitors' products. However, it is a challenge to offer the correct variance and also figure out how to control it. Too little variance will obstruct companies in developing their business, while too much variance will threaten to undermine the efficiency. When introducing new variants into a product portfolio it will most likely generate an increase in turnover. But it will at the same time lead to an increase in complexity related costs as multiple functions within the company such as development, engineering, production planning, sales and marketing need to deal with more variants. Furthermore, when complying with unique customer requests the company will have to initiate an engineering design process, for which the lead time and quality of the outcome cannot be determined beforehand. As stated earlier, the Marine Low Speed business unit is continually expanding their portfolio and offering more a more variance to the market, as it is believed that variance is key to maintaining the position as market leader. It is therefore a clear empirical objective for the company to acquire a better understanding of contingent performance trade-offs related to the expanding product portfolio.

The overall purpose of the papers presented in this section is to investigate whether there exist a dependency between an expanding product program and engineering design performance related to cost, lead time, on time delivery and quality. The papers therefore address research question 4.

P5 and P6 are quite similar in their structure, but the time lapse between the two articles is almost two years, with P6 written last in the spring of 2013. The maturity level of the results therefore differs and the depth of analysis is considerably deeper in P6. Thus, main focus is on the results generated in P6.

P5 AND P6 – IMPLICATIONS OF VARIANCE ON ENGINEERING DESIGN PERFORMANCE

P5 Title: Product Complexity Impact on Quality and Delivery Performance

P6 Title: The Cost of Customising – Assessing the Performance of a Modular Product Program

This paragraph presents the results obtained in the two papers P5 and P6. They should not be seen as a conclusion of the overall IPPM-procedure, but rather as a parallel and connected research stream related to especially phase 2 within the procedure. Phase 2 focuses on measuring the performance of engineering design processes, and the results of P5 and P6 can be considered as an elaboration of this focus.

The overall aim of the two papers is to investigate to which extent increases in product variety result in increases in cost and lead time as well as reduced quality and on time delivery performance, which is formulated in a list of hypotheses. P5 focus on overall product variant level, which in this case means specific diesel engines offered. P6 goes one spit deeper and investigates whether an increasing modular product architecture also leads to reduced performance.

The case is once again the Marine Low Speed business unit. As described several times, they are the market leader within their industry and the primary strategic goal is to maintain this position. In order to fulfil this goal the company strives to win every order by delivering customer specific, high quality products on time, even if it requires significant development and engineering work. The belief is that the best way to satisfy the customer is to offer the most technically advanced solution or to comply with the customer's request without trying to sway the customers towards choosing a product variant that is more frequently designed. The company fears that if an alternative variant is suggested to the customer, the customer will instead address a competitor and place the order there.

Furthermore, within the last years the market has gotten more diverse and more unique customer requests occur. The consequence has been a steep increase in the number of very customer specific product variants offered by the company. This is clearly reflected in the product program, which today is approximately twice the size as it was just 5 years ago. In parallel to this, a continual expansion of the product architecture is occurring in order to comply with the increasingly diversified demand for customised engines.

The strategic choice of complying with every unique customer request combined with a growing diversification of market requests drive the company to increase the variance offered to the market, which again enhances the complexity-related challenges faced by the company. It is not thoroughly investigated what the price is for this increasing complexity in terms of design cost, lead time, on time delivery and quality. The engineering departments have however experienced an increased pressure as they are required to design considerably more new variants than earlier both on modular and on product variant level.

VARIANCE & PERFORMANCE

The results of the two papers converge. Tendencies show that increases in variance offered to the market leads to decreased performance for the very specific variance being infrequently requested. This is visualised through a series of plots where the performance in terms of cost, lead time, on time delivery and quality is tested. P5 makes these tests on an overall product level whereas P6 goes into more details and focus on a modular level. Only a few plots will be presented in this paragraph alongside with the conclusions made. For a detailed exposition of all plots, please confer the full papers in the appendix.

The overall method for testing the hypothesis was the same for both papers. The idea was to plot variants offered on both product and module level arranged according to frequency versus the four performance parameters under investigation. The following table accounts for the composition of the plots, see Table 3.

Paper	Focus	Horizontal axis	Primary Vertical Axis	Secondary Vertical Axis
P5	Variance on Product Level	Product Variant	Designs Made	Cost Lead Time On Time Delivery Quality
P6	Variance on Modular Level	Module Class	Modules Designed	Cost Lead Time On Time Delivery Quality

TABLE 3: THE VARIABLES ADDRESSED IN PAPERS 5 AND 6

VARIANCE ON PRODUCT VARIANT LEVEL

The first finding of P5 was for instance to investigate the cost on product variant level, which is illustrated in Figure 14.

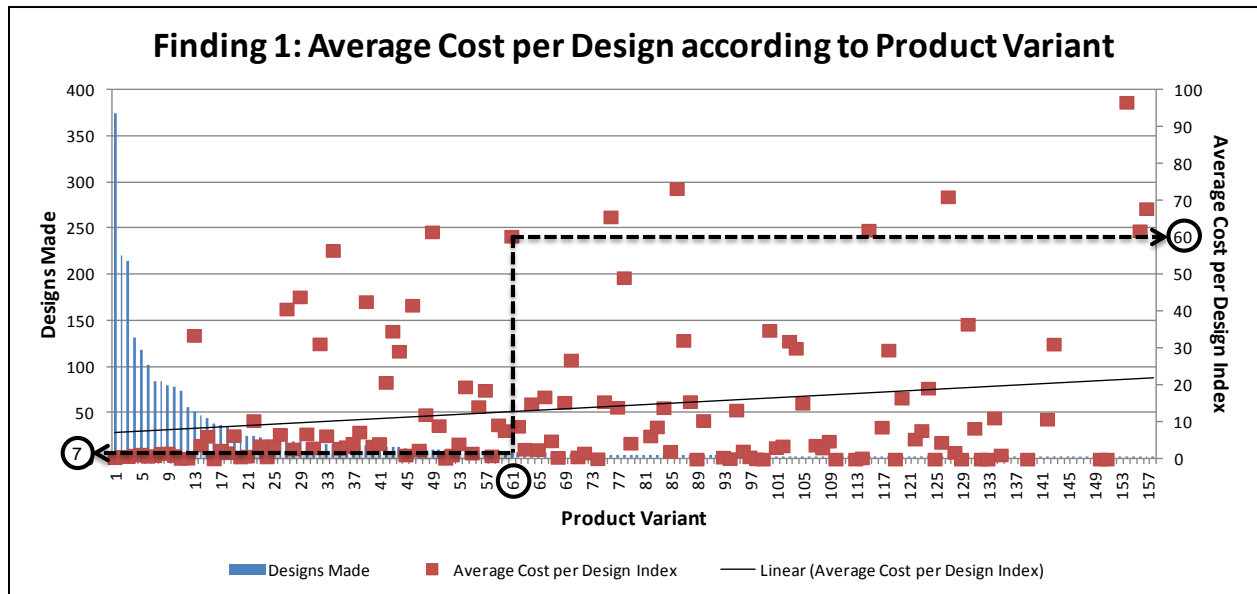


FIGURE 14: AVERAGE COST PER DESIGN ACCORDING TO PRODUCT VARIANT

Each of the plots within P5 has the same horizontal axis as well as primary vertical axis, to the left, designated 'Designs Made'. Along the horizontal axis, each product variant is shown arranged according to how often the specific variant has been redesigned, with the most frequent furthest to the left. Along the primary vertical axis is then the actual number of redesigns illustrated by the blue columns for every product variant. The plots then differ with respect to the secondary vertical axis, to the right, where the following four parameters are outlined; average cost per design, % of modules not delivered on-time, average lead time per design and average complaint related cost per design. The last parameter was used as an indicator for the quality-level of the designs made. For each parameter a linear tendency line is depicted in accordance with simple linear regression. These tendency lines give indications of whether the hypotheses can be substantiated.

Finding 1 in Figure 14 basically shows the relation between how often a product variant is designed and what the average cost of designing the variant is. As an example of how to read the plots consider product variant 61, marked with a circle. It has been redesigned 7 times, which can be read from the primary vertical axis to the left, and the cost index is approximately 60, as indicated on the secondary vertical axis to the right. The plot then illustrates that there is a tendency stating that product variants that are rarely designed are more costly to design. The same tendencies were found for the remaining three performance parameters. Infrequently designed product variants tended to exhibit poorer performance in terms of longer lead times, lower quality and a reduced ability to keep delivery deadlines.

P5 provided indications of whether reduced performance will occur when continually expanding a product program. The results obtained urged the author to go one spit deeper and focus on a modular level. Could the same tendencies be spotted on this level? Acquiring this insight was deemed to be a valuable contribution to the literature discussing the trade-offs of introducing modularity into a product program.

VARIANCE ON MODULAR LEVEL

Figure 15 from P6 shows the attempt to investigate whether an increasing product architecture leads to decreased quality for modules in classes being rarely designed.

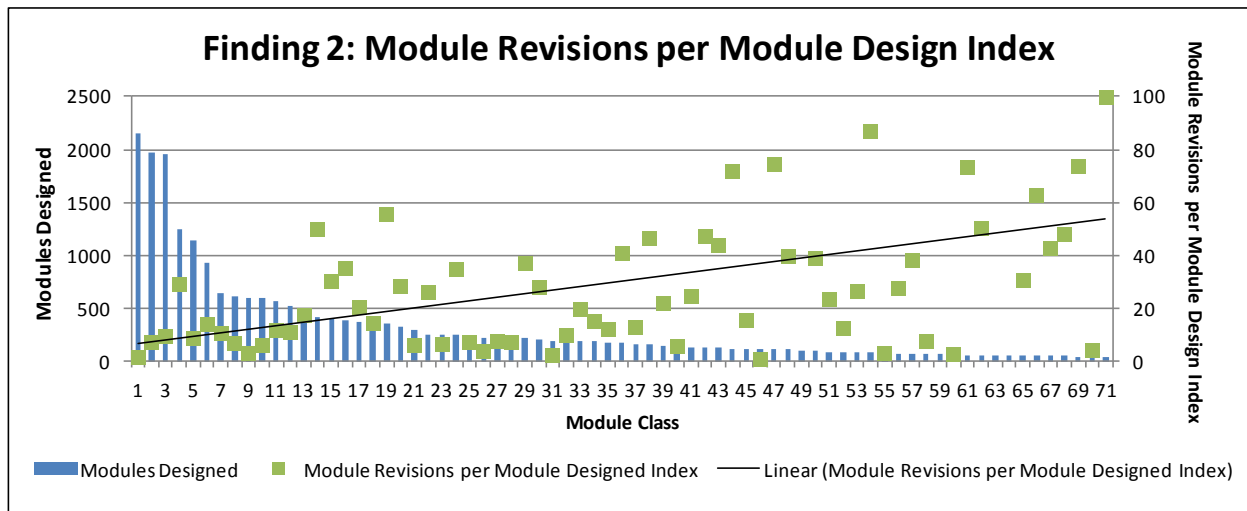


FIGURE 15: MODULE REVISIONS PER MODULE DESIGN INDEX

The plots in P6 had Module Class depicted on the horizontal axis with every module class arranged after how many modules that has been designed within each class, starting with the most frequent furthest to the left. The primary vertical axis, to the left, designated 'Modules Designed' was also the same for all plots, but the secondary axis differed showing the four performance parameters stated in Table 3. Again tendency lines were applied to give indications of whether the trade-offs between performance and variance occurred. Considering Figure 15, it illustrates an index for the number of module revisions that are made per module designed according to each module class, which is used as quality indicator for the modules designed in this analysis. For instance consider the last module class 71. For the modules in this

class the index is approximately 100 indicating that the company is having problems designing modules in sufficient quality within this class.

P5 being an introductory conference paper did not go deeper into testing the validity of the findings. It was concluded that there are tendencies showing that the more often a product variant is designed the lower is the cost and lead time for designing it, the ability to deliver on time is improved and the complaint related cost for the given product variant is lower. P6 did however scrutinise the results considerably further. Regression coefficients for the tendency lines as well as correlation coefficients for the variables included in the analysis were calculated. Two-tailed statistical significance tests were also conducted and associated p-values were calculated.

So going back to Finding 2 from P6 (see Figure 15) the regression coefficient equal to 0.67 reveals that considerable more revisions are needed for modules in classes being rarely included in the product. A correlation coefficient value of 0.47 ($p < 0.01$) furthermore suggests a rather strong linear dependency between module class and the revision index. As expected, only few revisions per module design are occurring for classes with modules that are frequently designed. The tendency is very clear and it is worth noticing that the dispersion of data is bigger for rarely designed modules. Corresponding analysis was made for all performance parameters in question and the outcome can be found in Table 4 below.

Variable	Regression Coefficient, α	Correlation Coefficient, r
Cost	0.18	0.17 *
Revisions (Quality)	0.67	0.47 ***
Lead Time	0.16	0.20 **
On Time Delivery	0.18	0.19 *

* $P < 0.2$ ** $P < 0.1$ *** $P < 0.01$

TABLE 4: REGRESSION AND CORRELATION COEFFICIENTS

Based on these results it was concluded that all in all the plots all exhibit an increasing tendency. Module classes containing fewer modules are likely to be more costly to design, to be of poorer quality, to have a longer lead time and to exhibit a more frequent failure to meet delivery deadlines. All four hypotheses related to the four performance parameters could therefore to some extent be substantiated. However, the regression and correlation coefficients for the parameters cost, lead time and on time delivery were rather low suggesting a somewhat weak relation between the variables with quite low negative impact. The statistical significance levels for these findings were also somewhat high adding some uncertainty to the findings related to those parameters. The findings related to the quality parameter were rather significant, though. The analyses suggested that there exist a dependency between module classes being rarely included in the product and the number of revisions needed for modules designed in those classes, which provided rather strong support for the hypothesis related to quality.

Based on the findings the hypotheses put up in P6 could only be substantiated to some extent. It was found that there were tendencies showing that modules in classes that are rarely designed in average

have a higher cost and lead time for designing them while the ability to deliver on time is reduced and the number of revisions per module design is increasing. Especially the quality performance parameter was showing a strong tendency, while performance related to cost, lead time and on time delivery seem somewhat less affected.

CONTRIBUTION

The empirical contribution of P5 and P6 has been to investigate the potential trade-offs related to the company strategy of winning every order by increasingly customising their products in accordance with all customer requests while delivering on time and in high quality. The findings reveal that they are not completely successful in doing so. The company belief is that by complying with every unique customer request the company will get the most satisfied customers. But if the customer experiences a longer lead time and a poorer quality, the customer is unlikely to be completely satisfied. The company's main objective of maintaining or expanding the market share is understandable. But the company should be careful that they in their pursuit of fulfilling every unique customer request, do not undermine the very same thing they are trying to achieve.

The main theoretical contribution is found within P6. It provides detailed insight into a company's competitive performance trade-off on a modular level after introducing mass customisation. It thereby supports similar trade-off studies in the claim that customisation is not free. Companies are likely to experience a trade-off in performance related to parameters such as lead-time and cost when increasing their customisation even through a modular based product program.

The paper furthermore triangulates the findings made by several survey-based studies with a concrete quantitative and detailed analysis of the performance of a modular product program. Especially the level of detail included in this paper adds to the existing body of literature as the study is not just assessing the overall performance of a company. It actually addresses the performance of the individual module classes within the product architecture applied by the case company.

5.3 SUMMARY

This chapter presents the results produced throughout the research project. In total six papers were written and the main outcome and contributions of each paper has been described above. Also all research questions from paragraph 4.3 have been addressed throughout the exposition of the papers.

The chapter is divided into two main parts reflecting the two main focus areas of the project. Part one describes the four papers (P1-P4) focusing on the formulation of a procedure for assessing and developing engineering design processes through integrated modelling of product and process. The remaining two papers (P5-P6) centre on performance measurement within engineering companies and they are described in the second part of the chapter.

P1 describes the initial attempts of formulating a modelling approach for performing integrated modelling of product and process. The most significant contributions in the paper are the Task Clarification Cards, used for describing every single engineering design task in details, and the Cross

Referenced PVM, in which the product model is enriched with process information. In conjunction these contributions build a bridge between the process and the product modelling tasks. Several inadequacies related to the modelling technique were however identified. It became clear that it is a significant challenge for the process modeller to include the right level of detail when applying the modelling technique. Also it became evident that additional support was called for in order to handle the large amount of cross references between the product and process models.

The papers P2 and P3 are highly interrelated and were therefore described in one setting. The papers contain a refined elaboration of the concepts introduced in P1 alongside a more comprehensive procedure for assessing and developing engineering design processes. The outcome was a 5-phased procedure, designated IPPM. The first phase focuses on characterising the existing process and understanding the most critical problems associated with the process. The purpose of phase 2 is to measure the performance of the existing processes and to formulate the performance requirements for the new and improved process. In phase 3 the actual modelling of the product and the process is initiated. A structural product model is constructed and Task Clarification Cards are made for all process steps utilising and producing crucial product features. The product model and the content from the Task Clarification Cards are integrated in phase 4 and finally the future engineering design process is developed in phase 5 by utilising the insight acquired. In summary the IPPM-procedure facilitates assessing, modelling and developing engineering design processes in a structured and systematic way. The procedure supports mapping and diagnosing of an existing process and it creates insight into the complex activities within a process that are usually unanalysed in most existing process modelling approaches. By utilising the insight gained through the IPPM-procedure, processes can be specifically configured to suit the product being engineered. Making use of this insight allows better planning and scheduling of the engineering design activities in a more optimal way followed by expected benefits related to increased efficiency, reduced lead time, improved ability to deliver on-time and improved quality of the engineering work carried out.

The purpose of P4 is to assess the applicability of the IPPM-procedure and investigate how to create as much value as possible when applying it. It presents an accumulation of the experiences gained throughout the application of the IPPM-procedure and introduces a list of characteristics identified as having significant impact on the applicability of IPPM. Based on the case studies conducted it has been possible to identify seven characteristics that have significant impact: Actors involved in process, whether the process is cross-disciplinary, level of detail included in analysis, maturity level of product, resource consumption within process, frequency of process and the nature of the process. By doing a preliminary assessment of an engineering design process with regards to the characteristics stated, the process modeller can firstly assess whether IPPM is an appropriate choice and secondly significantly enhance the output of applying the IPPM.

P5 and P6 address the second main objective of the research at hand related to engineering design performance. They focus on the significance of variance and more specifically the implications of increasing variance on the performance of engineering design. The overall purpose of the papers presented is to investigate whether there exists a dependency between an expanding product program

and performance related to cost, lead time, on time delivery and quality. The analyses showed that modules and products rarely designed tend towards having higher design costs, longer lead time, poorer on time delivery performance and lower quality.

The main contribution of the papers P5 and P6 is detailed insight into a company's competitive performance trade-off when increasing the product variance offered. It thereby supports similar trade-off studies in the claim that customisation is not free. Companies are likely to experience a trade-off in performance related to parameters such as lead-time and cost when increasing their customisation even through a modular based product program.

CHAPTER 6 – DISCUSSION

When having conducted research it is of high importance to critically evaluate the outcome of this research. This chapter will discuss the outcome in terms of validity, applicability of results, generalising potential and in general evaluate the contribution in relation to the chosen methodological approach. The chapter will also discuss the choices made along the way in developing the IPPM-procedure. It discusses why the modelling techniques included in the procedure are suitable for addressing the overall research problem. Finally, a few additional aspects are discussed in relation to maintenance of the outcome and results produced when applying IPPM.

6.1 ASSESSMENT OF CONTRIBUTION

As emphasised continually throughout the thesis, the aim of the research project has been to make a dual contribution of both managerial and theoretical significance. As no process modelling approach taking product features into account when developing engineering design processes was identified in existing body of literature, it can be claimed that the research at hand contributes to process development theories within an engineering design context. By including a model of the product features in the modelling of engineering design processes additional understanding of what actually takes place within the process can be acquired. It reveals what product features are used and produced in every process step. Utilising this insight enables that the processes in questions can be specifically configured to suit the product being engineered, thereby creating an optimal process flow for that specific product. The theoretical contribution is more specifically comprised by a 5-phased procedure, designated IPPM, for assessing and developing engineering design processes through integrated modelling of product and process.

The IPPM-procedure basically also constitutes the empirical contribution by providing a structured approach for process modellers to analyse and develop engineering design processes. Furthermore after having completed the 5-phased procedure the tangible outcome is a DSM containing knowledge on interdependencies between the individual process steps and between the product features utilised in every step. This DSM is aimed at managers who can apply it when organising engineering design activities and enable better planning. Finally, the empirical contribution is also aimed at designers who will acquire a better understanding of how their individual tasks are related to other designers' tasks. Especially the usage of Task Clarification Cards will support them in their daily work when coordinating with colleagues in relation to task interdependencies.

VALIDITY

Assessing the validity of the contribution is crucial when evaluating research, as it basically determines the strength of the research's conclusion. The research project at hand was founded within the case company, and the author therefore had free access to detailed data within the company allowing in-depth analyses over a period of several years. With such a setup the internal validity, which concerns the extent to which the research findings accurately represent what is really happening, is evaluated to be high. Furthermore, data from interviews, workshops and documents from internal company systems, was triangulated by collecting data at different times from different sources in the study of the same phenomenon. This also enhances the internal validity of the research carried out.

As the study at hand ascribes to critical realism, the validity of the findings are often evaluated by testing the obtained results in different settings. A phenomenon called 'retroduction' (Easton, 2010). In this research project, this is done by testing the IPPM-procedure in three rather different cases, which is described in detail in paper P4. However, all cases were within the same company. The fact that only data from one company has been analysed is a clear limitation. The external validity of the findings, which concerns whether the results are valid in a similar setting outside the studied objects, is therefore somewhat questionable (Karlsson, 2009). In order to enhance the external validity further case studies

should be conducted in other companies. This aspect is also discussed in further detail under Future Research in Chapter 8.

APPLICABILITY

When addressing the applicability of the research contribution, it is mainly referring to the empirical contribution. How much value does the proposed procedure actually create in an empirical context? This is not a straightforward question to answer. To acquire an understanding of interdependencies between engineering design tasks does definitely create value, as it provides enhanced understanding and enables better planning. Following quotes from a designer and a department manager exemplifies this value:

Having the Task Clarification Cards available supports me in understanding what I need to do in every engineering design task, and who I need to coordinate with.

(Designer)

The DSM helps me setting deadlines for the design tasks to be delegated in my group. It shows what tasks are interdependent and I can therefore set deadlines according to those interdependencies and thereby avoid unnecessary bottlenecks.

(Department Manager)

But when considering the value of the empirical contribution it should ideally be considered relative to how much effort that goes into revealing these interdependencies. However, no detailed cost/benefit analysis has been carried out in this project. To interview several designers, each with multiple design tasks, and clarify what specifications are used and produced in every task is beyond doubt very time consuming. There is therefore a risk that applying the procedure will cost more than it will benefit. P4 was aimed at addressing this issue by actually analysing the applicability of IPPM in different contexts. It was investigated what characteristics that should be in place in order to obtain maximum value of applying IPPM. But P4 does not provide an answer for what are the actual costs of applying it.

However, as stated in the delimitation of the project the primary scope of the research is to develop a procedure for assessing and developing engineering design processes and thereby acquiring a higher understanding of what actually takes place within the individual process steps. Due to constraints on time and resources of the actors involved, the scope has not been to conduct a detailed cost/benefit analysis. However, if this was done the assessment of the applicability of the developed procedure would be considerably more varied.

EVALUATING ACTION RESEARCH

As stated in Chapter 4, (Coughlan & Coughlan, 2002) list three pre-requisites for doing action research. Firstly, the outcome of the project needs to be of both theoretical and managerial significance.

Secondly, it is critical that the action researcher gains full access to the organisation in which the project is founded. And thirdly, involvement of key members should be ensured in order to collaboratively address real-life problems and come up with workable solutions through joint-meaning construction.

All these pre-requisites are generally considered to be fulfilled in the project at hand. As no structured approach for assessing and developing engineering design processes through integrated modelling of product and process exists, the research is considered theoretically significant. The case company furthermore has an aim of continuous improvement towards realising lower resource consumption, lower lead time and higher quality in their engineering design processes which makes the contribution managerial significant. As discussed above, it can be argued that further work has to be done in relation to analysing cost/benefit of applying the procedure in order to enhance the value of the managerial contribution. Nevertheless the insight acquired through IPPM in its current form is considered as being managerial significant.

As the author was employed in the company I had full access to information and I also had considerable support from management to carry out the research, which fulfilled the second pre-condition of conducting successful action research.

In relation to the third pre-requisite some challenges did occur. Occasionally difficulties appeared in relation to ensuring involvement of the necessary key members of the organisation as certain stakeholders experienced problems in allocating sufficient resources for participation in the project. This circumstance did not block the progress of the research project, but it probably limited the empirical outcome as only parts of the overall engineering design processes were covered.

When assessing the quality of an action research study, focus should be on aspects related to participation, real-life problems, joint-meaning construction and workable solutions. With regards to ensuring participation and joint-meaning construction this was supported by including the designers and department managers in the modelling of the engineering design tasks. Their knowledge was decisive for actually producing meaningful results, as only they could support identification of interdependencies between design tasks. Furthermore, as the engineering departments involved in this research project experienced increasing problems, especially with regards to keeping the delivery deadlines, underpins the fact that a real-life problem was addressed. With regards to the fourth evaluating factor related to creating workable solutions, it again becomes relevant to discuss the limitations of the research project. Focus has been primarily on developing the IPPM-procedure and not on evaluating it seen from a cost/benefit perspective. Without fully understanding the potential costs and gains of applying the procedure how can it be argued that a workable solution has been developed? Again I will refer to the initial delimitation and to the Applicability-paragraph above. The results suggest that the procedure is a workable solution for acquiring additional understanding of what takes place inside an engineering design process and that it enables better planning when scheduling interdependent engineering design tasks. Whether it is a workable solution seen from a more economical perspective largely remains unanswered. However, as stated by (Coughlan & Coughlan, 2002), generating theory through action research is situation specific and incremental, which is also the case with this research project.

Furthermore, being an exploratory research project, it should not necessarily provide conclusive answers to problems and issues, but give guidance on what future research, if any, should be conducted (Collis & Hussey, 2003). Future research will be discussed further in Chapter 8.

GENERALISING POTENTIAL

When evaluating the contribution it is also relevant to discuss the generalising potential of the results produced. The procedure developed in this research project is based on a single case study. The procedure was applied three times in different settings but it was within the same overall empirical context. Therefore it is important to question whether others would achieve the same results if the research was repeated in a similar context, and also whether it would be valuable to apply the same procedure in a different context.

The context in which the procedure has been applied can be described as complex, knowledge-intensive engineering design processes. Whether the outcome of the processes is a marine diesel engine or another product is in principle assessed to be secondary. However, the engineering of the product should be a complex process consisting of multiple interdependent engineering design tasks, involving several specialised actors mastering different engineering disciplines. If these pre-conditions are in place, the author believes that the results obtained in the specific empirical case could possess a high generalising potential. Before applying the procedure, it is however crucial that the process modeller assesses the process with regards to the characteristics identified in journal paper P4.

However, applying the procedure in a significantly different context could prove to be less rewarding. For instance a simple, well-defined business administration process will probably not be suitable. Application of the IPPM-procedure will be far too resource demanding and only add limited value as the content of the process could easily be revealed by utilising existing more generic process modelling techniques. It is important to acknowledge that if a model becomes more complex than the reality it describes, the model itself will become counter-productive.

Since the IPPM-procedure has not been applied in other empirical settings than the Marine Low Speed business unit of MAN Diesel & Turbo, it is clear that caution is called for when assessing the generalising potential of the research contribution. In order to achieve a higher understanding of the generalising potential, future research should focus on testing the procedure in other companies. If similar tendencies can be found, the external validity of the findings will be improved considerably and the generalising potential would be higher. Future research on this matter is discussed in more detail in Chapter 8.

6.2 DISCUSSION OF ISSUES RELATED TO IPPM

Whereas the previous paragraph discussed the general validity and applicability of the research project, this paragraph will discuss the choices made along the way in developing the IPPM-procedure. What modelling tools were included and why? Could alternative choices have been made? These and more questions will be addressed below.

WHY WAS THE PVM-MODELLING TECHNIQUE CHOSEN FOR MODELLING THE PRODUCT?

A significant strength of the developed IPPM-procedure is that it can not only reveal interdependencies between different design tasks. It goes a level deeper and identifies interdependencies on product feature level. This was due to the application of a product modelling technique that could describe a product on overall component level as well as on attribute and product feature-level. This level of detail is supported by the PVM-modelling technique, as it allows a hierarchical description of the product from main component level down to detailed property-level.

Furthermore, the PVM is very visual and supports describing products in an efficient and clear manner to all stakeholders involved. The hierarchical structure is easy understandable also for people not having applied the technique previously. This is a valuable property of the modelling technique when applying it in cooperation with several stakeholders not accustomed to perform product modelling, as it was the case in the research at hand.

The author is not ruling out that other product modelling approaches could have been applied as well. However, the modelling technique is well-established within the research group at the Technical University of Denmark. Thereby, the author could draw on the significant experience being present within the group.

A central weakness was however experienced when applying the PVM-modelling technique. When the amount of internal relations between product components and features increase significantly, the modelling technique has problems in accommodating and expressing these interdependencies in a concise and clear format. Therefore, the PVM-modelling technique was first extended into the Cross Referenced PVM, which allowed for noting interdependencies between product features, and then afterwards complemented with the Design Structure Matrix modelling technique. In unison, the models then provided a suitable approach for describing a product on component as well as on feature-level, expressing interdependencies between those components and features and finally dealing with the interdependencies.

WHY WAS BPMN, IDEF0 & DSM CHOSEN AS PROCESS MODELLING TECHNIQUES?

In overall, three process modelling techniques were applied and included in the IPPM-procedure for assessing and developing engineering design processes. This fact does by no mean suggest that no other process modelling approaches could be relevant for the overall research problem in question. However, together these three modelling techniques provided support for the modelling requirements in the specific case. The first requirement was a need to have an intuitive, easy-applicable and broadly well-known tool that could represent the actors involved in the overall process, what activities were carried out, in what generic sequence and by whom. All of these requirements were met by the BPMN-approach. However, there was a clear need to go deeper into detail of what actually took place within the process. More specifically there was a need to identify what product features were needed for the individual tasks as well as what features were produced within each process step. The IDEF0-approach

and the arrow-notation related to what data and objects are consumed by a certain function in order to produce specific outputs served as an inspiration for fulfilling this requirement. The notion of this notation form was therefore included in the development of the Task Clarification Cards. Finally, a requirement was to have a tool that could support in expressing and dealing with interdependencies between tasks and features, which was obtained by including the DSM-modelling technique.

As the three modelling techniques thereby fulfilled the requirements put up, no further techniques were included in the procedure. The scope of the project has not been to completely map out what modelling techniques exist, but rather solving a concrete managerial problem. Therefore, as the requirements were fulfilled, no further significant efforts were put into including or replacing the modelling techniques chosen.

WHAT DOES IPPM BRING THAT DSM CAN NOT DO?

As a main outcome of the IPPM is a DSM for optimising the sequence of engineering design tasks by minimising feedback loops in the process, one could question why not apply the DSM from the very beginning saving the effort of going through the first four phases of the IPPM-procedure. But this approach would take for granted that the interdependencies between tasks and features are well-known from the beginning. This has not been the case in this research project, and without clear identification of interdependencies, the DSM alone will not solve the problem.

In general, DSM-literature does not seem to be particularly occupied with the actual mapping of the interdependencies, but rather with how to deal with them after they have been identified. Identification of these interdependencies can only be found by involving the people possessing the detailed design knowledge. They alone have the overview over what features are decisive for their work, and what features they produce. This knowledge therefore needs to be extracted and articulated, which in the IPPM-procedure is done by constructing a structural product model and enriching it with information acquired through Task Clarification Cards. Doing this enables construction of the Cross Referenced PVM, which then finally feeds the DSM with the information on interdependencies between tasks and product features. If all information on interdependencies is available up front, one could argue that it will not make much sense to apply the IPPM-procedure, but if interdependencies are not clear, IPPM provides an operational procedure for identifying those.

THE STABILITY OF THE OUTCOME OF IPPM

Very few products are completely static, and marine diesel engines are no exception. Therefore, it must be anticipated that changes will occur in existing engineering design tasks and also that new tasks will appear, as the product evolves. Obviously, this means that the outcome of the IPPM-procedure can not be static either. This entails that every time changes occur, Task Clarification Cards need to be created or updated followed by incorporation in and eventually partitioning of the DSM. There is thus a clear maintenance aspect in order to continually create value of applying IPPM. If the process modeller is only temporarily involved in developing the engineering design processes, it is crucial that a responsible process actor is identified and entrusted with the responsibility of updating the product models, TCCs

and DSM when needed. Otherwise, the information initially gathered is in risk of being diluted and outdated. If this happens, process actors are likely to lose confidence in the procedure and it will not create any value. Resources therefore need to be allocated to continually keeping the product feature information up to date. However, it is the clear perception of the author that the first time gathering and compilation of information is beyond compare the most time-consuming.

THE SIGNIFICANCE OF A WELL-ESTABLISHED PRODUCT ARCHITECTURE

The Marine Low Speed business unit of Man Diesel & Turbo has for decades put a lot of effort into establishing and utilising a very clear product architecture, consisting of well-defined building-blocks. This architecture has historically served as a work break-down structure for how to define individual engineering design tasks. In the case study at hand there is therefore a very close relationship between the product model constructed and the tasks within the engineering design process, as the product model was greatly influenced by the existing company product architecture. This is obviously a clear advantage when applying the IPPM-procedure, as the actors involved had a clear understanding of the product model, which made it very easy to establish and obtain a mutual agreement upon. The outcome of the research based on the Marine Low Speed case therefore only addressed process development. However, it is not unlikely that it could also support development or redesign of a product architecture in other cases, where there is no clear coherence between the engineering design processes and the product being engineered.

Furthermore, if there is little coherence between the product model and the engineering design process it will require a higher effort of the process modeller when completing the Task Clarification Cards and compiling the information from them in the Cross Referenced PVM. In the case study conducted the individual tasks corresponded to designing a main component within the product model, so they were fairly easy to integrate. If product features being produced within a single task are distributed across many different components, it will be more challenging to deal with and compile all the information acquired from the TCCs. However, in the author's opinion it is quite unlikely that a massive discrepancy between the engineering design process and the product being engineered should exist.

6.3 SUMMARY

Chapter 6 discusses the results obtained and in general the choices made along the way in the development of the IPPM-procedure. Initially, the chapter opens with a discussion and evaluation of the research contribution in terms of validity, applicability, generalising potential and general evaluation. As the research was deeply rooted within the organisation the researcher had free access to information, and the internal validity of the findings is therefore assessed to be high. However, the external validity is more dubious as the findings are based on data from one company only.

When discussing the applicability of the findings it is emphasised that it should be seen in the light of the delimitation and scope of the research project. The contribution is considered to have high applicability in relation to identifying and dealing with interdependencies between tasks and product features in engineering design processes. It supports both designers and department managers in acquiring a better

understanding and overview and it enables them to conduct better planning with the aim of improving delivery performance and avoiding internal bottlenecks. However, it is not thoroughly investigated what the actual costs are of applying the procedure. It is acknowledged that it requires significant resources to apply IPPM, but it is not directly quantified, leaving some doubts related to the applicability when discussing concrete cost/benefit.

When evaluating action research it is highlighted as important that the outcome is related to real-life problems addressed through participation and joint-meaning construction with the stakeholders involved, and that the results constitute a workable solution. All these preconditions are evaluated to be in place as the results are produced in close collaboration with the stakeholders involved in the project. The aspect of a workable solution is however again discussed in relation to the project scope. IPPM constitutes a workable solution for identifying and dealing with interdependencies, but how economically sane it is, remains a more open question.

In evaluating the generalising potential of the IPPM-procedure, it is essential to acknowledge the limitations that are inherent in single case studies. The generalising potential is however assessed to be high in similar contexts, meaning development of complex knowledge-intensive engineering design processes. But in other contexts it is more questionable and further studies are needed to clarify this.

The second part of the discussion chapter is addressing the choices made along the way when developing the IPPM-procedure. It discusses why certain existing modelling techniques are included and clarifies the initial requirements that needed to be fulfilled in order to realise a suitable procedure that could address the overall research problem. Finally, other aspects are touched upon in relation to how the IPPM-procedure is different from other existing modelling techniques, how stable the outcome of the procedure is and the role and significance of well-established product architectures when applying IPPM.

CHAPTER 7 – CONCLUSION

This chapter will present the conclusions made throughout the research project. Each of the four research questions posed will be addressed and answered. Eventually the chapter will evaluate the scientific and empirical contribution.

Many engineering companies currently experience increasing demands from their customers for the delivery of customised products that have almost the same delivery time, price and quality as mass-produced products. Complying with this development requires efficient engineering design processes, so companies can design customised products faster and more efficiently. To model and develop engineering design processes is however not a straightforward task, as they are often iterative, ill-defined and complex.

A main proposition in this research project is that understanding an engineering design process fully requires understanding of the product being engineered. By merging the areas of product and process modelling, additional insight into the engineering design processes is acquired. An overall objective has been to investigate how integrating a product model into the process modelling can enable a better understanding and optimisation of the engineering design processes. This concluding paragraph will go through the research questions posed in Chapter 4 one by one and summarise the findings made throughout this thesis.

The first objective was to investigate how to operationally model products and processes in an integrated way. This was done by firstly applying the PVM-modelling technique followed by the introduction of Task Clarification Cards, which were used to acquire information on what product features that were decisive for every engineering design task. The PVM-technique was then extended by launching the Cross Referenced PVM that was used for compilation of all information obtained in the Task Clarification Cards.

Research question 2 went a step further by aiming at formulating a procedure for assessing and developing engineering design processes. The findings made in relation to research question 1 were included in a more comprehensive 5-phased procedure, designated IPPM, which also supported mapping and diagnosing of existing processes. Furthermore, the well-established DSM-modelling technique was included in the IPPM-procedure in order to deal with the large amount of interdependencies between tasks and product features. By utilising the insight gained through the IPPM-procedure, processes can be specifically configured to suit the product being engineered, thereby creating an optimal process flow for that specific product. This IPPM-procedure is considered the main contribution of this research project.

The third objective, posed in research question 3, related to assessing the applicability of the IPPM-procedure and to clarify how to create as much value as possible when employing IPPM. Analyses led to the identification of seven conditions that have significant impact on the applicability of IPPM and should be in place in order to obtain maximum value. A high number of actors should be involved in process and the more cross-disciplinary it is, the more suitable is IPPM. The level of detail included in the analysis should be carefully considered. Too much will make the analysis overwhelming while too little will make it worthless. The maturity level of the product in question should be high. Products on prototype level are hard to model as they continually develop causing the modelling task to extend significantly. Likewise, the resource consumption within the process and the frequency of the process should also be high. Finally, one should only address processes that are rather static. If the process flow

is too unsettled the process modelling task can be too tedious, as the process will continually evolve and dilute the mapping efforts.

The fourth and final research question focused on analysing how increases in product variance affects engineering design performance. It was therefore mainly related to the aspect of assessing existing engineering design processes. Comprehensive data analyses revealed that increases in product variance and customisation are not free. Companies are likely to experience a trade-off in performance related to especially quality, but also to parameters such as on-time delivery, lead-time and cost when increasing their customisation even through a modular based product program.

It is a declared objective of the research project to make a dual contribution of both empirical and theoretical significance. As no process modelling approach taking product features into account when developing engineering design processes was identified in existing body of literature, it can be claimed that the research at hand contributes to process development theories within an engineering design context. The main empirical contribution is an operational procedure aimed at process modellers to be applied when assessing and developing complex engineering design processes. The outcome of the procedure is a Design Structure Matrix containing knowledge on interdependencies between the individual process steps and between the product features utilised in every step. This is another significant empirical contribution and is intended for managers with the scope of improving planning and scheduling of interdependent engineering design tasks. Finally, IPPM and more specifically the Task Clarification Cards contribute to the daily work of the designers. The TCCs will support them in carrying out their individual tasks and facilitate a better coordination in relation to task interdependencies.

Therefore, when evaluating the applicability of the contribution, it is considered to be high in relation to identifying and dealing with interdependencies between tasks and product features in engineering design processes. IPPM supports both designers and managers in acquiring a better overview of engineering design processes and enables them to conduct better planning with the aim of improving delivery performance and avoiding internal bottlenecks.

The research project was deeply rooted within the case company and the author had free access to information. Therefore the internal validity of the findings is assessed to be high, whereas the external validity is more questionable as the findings are based on data from one company only. One should therefore also be cautious when evaluating the generalising potential of the IPPM-procedure. However, if applied in a context similar to the empirical case of this research project, the results obtained are evaluated to have a high generalising potential.

CHAPTER 8 – FUTURE RESEARCH

The research study at hand was conducted over a period of approximately three years. The fixed period posed some limitations on what could be included in the research. This chapter presents ideas for future research that would benefit the IPPM-procedure developed in the research project.

8.1 MORE CASES

All results in this research project are based on analyses carried out in collaboration with the Marine Low Speed business unit of MAN Diesel & Turbo. This clearly imposes some limitations on the generalising potential of the results as discussed in detail in Chapter 6. Probably the most obvious suggestion for future research would therefore be to conduct more case studies in other companies. However, it is the author's recommendation that additional cases should be carried out in companies working within the context of complex, knowledge-intensive engineering design. Applying the IPPM-procedure in less complex contexts might not be worth the effort, as other existing more easy-applicable process modelling techniques probably could create sufficient insight into such processes. It is important to acknowledge the significant resources required for application of IPPM, and assess whether the gains can be expected to match the efforts needed. This aspect can however be difficult without an understanding of what the specific costs of applying IPPM actually are, which brings us to the next suggestion for future research.

8.2 ECONOMICAL ASSESSMENT

As stated above it is recommended that the process modeller carefully assess whether the IPPM is a suitable procedure in terms of how much effort it takes to conduct an IPPM-analysis. In order to make this assessment, the process modeller and the company or department considering applying IPPM need to make an upfront cost/benefit analysis. As stated several times throughout this thesis, the primary scope of the research has been to develop a procedure for assessing and developing engineering design processes. The scope has not been to conduct a detailed cost/benefit analysis. This does by no mean suggest that it is irrelevant to carry out such an analysis. In the author's opinion this is highly relevant, but due to constraints on time and resources of the actors involved, this has not been within the scope of the project.

Phases 1 and 2 of the IPPM-procedure actually support decision makers in assessing the potential benefits of applying IPPM. Phase 1 supports acquiring an overview of the current processes as well as an understanding of the most critical problems associated with the process, whereas phase 2 supports assessing the current performance of the engineering design processes in question. Understanding the current performance and the problems inherent in the AS-IS state, enables better estimation of the magnitude of potential gains of applying IPPM. However, the procedure does not consider how much effort that is needed to actually improve the current performance.

The costs of applying IPPM are obviously dependent on the number of people who need to allocate resources to the application. All five phases obviously require the process modeller to allocate resources when applying IPPM. Phase 1 requires input from managers and key stakeholders in order to map the current process. In phase 2 it might be sufficient only to allocate one person if all performance data is available. If that is not the case, phase 2 will require substantial resources as several persons might need to be involved in determining the current performance of the processes. Phase 3 is probably the most time-consuming phase, as all engineering design tasks are to be described in Task Clarification Cards,

which can only be done by the designers. Phase 4 and 5 are mainly compiling and analysing all the gathered information, so this is likely to be done by one person only.

These considerations are however not that quantitative, which is a requirement for more specifically estimating the costs of applying IPPM. Therefore it is suggested that future research should make these considerations more operational and implement them in the very initial phases of the IPPM-procedure. It could be in the form of a set of concrete questions to be investigated and estimated, such as: How many stakeholders need to be involved in mapping of the current process? Is performance data available or does it need to be collected through analyses and interviews? How many engineering design tasks need to be mapped and described in Task Clarification Cards? And obviously how much time needs to be allocated to each of the tasks? By acquiring answers for these questions up front, the decision makers could better assess whether the potential gains of applying IPPM are higher than the efforts needed to carry out the analyses.

8.3 MAINTENANCE OF IPPM

The analyses conducted in this research have focused on assessment and development of engineering design processes through integrated modelling of product and process. It is however relevant also to consider maintenance of the developed engineering design processes. The product being engineered will most likely change over time, and so will the processes. In order to continually draw advantage of the outcome of the IPPM-procedure it is therefore important to formulate a procedure for maintaining the product models, Task Clarification Cards and Design Structure Matrices when needed. This has not been done in this research project, but future researchers are encouraged to investigate how this can best be done.

8.4 TESTING THE POTENTIAL OF TASK CLARIFICATION CARDS FURTHER

When developing the Task Clarification Cards the ambition was to create a template that could describe every engineering design task in detail. Besides clarifying the input and output product features and specifications of the individual tasks, they also support further characterisation of the tasks by describing what competencies, database and IT-systems are needed to carry out the task. They also support describing interfacing components in detail and potential division of the task into sub-tasks. However, in the analyses conducted only the information on product features needed as input and output were really put into use when developing the engineering design processes. The author do however believe that the concept of describing every engineering design task in detail using a fixed template possesses higher potential, and future researchers are encouraged to try to make further use of the Task Clarification Cards or something similar.

8.5 SUMMARY

Throughout this final chapter future research has been suggested that would greatly supplement the results produced in the research project at hand. First and foremost, more case studies are called for, as this would test the generalising potential of the findings further. As the researcher had free access to the case company the internal validity of the findings is high. However, the external validity would

greatly improve if additional case studies in other companies were conducted. Another evident future initiative is thorough investigations of the cost/benefits of applying IPPM. Having a better understanding of the efforts needed to apply the IPPM-procedure would support decision makers in their choice of process modelling approach. Finally, future research related to maintenance of the outcome of IPPM as well as a wider application of the Task Clarification Cards is suggested.

CHAPTER 9 – LITERATURE

All references used within this thesis will be presented alphabetically in this chapter, according to the family name of the primary author. The primary type of references used is articles, but also books and web pages have been used. Harvard – British referencing style is applied, and the detail sequence is Author(s), Year, Publication name, Journal name and finally details on the specific Volume and Number.

- Albers, A. and Braun, A. (2011), "A generalised framework to compass and to support complex product engineering processes", *International Journal of Product Development*, vol. 15, no. 1-3, pp. 6-25.
- Åhlström, P. and Westbrook, R. (1999), "Implications of mass customization for operations management. An exploratory study", *International Journal of Operations & Production Management*, vol. 19, no. 3, pp. 262-274.
- Bare, M and Cox, J. J. (2008), "Applying principles of mass customization to improve the empirical development process", *Journal of Intelligent Manufacturing*, vol. 19, no. 5, pp. 565-576.
- Bettig, B. and Gershenson, J. K. (2010), "The representation of module interfaces", *International Journal of Product Development*, vol. 10, no. 4, pp. 291-317.
- Bilalis, N. and Maravelakis, E. (2006), "Analysing the dependencies between the Innovation Attributes in NPD using Design Structure Matrix – the I-DSM tool", *International Journal of Product Development*, vol. 3, no. 3/4, pp. 432-446.
- Closs, D.J., Jacobs, M.A., Swink, M. and Webb, G.S. (2008), "Toward a theory of competencies for the management of product complexity: Six case studies", *Journal of Operations Management*, vol. 26, pp. 590-610.
- Collis, J. and Hussey, R. (2003), *Business Research. A practical guide for undergraduate and postgraduate students*. 2nd edition. Palgrave Macmillan, New York.
- Coghlan, D. and Brannick, T. (2005), *Doing Action Research in Your Own Organization*, 2nd edition. Sage, London.
- Coughlan, P. and Coghlan, D. (2002), "Action Research for Operations Management", *International Journal of Operations & Production Management*, vol. 22, no. 2, pp. 220-240.
- Croom, S. (2009), "Introduction to Research Methodology in Operations Management", in Karlsson, C. (Ed.), *Researching Operations Management*, Routledge, New York and London.
- Da Silveira, G. and Slack, N. (2001), "Exploring the trade-off concept", *International Journal of Production Management*, vol. 21, no. 7, pp. 949-964.
- Danermark, B., Ekström, M., Jakobsen, L. and Karlsson, J.C. (2002), *Explaining society – Critical realism in the social sciences*, Routledge, London.
- Davenport, T. and Harris, J. (2007), *Competing on Analytics. The New Science of Winning*, Harvard, Harvard Business School Press.
- Ding, L., Matthews, J. and Mullineux, G. (2011), "Capturing constraint evolution: a technique to preserve and handle design knowledge", *International Journal of Product Development*, vol. 15, no. 1/2/3, pp. 135-155.
- Easton, G. (2010), "Critical realism in case study research", *Industrial Marketing Management*, vol. 39, no. 1, pp. 118-128.

- Eiríksdóttir, A. (2012), *Including Product Features in the Development of Engineering Design Processes*, MSc-thesis, Department of Management Engineering, Technical University of Denmark, Lyngby.
- Eiriksson, Y. and Sigurjónsson, P. (2011), *Applying the IPPM Methodology at Part-Level of Abstraction*, MSc-thesis, Department of Management Engineering, Technical University of Denmark, Lyngby.
- Eppinger, S. D. and Browning, T. R. (2012), *Design Structure Matrix Methods and Applications*, Massachusetts Institute of Technology.
- Eppinger, S. D., Whitney, D. E., Smith, R. P. and Gebala, D. A. (1994), "A model-based method for organizing tasks in product development", *Research in Engineering Design*, vol. 6, pp. 1-13.
- Eckert, C. and Clarkson, J. (2005), "The reality of design", in Eckert, C. and Clarkson, J. (Ed.), *Design Process Improvement – A review of current practice*, Springer-Verlag, London, pp. 1-29.
- Filippini, R., Forza, C. and Vinelli, A. (1998), "Trade-off and compatibility between performance: definitions and empirical evidence", *International Journal of Production Research*, vol. 36, no. 12, pp. 3379-3406.
- Fixson, S. K. (2004), "Product architecture assessment: a tool to link product, process, and supply chain design decisions", *Journal of Operations Management*, vol. 23, pp. 345-369.
- Ford, H. and Crowther, S. (1922), *My Life and Work*, Garden City, New York, USA: Garden City Publishing Company.
- Graner, M. and Mißler-Behr, M. (2012), "The use of methods in new product development – A review of empirical literature", *International Journal of Product Development*, vol. 16, no. 2, pp. 158-184.
- Gummesson, E. (1991), *Qualitative Methods in Management Research*, Newbury Park, SAGE
- Hammer, M. and Champy, J. (1993), *Reengineering the Corporation: A Manifesto for Business Revolution*. Harper Collins Publishers, New York.
- Harbour, J. L. (1997), *The Basics of Performance Measurement*, New York: Quality Resources.
- Harlou, U. (2006), *Developing product families based on architectures - Contribution to a theory of product families*, Dissertation, MEK, Technical University of Denmark.
- Haug, A., Hvam, L. and Mortensen, N. H. (2010), "A layout technique for class diagrams to be used in product configuration projects", *Computers in Industry*, vol. 61, no. 5, pp. 409-418.
- Haug, A., Hvam, L. and Mortensen, N. H. (2010), "Produktsanering i praksis. Et casestudie hos Novenco A/S", *Børsen Ledelseshåndbøger: Supply Chain Management*, vol. 3, november 2010.
- Hvam, L. (1999), "Procedure for building product models", *Robotics and Computer-Integrated Manufacturing*, vol. 15, no. 3, pp. 77-87.

- Hvam, L. (2001), "A Procedure for the Application of Product Modelling", *International Journal of Production Research*, vol. 39, no. 5, pp. 873-885.
- Hvam, L. and Jensen, K. R. (2007), "A multi perspective approach for the development of visual configuration systems", *Computers & Industrial Engineering*, vol 53, no. 3, pp. 401-419.
- Hvam, L., Mortensen, N. H. and Riis, J. (2008), *Product customization*, Springer-Verlag, Berlin Heidelberg.
- Hvam, Lars, and Pape, Simon. (2006), "Improving the quotation process with product configuration", *Computers in Industry*, vol. 57, pp. 607–621.
- Hvam, L., Pape, S. and Riis, J. (2005), "Development and maintenance of product configuration systems: Requirements for a documentation tool", *International Journal of Industrial Engineering*, vol 12, no.1, pp. 79-88.
- Hvam, L. Riis, J. and Hansen, B. (2003), "CRC-cards for product Modelling", *Computers in Industry*, vol. 50, no. 1, pp. 57 – 70.
- IDEF, The Federal Information Processing Standards Publications 183. 1993. *Announcing the Standard for Integration Definition for Function Modeling (IDEF0)*. The National Institute of Standards and Technology, USA. <http://www.idef.com/IDEF0.htm> (viewed 2013.12.10)
- Jacobs, M., Vickery, S. & Droge, C. (2007), "The effects of product modularity on competitive performance", *International Journal of Operations Management*, vol. 27, vo. 10, pp. 1046-1068.
- Jarratt, T., Eckert, C. and Clarkson, J. (2011), "Engineering Change: an overview and perspective on literature", *Research in Engineering Design*, vol. 22, pp. 103-124.
- Jespersen, J. (2005), "Kritisk realisme", *Videnskabsteori i samfundsvidenskaberne* (pp. 145-177), Roskilde Universitetsforlag, Frederiksberg.
- Kagan, C., Burton, M., and Siddiquee, A. (2008), "Action research", in C. Willig & W. Stainton-Rogers (Eds.), *The SAGE Handbook of Qualitative Research in Psychology* (pp. 32–53). Sage Publications, London.
- Kaltoft, J. (2011), "Tier III EGR for large 2-stroke MAN B&W diesel engines", *Proceedings of the International Symposium on Marine Engineering (ISME)*, October 17-21, 2011, Kobe, Japan, Paper-ISME586.
- Karlsson, C. (2009), "Researching Operations Management", in Karlsson, C. (Ed.), *Researching Operations Management*, Routledge, New York and London.
- Kaydos, W. (1999), *Operational Performance Measurement. Increasing Total Productivity*, Taylor & Francis Group, Florida.
- Koh, E. C. Y., Caldwell, N. H. M. and Clarkson, J. (2012), "A method to assess the effects of engineering change propagation", *Research in Engineering Design*, vol. 23, pp. 329-351.

- Levin, M. (2003), "Action Research and the Research Community", *Concepts and Transformation*, vol. 8, no. 3, pp.275-280.
- Lindemann, U., Maurer, M. and Braun, T. (2009), *Structural Complexity Management. An Approach for the Field of Product Design*. Springer-Verlag, Berlin Heidelberg.
- Li, S. (2009), "Matrix-based decomposition algorithms for engineering applications: the survey and generic framework", *International Journal of Product Development*, vol. 9, no. 1/2/3, pp. 78-110.
- Lindström, J., Löfstrand, M., Karlberg, M. and Karlsson, L. (2012), "Functional product development: what information should be shared during the development process?", *International Journal of Product Development*, vol. 16, no. 2, pp. 95-111.
- Madison, D. (2005), *Process Mapping, Process Improvement and Process Management*, Paton Press, Chico California.
- Maier, A. M. and Störrle, H. (2011), "What are the characteristics of engineering design processes?", *18th International Conference on Engineering Design (ICED)*, Copenhagen, 15-18 August 2011.
- Meyer, M. H. and Lehnerd, A.P. (1997). *The Power of Product Platforms*. Free Press, New York.
- Neely, A., Gregory, M. and Platts, K. (2005), "Performance measurement system design", *International Journal of Operations & Production Management*, vol. 25, no. 12, pp. 1228-1263.
- Mortensen, N. H., Pedersen, R., Kvist, M. and Hvam, L. (2008), "Modelling and visualising modular product architectures for mass customization", *International Journal of Mass Customization*, vol. 2, no. 3/4, pp. 216-239.
- Mortensen, N. H., Hvam, L., Haug, A., Boelskifte, P. and Hansen, C. L. (2010), "Making Product Customization Profitable", *International Journal of Industrial Engineering*, vol. 17, no. 1, pp. 25-35.
- Mortensen, N. H., Harlou, U., Hvam, L. and Haug, A. (2011). "Improving decision making in the early phases of configuration projects", *The International Journal of Industrial Engineering*, vol. 18, no. 9, pp. 452-461.
- O'Donovan, B., Eckert, C., Clarkson, J. and Browning, T. R. (2005), "Design planning and modelling", in Eckert, C. and Clarkson, J. (Ed.), *Design Process Improvement – A review of current practice*, Springer-Verlag, London, pp. 1-29.
- Pahl, G., Bietz, W., Feldhusen, J. and Grote, K. H. (2007), *Engineering Design. A Systematic Approach*, 3rd Ed., Springer-Verlag, London.
- Pasqual, M. C. and de Weck, O. L. (2012), "Multilayer network model for analysis and management of change propagation", *Research in Engineering Design*, vol. 23, pp. 305-328.
- Pine, J. (1993), *Mass Customization: The new frontier in Business Competition*, Harvard Business School

Press, Harvard.

- Pine, J. (2004). "Joseph Pine: What consumers want", viewed 2013-11-21, http://www.ted.com/talks/joseph_pine_on_what_consumers_want.html
- Rummler, G. A. and Brache, A. P. (2012). *Improving Performance: How to Manage the White Space in the Organization Chart*, 3rd Ed. Jossey-Bass, San Francisco, California.
- Salvador, F., Forza, C. and Rungtusanatham, M. (2002), "Modularity, product variety, production volume and component sourcing: theorizing beyond generic prescriptions", *Journal of Operations Management*, vol. 20, pp. 549-575.
- Salvador, F., De Holan, P. M. and Piller, F. (2009), "Cracking the code of Mass Customization", *MIT Sloan Management Review*, vol. 50, no. 3.
- Sanchez, R. (2000), "Modular architectures, knowledge assets and organizational learning: new management processes for product creation", *International Journal of Technology Management*, vol. 19, no. 6.
- Schilling, M. A. (2000), "Toward a general modular systems theory and its application to interfirm product modularity", *Academy of Management Review*, vol. 25, no. 2, pp. 312-334.
- Schwarze, S. (1996), *Configuration of multiple-variant products*, Dissertation, Swiss Federal Institute of Technology Zürich, Zürich.
- Smith, M. L. (2006), "Overcoming theory-practice inconsistencies: Critical realism and information systems research", *Information and Organization*, vol. 16, no. 3, pp. 191-211.
- Steward, D. V. (1981), "The design structure matrix: a method for managing the design of complex systems", *IEEE Transactions on Engineering Management*, vol. EM-28, no. 3, pp.71-74.
- Squire, B., Brown, S., Readman, J. and Bessant, J. (2006), "The impact of mass customisation on manufacturing trade-offs", *Production and Operations Management*, vol. 15, no. 1, pp. 10-21.
- Tanner, H. R. (2009), "Complexity Management in a Nutshell", *Complexity Management Journal*, vol. 2, pp. 19-23.
- Tseng, M. M. and Piller, F. (2003), *The Customer Centric Enterprise. Advances in Mass Customization and Personalization*, Springer, Berlin.
- Tu, Q., Vonderembse, M. and Ragu-Nathan, T. A. (2001), "The impact of time-based manufacturing practices on mass customization and value to customer", *Journal of Operations Management*, vol. 19, no. 2, pp. 201-217.
- Ulin, P., Robinson, E., & Tolley, E. (2005), *Qualitative methods in public health*, 1 Ed, Jossey-Bass, San Francisco.
- Ulrich, K. (1995), "The role of product architecture in the manufacturing firm", *Research Policy*, vol 24,

pp. 419-440.

Ulrich, K. T. and Eppinger, S. D. (2003), *Product Design and Development*, McGraw-Hill/Irwin, New York.

Veldman, J. and Alblas, A. (2012), "Managing design variety, process variety and engineering change: a case study of two capital good firms", *Research in Engineering Design*, vol. 23, pp. 269-290.

Voss, C., Tsikriktsis, N., and Frohlich, M. 2002, "Case research in operations management", *International Journal of Operations & Production Management*, vol. 22, no. 2, pp. 195-219.

Walters, B. & Young, D. (2005), "Further Reflections on Critical Realism", *Review of Political Economy*, vol. 17, no. 4, pp. 601.

Wilson, S. A. and Perumal, A. (2010), *Waging War on Complexity Costs. Reshape Your Cost Structure, Free Up Cash Flows and Boost Productivity by Attacking Process, Product and Organizational Complexity*. McGraw-Hill, U.S.A.

White, S.A. (2004), *Introduction to BPMN*, IBM Cooperation, BP Trends.

Worren, N., Moore, K. and Cardona, P. (2002), "Modularity, strategic flexibility, and firm performance: a study of the home appliance industry", *Strategic Management Journal*, vol. 23, no. 12, pp. 1123-1140.

Yang, F. and Duan, G. (2012), "Developing a parameter linkage-based method for searching change propagation paths", *Research in Engineering Design*, vol. 23, pp. 353-372.

Yassine, A. A. (2004), "An Introduction to Modeling and Analyzing Complex Product Development Processes Using the Design Structure Matrix (DSM) Method", *Quaderni di Management (Italian Management Review)*, vol. 9.

Zhang, M. and Tseng, M.M. (2007), "A product and process modeling based approach to study cost implications of product variety in mass customization", *IEEE Transactions on Engineering Management*, vol. 54, no. 1, pp. 130-144.

CHAPTER 10 – APPENDED PAPERS

The six scientific papers upon which this thesis is built are appended in their full version in this chapter. Three of the papers have been submitted, accepted and presented at scientific conferences. The remaining three papers have been submitted to international scientific journals. By December 2013 one of the journal papers has been accepted, whereas the other two are still in the review process. Full publication details are provided for each paper if applicable.

PAPER 1 - DEVELOPING ENGINEERING PROCESSES THROUGH INTEGRATED MODELLING OF
PRODUCT AND PROCESS

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Developing engineering processes through integrated modelling of product and process

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Abstract

This article aims at developing an operational tool for integrated modelling of product assortments and engineering processes in companies making customer specific products. Integrating a product model in the design of engineering processes will provide a deeper understanding of the engineering activities as well as insight into how product features affect the engineering processes. The article suggests possible ways of integrating models of products with models of engineering processes. The models have been tested and further developed in an action research study carried out in collaboration with a major international engineering company.

Keywords: Product modelling, Engineering processes, Integrated modelling of product and process.

Introduction

In order to understand what is going on in an engineering process, it is vital to understand the product being engineered. Current methods for redesigning and developing engineering processes do not take into account the product features to be used in every process step. Therefore it is difficult to obtain a detailed understanding of the activities in the processes and to come up with significant improvements. The suggestion is that by integrating a product model in the design of engineering processes, a better understanding of the engineering activities will be acquired. Furthermore, insight into how different decisions on product features affect the engineering process will be achieved. Making use of this insight will allow us to organise the engineering activities in a more optimal way and thereby increase the efficiency, reduce lead time, improve ability to deliver on-time and improve the quality of the engineering work carried out. However, it is a considerable challenge to deal with the complexity that occurs when considering complicated products. It is therefore of crucial significance to address the right level of detail.

The potential benefits of understanding the relationship between product and process have been acknowledged by several scholars (Eckert & Clarkson, 2005) and (Fixson, 2005), but to the knowledge of the authors no structured approach to coordinate decisions across the domains has been fully developed.

The research at hand is based on empirical data concerning introduction of new emission technology at MAN Diesel & Turbo, a world leading designer of two-stroke marine diesel engines. The company has developed the emission technology but it has not yet been adapted to comply with their entire product range. They therefore now face the task of developing a complete set of engineering processes for specifying their products including the new emission technology. How to operationally model these processes and the emission product features in an integrated manner is the scope of this article.

Theoretical Background

The suggested modelling method is based on theory on product modelling including the Product Variant Master method for modelling product families (Hvam et al., 2008). Also process mapping theories including Business Process Modelling Notation (BPMN), IDEF and Design Structure Matrix (DSM) are used.

Product Modelling

Many companies often face significant challenges when trying to get an overview of their entire product portfolio. Using product modelling techniques can be a mean to acquire this overview. By modelling your product range you will achieve a better understanding of the product portfolio and be able to control the complexity that exists within it. In general, product modelling can be interpreted as the logical accumulation of all relevant information concerning a given product

range. But to do so you need a tool, such as the Product Variant Master, that can describe the complete product assortment in an efficient manner to all stakeholders (Hvam et al., 2008).

The Product Variant Master modelling technique

The Product Variant Master (PVM) is a tool for modelling and visualising product families (Hvam et al, 2008). It provides an overview of the product range offered by a company and illustrate how the products can vary. The tool has its basis in object oriented modelling, and simply put, it can be said that a PVM contains a description of the company’s product range and the associated knowledge (Harlou, 2006).

A PVM consists of two parts. The left hand side of the model describes the product’s generic structure, and is called the ‘part-of’-structure. It contains the modules and parts which appear in the entire product family. For instance, a bicycle consists of a bicycle frame, handlebar, wheels etc. These modules and parts are then modelled with a series of attributes and constraints which describe their properties and rules for how classes and attributes can be combined. The right hand side of the PVM, called the ‘kind-of’-structure, describes how the individual modules and parts can appear in several variants. Using the bicycle example again, the wheels could be either mountain bike or racer for instance. The ‘part-of’ and ‘kind-of’-structure are analogous to the structures of aggregation and generalisation/specialisation within object oriented modelling. The structure of the PVM can be seen in Figure 1.

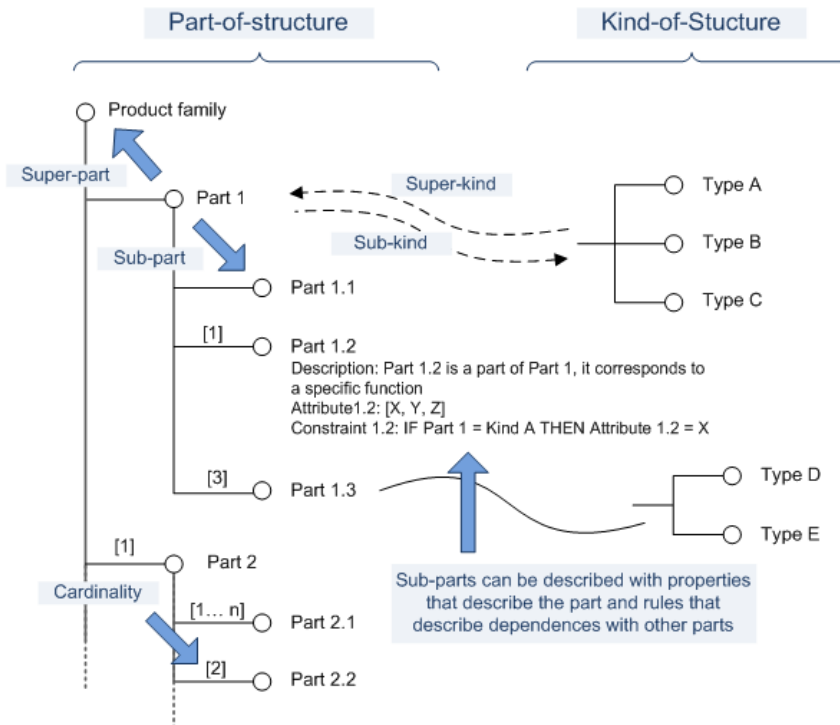


Figure 1: The structure of a PVM (Hvam et al., 2008).

If further information on the PVM-method is wanted please refer to (Harlou, 2006) and (Hvam et al., 2008).

Process Modelling

Several tools for modelling processes have been developed in the course of time. The most well known tool for mapping processes is probably the Business Process Modelling Notation, BPMN. BPMN is a flowchart tool used to create graphical models of business processes. By using the tool you can create models that clarify which activities are performed by whom within the company. Furthermore it clarifies which communication is occurring between different departments and external stakeholders (White, 2004). The notation form is quite straightforward and easy to put into use which makes it a popular choice.

The IDEF method is another widely used process mapping tool. IDEF is not just a single model but a family of 16 different modelling structures. However, in this article it is only IDEF0 which is put into use. The IDEF0 was originally intended to model the functional behaviour of engineering systems. And yet it is now being applied to a wide variety of business processes. Each activity or process step is described according to input, output, controls and mechanisms. IDEF0 has a strong hierarchical structure which can be used for decomposing activities within the process into more detailed sub- or component-activities (O'Donovan et al., 2005).

The third and last modelling approach presented here is the Design Structure Matrix, DSM. This tool is especially suitable for engineering design projects, which involves specification of many interdependent variables which together define a product, how it is made and how it behaves (Steward, 1981). The DSM is a matrix structure representation that captures the sequence and the technical relationships among different design tasks in a project. By using the modelling technique it becomes possible to find alternative sequences of the tasks and streamline the inter-task coordination (Eppinger et al., 1994). The relationships between the tasks are divided into dependent, independent and interdependent. The dependent relationships have to be performed sequentially, the independent can be performed in parallel whereas interdependent activities have to be coupled. A central strength of DSM is that it provides a concise visual format for representing processes. It becomes apparent how the individual activities affect the overall process and which activities that may trigger rework (O'Donovan, 2005). The research presented in this article has drawn on all of the modelling techniques presented above.

Development vs. Specification Process

When using the term engineering processes we are referring to the specification process of the product rather than the development process. Using the definitions formulated by (Schwarze, 1996) a product development process is about generating knowledge and designing new components in a creative process. The specification process however is characterised by having low degrees of freedom and by utilising existing knowledge to specify and adapt existing components in a routine manner. It is important to emphasise this difference. To detailed model a

development process, which has a completely open solution space with high degrees of freedom, would have little value as the process might be significantly different for the next development project. Repeatability is a central criterion for creating value with the analysis at hand, and the authors believe that it is considered possible to model the products and processes in question as we are working within a closed world assumption, focusing on designing variants of existing products and not on developing new products.

Empirical Background

This article is based on empirical data collected in collaboration with MAN Diesel & Turbo. MAN Diesel & Turbo is a large international engineering company designing customer specific two-stroke diesel engines for large containerships. The company has no physical production but is only designing the products - a company form that is becoming increasingly more common in knowledge societies such as Denmark. They are the market leader within their industry and the primary strategic goal is to maintain this position. In order to fulfill this goal the company strives to win every order, even if it requires significant development and engineering work.

The marine industry is currently experiencing increasing demands concerning emission requirements set by the International Maritime Organization, IMO. IMO is a United Nations agency that sets international standards to regulate shipping (www.imo.org, 2012). Since the ratification of the IMO Tier III criteria for NO_x emission in Emission Controlled Areas (ECA's) from large marine diesel engines, the world's marine engine manufacturers have been challenged to develop new measures in order to reduce NO_x. The extent of the necessary measures for NO_x reduction up to 80% for meeting the IMO NO_x-criteria from January the 1st 2016, is beyond well known adjustments of the combustion process in two-stroke diesel engines (Kaltoft, 2012).

These new requirements comprise a considerable threat to the producers of marine diesel engines as only engine producers fulfilling these requirements are allowed to sell their products. If the producers do not have a viable solution ready for implementation in 2016 the consequence can be a substantial shift in the market share distribution.

MAN Diesel & Turbo are developing and testing several technologies to comply with the future emission requirements, among these Exhaust Gas Recirculation (EGR), which has focus in this study. The EGR-system principle is based on exchange of the in-cylinder oxygen (O₂) with carbon dioxide (CO₂) from the exhaust gas which is re-circulated into the scavenge air. This leads to a decrease of the combustion speed which then leads to lower peak temperatures during combustion. In addition, the increased amount of CO₂ and the decreased amount of O₂ in the scavenge air also leads to a slightly higher in-cylinder heat capacity of the gas which then leads to a lower combustion temperature. Lower combustion temperatures and especially lower peak temperature generate lower amounts of NO_x during the combustion process. The effect of EGR on smaller four-stroke diesel engines used in the automotive sector has been known since the

1970'ies as a very efficient means to reduce NO_x in combustion engines. However the technology has not been used on large two-stroke marine diesel engines (Kaltoft, 2011).

A main challenge for MAN Diesel & Turbo is of course to develop a technological solution that can reduce the emission. Another significant challenge is how to organise the work around designing this solution in full scale across the entire engine program as more than 50 people are expected to be involved in the process. Several initiatives have been initiated in order to anticipate these futures challenges. The work documented in this article is a part of these initiatives.

Research Objective

In order to obtain detailed insight into the engineering process dealing with design of EGR-systems it is our suggestion to model the product features used in the process and clarify in which steps of the specification process the specific product features are used.

The research questions for the project are:

- How to model the product and identify the relevant features?
- How to model the engineering process and the activities carried out within the process?
- How to operationally model products and process in an integrated way?
- How to apply the modelling technique in developing design processes in engineering companies?

The conviction is that in order to develop engineering processes it is necessary to visualise, characterise, model and understand both the product being designed as well as the processes undergone to design the product.

Research Methodology

As no structured approach for doing integrated modelling of product and process has been identified, the research at hand must be characterised as exploratory research, with focus on theory development rather than theory testing. The aim is to assess which existing theories and concepts can be applied to the problem or whether new ones should be developed (Karlsson, 2009). The study can furthermore be described as an inductive study in which theory is being developed from the observation of empirical reality (Collis & Hussey, 2003). It is also a preliminary study where the focus is on gaining insights and familiarity with the subject area for more rigorous investigations at a later stage.

The research has been carried out using qualitative methods. A number of design teams as well as R&D-personnel have participated in the development of the framework for improving the design processes. The methodology is therefore action research where the aim is to enter a situation (the design of new components for two-stroke marine diesel engines), attempt to bring about change and to monitor results (Collis & Hussey, 2003). The scope has not just been to

observe what is happening but actually participate in solving a managerial problem while attempting to contribute to existing body of theory, which also characterises Action Research (Coughlan & Coughlan, 2002).

The main source of data is interviews with the designers who have provided insight into both processes and products. Additional product and process information has been found in information systems within the company.

Analysis

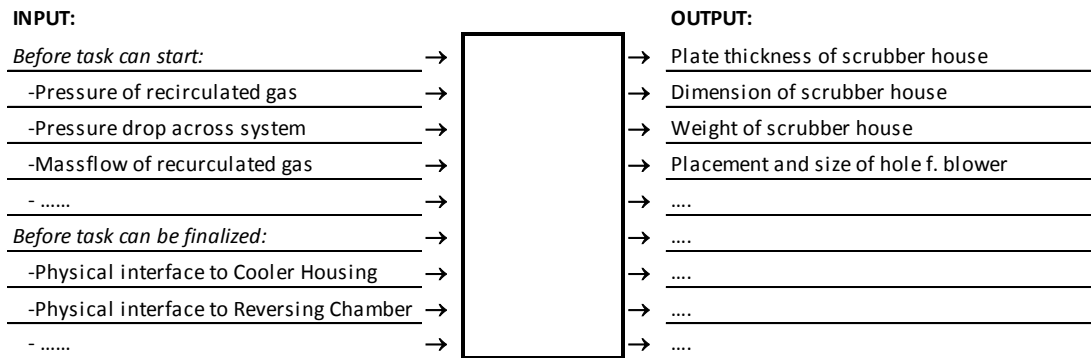
As initially stated MAN Diesel & Turbo has developed the technology needed to comply with IMO's new emission regulations. However, so far it is only in prototype versions for a limited segment of the product range. When the regulations become effective in 2016, marine diesel engines in all sizes will be required for the market. The task is therefore now to model and eventually develop the engineering processes for specifying the Exhaust Gas Recirculation systems across the entire product range.

A central hypothesis in the research at hand is that in order to understand and develop engineering processes it is necessary to understand the product being engineered. Therefore the first step is to make a product model of the EGR-system using the PVM-method.

It quickly became evident that complexity is a central issue to deal with when modelling the product. The EGR-system alone without the interfacing components consists of more than 500 drawings and specifications. To assess the potential process implications of each of these parts will be very time consuming and only add limited value. It is therefore crucial to identify the relevant product features that are decisive for the engineering process. This is done through interviews with product experts.

The next step is then to identify the central engineering activities through which specification of the product takes place. Trivial and simple administrative activities that are not time consuming should be noted in the process mapping but not analysed further. Focus should be on complex engineering activities where the crucial product features determined in the PVM are specified. Exactly these activities are often complex tasks carried out by product experts. Due to this fact, such tasks often end up as a 'black boxes' in a process map, as no known existing modelling techniques are able to deal with and express this complexity in a suitable way. By clarifying which product features and specifications are used as well as produced, the content of the task becomes more transparent. This allows for a characterisation and assessment of the engineering work carried out within the task. It also enables identification of task interdependencies caused by product features that are decisive for several activities within the overall specification process. In order to represent this knowledge in a formalised manner we have developed the Task Clarification Card, see Figure 2.

Process step name: Design Scrubber Housing	Date: DD.MM.YYYY	Author: Dr. Hansen	Step no. 7
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SUB TASKS:

Process Sub Step Name	Sub Step No.
Spec. of sight glass	7.1
.....

MECHANISMS:

IT Systems: CAD system

Databases: PLM system (older drawings)

Competencies: 3D modelling, Statics

INTERFACES:

Part	Feature	Step
EGR-Cooler Housing	Dimensions of housing	4
Reversing Chamber	Dimensions	11
.....

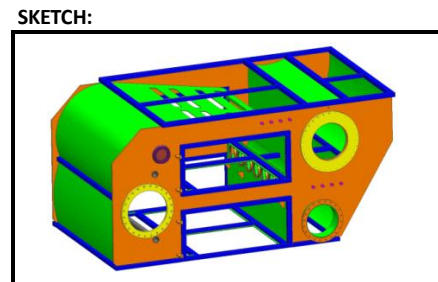


Figure 2: The Task Clarification Card

In the Task Clarification Card input and output features and specifications of the activity are identified. Inputs can with advantage be grouped into inputs needed before task can start and inputs needed before task can be finalised. This allows performing certain tasks in parallel rather in sequence, which obviously reduces lead time. Some tasks are more complex than others if several specifications are to be produced. Therefore it can be advantageous to split the task into several sub tasks with corresponding Task Clarification Cards. The ‘Mechanisms’-paragraph supports characterisation of the engineering task, by clarifying with competencies are needed to complete the task as well as which IT-systems and databases should be used. In the lower left corner interfacing components are listed with cross references to which product features are critical for ensuring valid interface. The step numbers for the design of the interfacing components are also stated. Finally a sketch of the component in question is included. It can be convenient to include a sketch when working with product descriptions. Geometric relationships are usually easier to explain using a sketch rather than words.

The strength of the Task Clarification Card is that it provides significant insight into the single activity. It shows what is needed to carry out the activity, what is produced, what sub tasks it consists of, competencies needed, interfacing components etc. However it does not clearly identify the dependencies of the product features across engineering tasks in the overall specification process. In order to identify task interdependencies caused by product features that are used in several process steps the PVM is again brought into play in a revised version designated as the Cross Referenced PVM, see Figure 3.

	Used in Step:	
	Input	Output
EGR-system		
Performance Specification Performance requirements for overall system		
• Massflow of recirculated gas	5,6, 7	2
• Pressure of recirculated gas	3,5, 7	2
• Pressure drop across system	4,6, 7	2, 5
• Temperature of recirculated gas		2
•		
EGR-Cooler For cooling of the EGR-gas		
• Dimensions of housing	7	4
•		
Pre Scrubber For removal of SO ₂ in the exhaust gas		
•		

Scrubber Housing Contains the Scrubber Unit		
• Plate thickness of scrubber house		7
• Dimensions of scrubber house		7
• Weight of scrubber house		7
•		
•		
Water Treatment System For cleaning the scrubber water in the system.		
•		

Figure 3: The Cross Referenced PVM

Every time a product feature appears as an input or output in the Task Clarification Cards, it is noted in the Cross Referenced PVM next to the product features in designated input and output-columns. The information in the Task Clarification Card presented in Figure 2 is noted with red numbers. These cross-references between the PVM and process steps provide valuable information on how to organise the sequence of the engineering tasks. An important observation

to make is the relation between the step number references in the input and output columns for every product feature. If the latest process step in which the output is potentially changed is after any of the input process steps, there will be a risk of either engineers having to redo certain tasks or even ending up with a faulty final specification. Consider the product feature 'Pressure drop across system'. The Cross Referenced PVM identifies the feature as an input in step 4, 6 and 7 while the feature might change due to the engineering activities carried out in step 2 and 5. If the value of the feature is affected by the activity in step 5, then step 4 will be based on an incorrect pressure drop making the outputs of step 4 potentially erroneous. This calls for activity 5 being carried out earlier in the process or in other ways making sure that changes will not affect subsequent activities.

Thus, by making use of the cross-references it becomes possible to resequence engineering tasks in order to facilitate a more optimal project flow and thereby promote increased efficiency, reduced lead time, improved ability to deliver on-time and improved quality of the engineering work carried out.

Results

The main result of this article is a formalised tool for operational modelling of product and process in an integrated manner. Task Clarification Cards are used for identifying what product features are used and produced in every significant engineering task. They also support a characterisation of the activities carried out during the specification process allowing for a deeper understanding of what competencies and tools are needed, as well as which sub activities comprise the overall design task. The Cross Referenced PVM is subsequently used for compiling the information on the significance of every product feature throughout the complete specification process, providing insights into how the engineering tasks can be restructured in a more optimal way.

However complexity is a critical issue that needs to be dealt with when performing integrated modelling of product and process. This especially becomes evident when considering complex engineering products such as marine diesel engines. It is therefore crucial to focus on the product features that are decisive for the engineering process. These have to be identified through interviews with the product experts who possess a thorough understanding of the complexity of the product.

The authors believe that it is relevant to address modelling of engineering processes as companies making customer specific products face a significant challenge in setting up efficient business processes for specifying the products and ensuring products being delivered on time and in high quality. The belief is that the tools presented in this article will support managers when they are to develop these processes. However the tools are not fully developed and further studies need to be carried out.

Within MAN Diesel & Turbo the Task Clarification Cards and the Cross Referenced PVM will be used for getting a deeper understanding of the process dependencies that exist between the engineering tasks required for designing the EGR-systems. Also the Task Clarification Cards will be considered as design manuals which can clearly communicate what needs to be done in every engineering task. This will be beneficial in terms of knowledge sharing and also when new employees are to be trained.

To the knowledge of the authors no current methods for redesigning and developing engineering processes do take into account the product features to be used in every process step. We therefore believe that our research on this matter could provide a contribution to process development theories. Generating theory through action research is situation specific and incremental (Coughlan & Coughlan, 2002). This is also the case with the research at hand. However the belief is that a significant step from particular to general can be taken with this research, as the case company represents a typical engineering company. The authors therefore believe that the suggested modelling technique can support the development of engineering processes in many companies, and we will continue our efforts on this matter in the years to come.

Further research

Our studies have revealed a need for controlling the complexity that appears when modelling complex products. It has become evident that it is challenging to find the right level of detail. If too little detail is included we might miss critical process dependencies caused by certain product features. However, if too much detail is included, the modelling task will explode and carrying out the analysis will require disproportionate large resources reducing the value of the analysis. We will therefore put focus on how to address the proper level of detail and also formulate some generic criteria for when the modelling technique is suitable. If both the process and the product are very complex and the amount of cross references are substantial, it might be desirable to come up with a computational tool that can aid in revealing potential adverse dependencies, like it is done when applying the DSM-method.

In this article the modelling technique has been applied for supporting the development of new engineering processes. However the authors believe that the method will also be valuable for diagnosing existing processes. By mapping an ongoing processes and integrating the findings with a Cross Referenced PVM, inexpediencies in terms of e.g. non value adding waiting time, loops and rework of specifications could be revealed and addressed. Studies on this matter are expected to be carried out in the fall of 2012.

References

Collis, J. and Hussey, R. (2003), *Business Research. A practical guide for undergraduate and*

- postgraduate students*. 2nd edition. Palgrave Macmillan, New York.
- Coughlan, P. and Coghlan, D. (2002), "Action Research for Operations Management", *International Journal of Operations & Production Management*, vol. 22, no. 2, pp. 220-240.
- Eppinger, S. D., Whitney, D. E., Smith, R. P. and Gebala, D. A. (1994), "A model-based method for organizing tasks in product development", *Research in Engineering Design*, vol. 5, pp. 1-13.
- Eckert, C. and Clarkson, J. (2005), "The reality of design", in Eckert, C. and Clarkson, J. (Ed.), *Design Process Improvement – A review of current practice*, Springer-Verlag, London, pp. 1-29.
- Fixson, S. K. (2004), "Product architecture assessment: a tool to link product, process, and supply chain design decisions", *Journal of Operations Management*, vol. 23, pp. 345-369.
- Hvam, L., Mortensen, N. H. and Riis, J. (2008), *Product customization*, Springer-Verlag, Berlin Heidelberg.
- Harlou, U. (2006), *Developing product families base on architectures - Contribution to a theory of product families*, Dissertation, MEK, Technical University of Denmark.
- Kaltoft, J. (2011), "Tier III EGR for large 2-stroke MAN B&W diesel engines", Proceedings of the International Symposium on Marine Engineering (ISME) October 17-21, 2011, Kobe, Japan Summary or Paper-ISME586.
- Karlsson, C. (2009), "Researching Operations Management", in Karlsson, C. (Ed.), *Researching Operations Management*, Routledge, New York and London.
- O'Donovan, B., Eckert, C., Clarkson, J. and Browning, T. R. (2005), "Design planning and modelling", in Eckert, C. and Clarkson, J. (Ed.), *Design Process Improvement – A review of current practice*, Springer-Verlag, London, pp. 1-29.
- Prevention of Air Pollution from Ships: IMO.org. (2011). Retrieved April 27, 2012, from IMO website: www.imo.org/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Air-Pollution.aspx
- Steward, D. V. (1981), "The design structure matrix: a method for managing the design of complex systems", *IEEE Transactions on Engineering Management*, vol. EM-28, no. 3, pp.71-74.
- Schwarze, S. (1996), *Configuration of multiple-variant products*, Dissertation, Swiss Federal Institute of Technology Zürich, Zürich.
- White, S.A. (2004), *Introduction to BPMN*, IBM Cooperation, BP Trends.

PAPER 2 - INCLUDING PRODUCT FEATURES IN THE DEVELOPMENT OF ENGINEERING DESIGN PROCESSES

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Including Product Features in the Development of Engineering Design Processes

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Abstract

Engineering companies offering customised products face growing demands to design products faster and more efficiently. To meet these demands, efficient engineering design processes for specifying customised products need to be in place. A new engineering design methodology currently under development, called Integrated Product and Process Modelling (IPPM), analyses process and product models simultaneously in order to improve engineering design processes. The method provides detailed insight into the activities within an engineering design process by modelling the product features used in the engineering design process and by clarifying in which process step the specific product features are used. The insight gained by the IPPM-method can then be utilized to improve the engineering design process and identify inefficient elements that can be improved within the process flow. The methodology have been tested and further developed in an action research study carried out in collaboration with a major international engineering company.

Keywords: Engineering Design Processes, Product Modelling, Integrated Modelling of Product and Process

Introduction

In today's working environment most engineering companies face rapid technological developments and strong competition due to the growing international markets and increasing customer demand. The reality of this new working environment is the need to have efficient engineering design processes in place, so companies can design customised products faster and more efficiently.

Creating or re-engineering complex engineering design processes is however not an easy and straightforward task. Most process modelling approaches today are too general in scope and prescriptive in nature for easy application (Eckert & Clarkson, 2005). The reason for this may lie in the fact that the scope of design is vast and engineers design everything from screwdrivers to aircrafts (Ulrich & Eppinger, 2003). Only at a very abstract level can the design process of such different products be the same. Therefore, design methodology typically has looked at what is general in design processes, ignoring factors such as how the product itself affects the process. And without understanding the link between the engineering design process and the product being engineered it becomes very difficult to understand and address the complexity inherent in the processes. According to Eckert & Clarkson (2005), there is little theoretical understanding of how products affect the processes by which they are designed and vice versa.

The contribution of this paper is a new engineering design methodology, called Integrated Product and Process Modelling (IPPM). The methodology aims at analysing engineering design processes and product models simultaneously in order to create or improve engineering design processes. The method provides detailed insight into the activities within an engineering design process by modelling the product features used in the process and by clarifying in which process step the specific product features are used. The insight gained by the IPPM-method can then be utilized to sequence the process steps and identify inefficient elements that can be improved within the process flow.

Theoretical Background

The research at hand is rooted in the engineering design literature and on engineering change in particular. The suggested modelling technique furthermore draws on theory on product modelling including the Product Variant Master method for modelling product families (Hvam et al., 2008). Also several process mapping theories are included.

Engineering Change

Academic design literature such as (Pahl & Bietz, 1996) has traditionally had a strong focus on the development of new products. The modification of existing products has however been given an increased focus during recent years especially by (Jarratt et al. 2011), and the significance of engineering change has eventually been quite recognised. This research continues down the path focusing on the challenges associated with developing the engineering change processes creating

variants of existing products. (Jarratt et al. 2011) defines engineering change as alterations made to parts, drawings or software that has already been released during the product design process. A change may encompass any modifications to the form, fit and/or function of the product as a whole or in a part, and may alter the interactions and dependencies of the constituent elements of the product.

Product Modelling

Many companies often face significant challenges when trying to get an overview of their entire product portfolio. Using product modelling techniques can be a mean to acquire this overview. By modelling your product range you will achieve a better understanding of the product portfolio and be able to control the complexity that exists within it. But to do so you need a tool, such as the Product Variant Master, that can describe the complete product assortment in an efficient manner to all stakeholders (Hvam et al., 2008). The Product Variant Master (PVM) is a tool for modelling and visualising product families. It provides an overview of the product range offered by a company and illustrate how the products can vary. The tool has its basis in object oriented modelling, and simply put, it can be said that a PVM contains a description of the company's product range and the associated knowledge (Harlou, 2006).

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Several tools for modelling processes have been developed in the course of time. The most well known tool for mapping processes is probably the Business Process Modelling Notation, BPMN. BPMN is a flowchart tool used to create graphical models of business processes. By using the tool you can create models that clarify which activities are performed by whom within the company. Furthermore it clarifies which communication is occurring between different departments and external stakeholders (White, 2004). The notation form is quite straightforward and easy to put into use which makes it a popular choice.

Another modelling approach applied in this study is the Design Structure Matrix, DSM. This tool is especially suitable for engineering design projects, which involves specification of many interdependent variables which together define a product, how it is made and how it behaves (Steward, 1981). The DSM is a matrix structure representation that captures the sequence and the technical relationships among different design tasks in a project. By using the modelling technique it becomes possible to find alternative sequences of the tasks and streamline the inter-task coordination (Eppinger et al., 1994).

Empirical Background

This article is based on empirical data collected in collaboration with MAN Diesel & Turbo. MAN Diesel & Turbo is a large international engineering company designing customer specific two-stroke marine diesel engines. The company has no physical production but is only designing the products.

The unit of analysis in this article is a subset of the order process within the company. Based on an order from a customer it is analysed how a specific engineering department designs a solution fulfilling the customer request.

The company is using a modular based product platform, which allows for reuse of modules across specific orders. Thus when complying with a unique customer request, it doesn't necessarily mean that all modules are new. A manual configuration process is taking place every time an order is placed. During this configuration it is identified which modules can be reused and which that has to be designed in accordance with the customer requests. For every missing module an engineering task is created, delegated and a deadline for the task is set. Different modules are mutually interdependent but there is currently no clear mapping of these interdependencies.

Recently the department in question has experienced increasing lead time and efficiency problems due to lack of overview over these dependencies. Too often bottlenecks are identified which are caused by dependencies not taken into account when internal deadlines are set for the different engineering tasks. The empirical objective for this study has therefore been to map these interdependencies so they can be taken into account when setting deadlines for the engineering tasks.

Research Objective

In order to obtain detailed insight into the engineering design process dealing with design of new modules it is our suggestion to model the product features used in the process and clarify in which steps of the engineering design process the specific product features are used.

The research questions for the project are:

- How to operationally model the product and identify the relevant features?
- How to model the engineering design process and the activities carried out within the process?
- How to operationally model products and processes in an integrated way?
- How to apply the modelling technique in developing design processes in an engineering company?

Research Methodology

As no structured approach for doing integrated modelling of product and process has been identified, the research at hand must be characterised as exploratory research, with focus on theory development rather than theory testing. The aim is to assess which existing theories and concepts can be applied to the problem or whether new ones should be developed. It is a preliminary study where the focus is on gaining insights and familiarity with the subject area for more rigorous investigations at a later stage.

The research has been carried out using qualitative methods. A department with 10 designers as well as their group leader have participated in the development of the framework for improving the engineering design processes. The methodology is therefore action research where the aim is to enter a situation (the design of new modules for two-stroke marine diesel engines), attempt to bring about change and to monitor results. The scope has not just been to observe what is happening but actually participate in solving a managerial problem while attempting to contribute to existing body of theory, which also characterises action research (Coughlan & Coughlan, 2002).

The main source of data is semi-structured interviews with the designers who have provided insight into both processes and products. Additional product and process information has been found in information systems within the company.

The research is a single case study, which can affect the validity, reliability and generalising potential of the study. Context-dependent knowledge gives this type of science a basic limitation when generalising the conclusions made on the basis of a single experiment. However (Gummesson, 1991) contends it is possible to generalise from a very few cases, or even a single case, if the analysis has captured the characteristics of the phenomena being studied.

The authors have had free access to information and personnel within the company allowing an in depth analyses. The validity, which concerns the extent to which the research findings accurately represent what is really happening, is therefore assessed to be high. The reliability concerning whether anyone would get the same results as you if they were to repeat the research, might be more questionable. The authors do however believe that the case company represents a typical engineering company designing customer specific products, supporting the reliability of the findings. It is nevertheless clear that it is a limitation that only data for one company has been analysed. In order to generically test the hypothesis, similar analysis should be carried out in other companies.

Research Framework

The underlying proposition of the method introduced in this paper is that in order to understand an engineering design process it is necessary to understand the product being engineered. By recognising what product features are used, defined and modified in every process step, better understanding of the engineering activities will be acquired, which can then be utilized to improve the process. In this study, the product features stated on the product model and the tasks in the engineering design process model are analysed simultaneously. This is done by linking together the product model and process model, thereby revealing where and how specific product features are used in the process flow. Utilizing this insight will allow us to improve the project flow leading to significant advances such as: increased efficiency, reduced lead time, improved ability to deliver on-time and improved quality of the engineering work. A 5-step procedure for

developing engineering design processes through integrated modelling of product and process is proposed, see Figure 1.

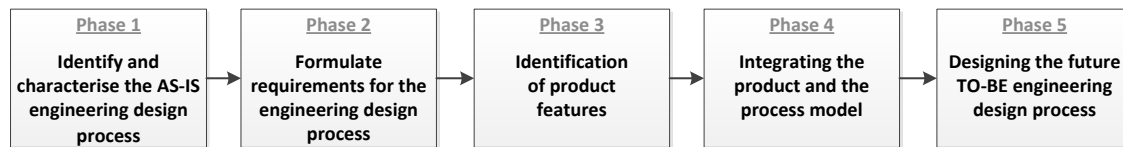


Figure 1: Phases for Developing Engineering Design Processes

Phase 1 – Identify & Characterise AS-IS

When dealing with existing engineering design processes the first step is to map out the AS-IS process and identify the process steps where product information is being processed and specifications are produced. This can be done using numerous process mapping tools. Basically we needed a tool that could easily help us identify all actors involved in the process and allow a straightforward mapping of activities and the sequence in which the activities were carried out. In this study we therefore chose the Business Process Modelling Notation as it is deemed suitable for the task at hand. As the designers involved in the process assisted in mapping the process, it proved valuable that the mapping technique was easy comprehensible and well-known to most involved people.

The purpose of phase 1 is to get an overview of the process. The activities within the process will be analysed further in phase 3. Process steps that are identified as tasks where product features are specified are highlighted as they are of particular interest.

After having mapped the existing process it can be assessed by identifying the most critical problems associated with the process. This will provide insight into which problems need to be addressed in the development of a new and improved process. Examples of problems could be too many transfers of responsibility, too many loops etc.

Phase 2 – Requirements for New Process

After having identified and characterised the existing engineering design process, the next step is to make clear what requirements are to be placed on the process. (Hvam et al., 2008) points out following targets as appropriate measures for a company's engineering design process:

- Lead time for producing specifications.
- On time delivery for specifications.
- Resource consumption for producing specifications.
- Quality of specifications.

When quantifiable targets have been set, then the next step is to carry out a series of measurements to determine the current level of performance. Then the current level of performance and the target goals can be compared and the largest gaps can be identified. This will indicate where the greatest potential for improving the engineering design process will be.

Phase 3 – Identify Product Features

Phases 3 to 5 are closely interconnected as these are the phases in which the actual integrated modelling of product and process takes place. Figure 2 illustrates how these are interrelated and will be used as reference for the rest of this chapter.

As stated earlier the basic proposition of this study is that it is necessary to understand the product being engineered in order to address the engineering design process. In phase 3 the first objective is therefore to construct a product model. In the study at hand the authors needed a structured approach for modelling and visualising a complete product range and which allowed for modelling of components and appurtenant attributes and features. The authors therefore applied the Product Variant Master as product modelling tool. Other tools could probably also have been applied, but the PVM-technique fulfilled the requirements and was therefore considered suitable.

The main focus of the product model is to document the structure of the product, see upper left side of Figure 2. Normally when applying the PVM-technique it is also part of the task to identify all features and constraints of the product. However this is neither necessary nor practical when modelling complicated products for the purpose of integrating the model with an engineering design process. Complicated products can consist of hundreds even thousands of product features. To assess the potential process implications of every product feature can therefore be very complex, time consuming and only add limited value. Earlier studies have confirmed this matter [Nielsen & Hvam, 2012]. It is therefore vital to identify the relevant product features that are decisive for the engineering design process and not waste time on less significant product features.

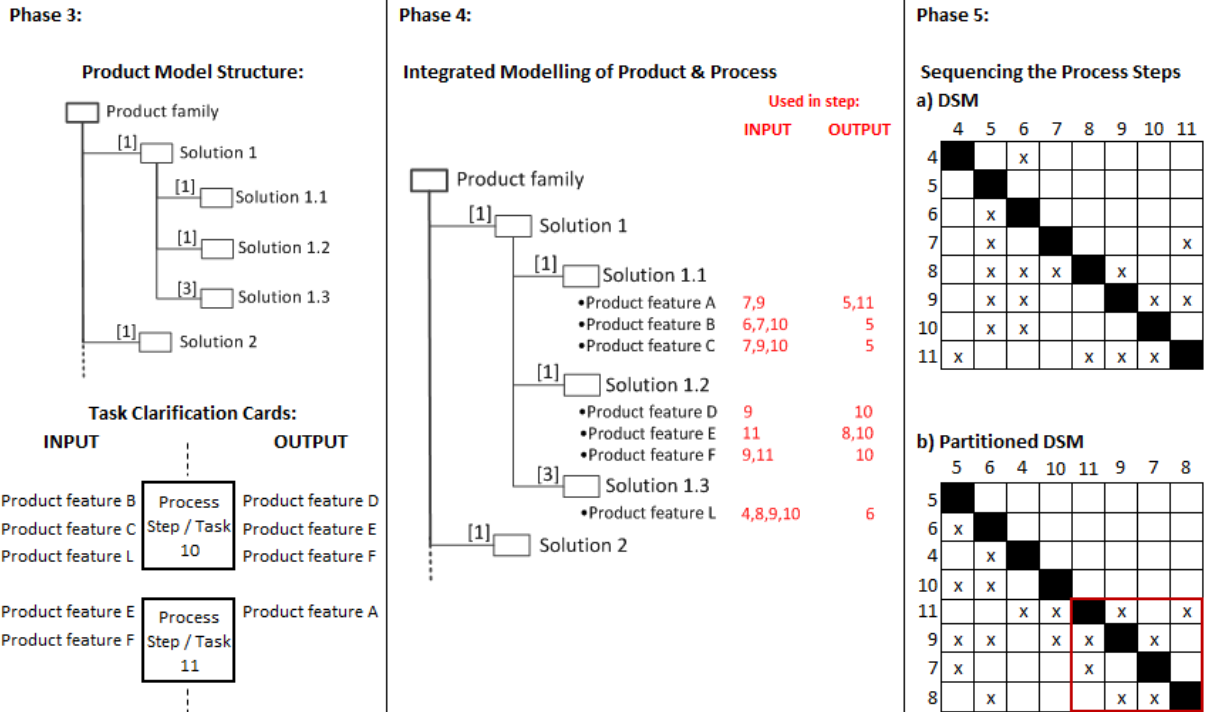


Figure 2: Phases 3 – 5

Identifying relevant product features is mainly done through interviews with product experts, as they are the most likely to be able to identify which product features are critical to the process. In order to support these interviews and document the knowledge provided by the designer we introduce the Task Clarification Card, TCC.

Basically the TCC is a formalised description of an engineering activity. It supports clarification of which product features are critical for an activity to be carried out as well as characterisation of the process steps and identification of task interdependencies. Engineering activities are often complex tasks that are carried out by product experts. Therefore, such activities end up as “black boxes” in a process map using known modelling techniques. Hence, the TCC was developed to provide significant insight into the single activity of a process step. The TCCs should only be made for process steps where engineering activities involving production of specifications take place. A template for a Task Clarification Card can be found in Figure 3.

Process step name:		Unique Identifier:	Author:	Date:
INPUTS:	SOURCE	<div style="border: 1px solid black; width: 60px; height: 80px; margin: 0 auto;"></div>	OUTPUTS:	
<i>Before task can start:</i>	→		→	_____
_____	→		→	_____
_____	→		→	_____
<i>Coordination needed:</i>	→		→	_____
_____	→		→	_____
_____	→		→	_____
_____	→		→	_____
_____	→		→	_____
_____	→		→	_____
SKETCH:		↑	MECHANISMS:	
			IT Systems:	_____
			Databases:	_____
			Competencies:	_____

Figure 3: Task Clarification Card

The TCCs are primarily used to describe the engineering task in terms of input and output product features with process significance. As part of the input declaration the source of the input is stated. The reasons for this will be elaborated below. The inputs are grouped into two. First product features that are needed before the task can start are stated. This means that the task acting as source and the task in question need to be performed in sequence with the source task first. The other inputs are product features that require some mutual coordination to other tasks. The tasks therefore need to be carried out in a coupled manner exchanging information. The TCCs also contain the name of the engineering task, a unique identification number together with a date and name of the person responsible for the card. In addition, a sketch and the mechanisms that are needed to carry out the task are given.

The idea is then to conduct interviews with the employees who perform tasks identified as having process implications in the AS-IS diagram from Phase 1. For each interview the scope is to fill in all the information except the output column. In stead, after having conducted all interviews, the output columns are filled out tracing back the stated inputs using the source information. This way only product features having an impact on the engineering design process are included, ensuring a suitable level of detail. This is done as earlier studies [Nielsen & Hvam, 2012] resulted in an information overload in the output columns of the Task Clarification Cards. Back then the designers stated every nut and bolt which they specified as outputs. However these had no significance for the engineering design process and only added unnecessary complexity to the modelling task.

Phase 4 – Integrating the Product and the Process Model

In phase 4 the integration of the product features and the process steps takes place. The scope is to clarify where all product features are defined or modified. This is done by cross referencing the product features on the TCCs with the PVM from phase 3. However, by using a PVM with the purpose of redesigning an engineering design process, some alterations are called for. Some

new features need to be incorporated to help fulfil its purpose. The PVM is therefore introduced in a revised version designated as the Cross Referenced PVM.

The Cross Referenced PVM is made by adding two columns to the PVM, an input and an output column. Then every time a product feature appears as an input or output on the TCCs, the unique identifier of the card is noted on the Cross Referenced PVM next to the appropriate product feature in the designated input and output column, see Figure 2. Consider for example process step (task) 10 to understand better the link between the three phases. Phase 3 on the left side of the figure shows that product features B, C and L are inputs for the process step 10 and product features D, E and F are outputs. In phase 4 (the middle part of the figure) the number ten has been placed in the designated input and output columns besides the appropriate product features in the Cross Referenced PVM. Now consider the product feature B in the Cross Referenced PVM. It here becomes evident that the specification of product feature B takes place in process step 5 and the specification is used to produce specifications in task 6, 7 and 10. These cross references between the PVM and process steps provide valuable information on how to organise the engineering tasks.

Phase 5 – Designing the TO-BE Engineering Design Process

The 5th and final phase is about designing the new improved engineering design process based on the insight acquired through the previous phases. The Cross Referenced PVM-tool introduced in phase 4 clearly displays the dependency relationships of the process steps. Nevertheless, engineering design processes are often very complex. Thus, the interdependencies in such processes are numerous and intertwined, making the job of reorganising the process steps in an optimal order too difficult without some kind of algorithm. The authors have chosen the Design Structure Matrix as a tool for dealing with this complexity. The DSM modelling method uses a simple algorithm to organise elements based on their relationship dependencies and it is an ideal modelling tool to utilize in conjunction with the Cross Referenced PVM-tool.

The information from the Cross Referenced PVM is therefore transferred to the DSM with the output columns controlling the columns in the matrix while the input columns control the rows. Consider product feature B again, see Figure 2. The specification of the feature takes place in step 5 and is used as input in steps 6, 7 and 10. Therefore ‘X’s are placed in the DSM in rows 6, 7 and 10 under column 5. When this is done for all input and output values for all product features the DSM is filled.

After the DSM is filled it is partitioned. The partitioning reveals the optimal sequence for the process steps based on minimising feedback loops in the process. Using the information displayed in a partitioned DSM, a new TO-BE process map can be configured.

In summary, the five phases will reveal a detailed understanding of the single activities in a process, which then can be utilized to reorganise the sequence of process steps in an engineering design process. By utilizing the insight gained by the IPPM, an engineering design process can

be redesigned leading to improvements in process efficiency, quality, lead time and on-time delivery.

Findings

The 5 phase-procedure proposed above has been applied within a design department in MAN Diesel & Turbo during the fall of 2012. The main objective was to develop the engineering design processes taking place every time an order was to be processed within the department in question. The department is not designing the full engine, but has the responsibility for approximately 100 modules within the overall product architecture. These modules differ significantly in size as well as the corresponding workload required for designing it.

Phase 1 – Identify & Characterise AS-IS

As mentioned earlier a manual configuration process is taking place every time an order is placed. Here it is identified which modules can be reused and which that has to be redesigned in order to comply with the customer requests. The configuration team afterwards informs the group leaders of the different design departments which modules they need to design. The group leader then creates a task per module and delegates the task after having set a deadline for it. Finally the designers carry out the tasks and then submit them to the configuration team who then forwards the drawings to the customer. Due to the customisation it differs which modules are to be designed for each engine order. Accordingly, it then also differs which designers will be given a task. Therefore it is not possible to map a detailed generic process flow as the actors involved changes from order to order. However a conceptual flow has been mapped in Figure 4. The process steps marked with red indicates the engineering tasks producing specifications.

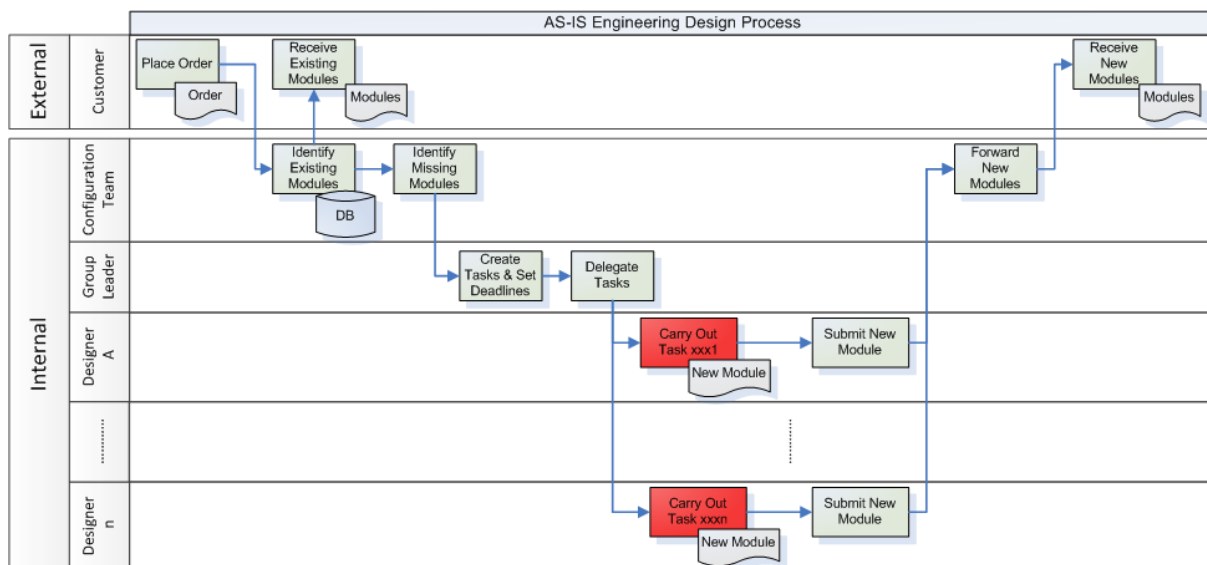


Figure 4: AS-IS Engineering Design Process

Phase 2 – Requirements for New Process

As stated, bottlenecks have been identified in the current engineering design process causing problems with delivery deadlines and lead times. These are therefore central targets that need to be improved. Due to the lack of overview of interdependencies between design tasks, design work occasionally has to be redone. This affects the resource consumption and potentially the quality of the design work. However, no structured measurement of performance has taken place. It has therefore not been possible to quantify the current level of performance. Phase 2 therefore focused primarily on determining more generic objectives for the future engineering design process, which are as follows:

- All specifications are to be delivered on time.
- No resources should be needed to redo engineering work.
- Lead time is obviously a problem since some specifications are not delivered on time.

These objectives are to be kept in mind when carrying out the remainder of the analysis. They can be considered as guidelines for how the future engineering design process should be designed. In order to obtain the full benefit of the procedure proposed, specific measurements should clearly be made.

Phase 3 – Identify Product Features

The main objective of phase 3 is to identify those product features that are decisive for the engineering design process. First a structural product model is constructed without including any product features. Instead Task Clarification Cards for the highlighted engineering tasks from Figure 4 are made based on interviews with product experts. In the specific case this means interviews with designers A to n concerning all tasks that they are responsible for. In order to create maximum value with the analysis TCCs are made for all highlighted engineering tasks and not only for tasks occurring in selected orders. Thereby a master mapping of all dependencies covering all potential order process flows regardless of customer requirements are included. Then when a specific order is placed only the dependencies for the tasks needed are included in the planning of the execution of the specific order.

In terms of data collection phase 3 turned out to be an iterative process. First the structural product model was determined in collaboration with the entire department ensuring that consensus existed on how the product is constructed. Then through interviews with the individual designers identified in the AS-IS process flow, inputs were added to the TCCs alongside with the output sources for those inputs. The sources were then confirmed through a second round of interviews.

With the PVM outlining the product being engineered and the TCCs describing the process steps producing product specifications, the integration of the product and process could now take place.

Phase 4 – Integrating the Product and the Process Model

Phase 4 started with the rather tedious task of compiling all information from the collected TCCs into the structural PVM thereby creating the Cross Referenced PVM. This is basically the integration of the process and the product model. A subset of the Cross Referenced PVM can be seen in Figure 5.

The product model from phase 3 has been extended in two ways. First the specifications with process implications are added in the appropriate places in the model. These are all specifications explicitly stated within the TCC's. Then cross references for the included specifications and the process steps in which they occur are stated with red writing on the right-hand side of the model.



Figure 5: Subset of Cross References PVM

Phase 5 – Designing the TO-BE Engineering Design Process

By integrating the information from the TCCs with the product model an understanding of the process implications of each product feature was achieved. This insight was used for redesigning the process. However the Product Variant Master modelling techniques is not suitable for handling extensive internal relations. Therefore the Design Structure Matrix is applied by feeding the information from the Cross Referenced PVM into the DSM. In the MAN Diesel & Turbo case this resulted in a large 70 x 70 master matrix containing all engineering tasks producing specifications. However when partitioned, the matrix revealed a substantial amount of interdependent coupled tasks. In order to maximise the value of the analysis an additional DSM on product feature level for the coupled tasks were made and partitioned. This revealed that a few critical specifications really caused the major clustering of the engineering tasks. The remaining issue is then how to create value utilizing this insight. The proposition is to have the group leader confer the two partitioned matrices before setting deadlines and distributing the engineering tasks.

Applying the 5-phase procedure proposed in this paper has allowed us to map the existing engineering design process within the specific design department in MAN Diesel & Turbo and identify the most critical problems. By carefully modelling both the product being engineered as

well as the engineering design process itself in an integrated manner, we achieved a detailed insight into how the different product features were decisive for the performance of the engineering design process. By compiling all of this information into first a Cross Referenced PVM and thereafter a DSM we have created a decision support tool which the group leader can apply when delegating tasks and setting deadlines. As the testing of the tool is still in its very initial phase, the effects can not yet be quantified. However the belief is that applying the tool will cause fewer bottlenecks in the engineering design process leading to lower lead times, improved ability to deliver on-time, fewer resources and higher quality of the engineering work carried out.

Discussion & Conclusion

As a main objective of this study is to develop engineering design processes one could question why not apply the DSM right away, saving us a lot of effort in making the product model and the Task Clarification Cards. The authors believe that it is not possible to fully comprehend the engineering design process without prior analyses of the product being engineered. The Product Variant Master modelling technique provides us with an easy applicable tool to thoroughly map a product's structure, attributes and behaviour. Using the PVM will help us identify what to actually add to the DSM. However the PVM-modelling technique has its limitations. When relations between the elements in the model increase in numbers, the PVM is inadequate in dealing with those relations. As this is where the DSM is particularly strong the authors recommend combining the strengths of the two modelling techniques as it is done in the 5-phase procedure introduced in this paper.

As one might question, the method introduced seems quite comprehensive and time-consuming. It is true that it requires a significant effort to make TCCs for every engineering design task being carried out. The compilation of the information from all cards also requires substantial work. However when the cards are made and the information is compiled the maintenance effort is quite manageable. The benefits will depend on the complexity and performance of the current processes. The more problems encountered the higher will the improvement potential be. As stated above it is not yet possible to quantify the benefits of applying the method as the testing of the tool is still in an initial phase.

The main contribution of the paper is a new engineering design methodology (IPPM) that aims at analysing engineering design processes and product models simultaneously in order to create or improve engineering design processes. It is believed that the IPPM-approach has potential to become an effective method to sequence and improve complex engineering design processes. It can create insight into the complex activities within a process that are usually unanalysed when using most known process modelling approaches. By utilizing the insight gained through the IPPM-approach, processes can be specifically configured to suit the product being engineered, thereby creating an optimal process flow for that specific product.

The 5-phase procedure presented is an operational tool for how engineering design processes can be developed in a structured and systematic way. By analysing the product and process models together it becomes possible to identify relationship dependencies between the tasks. Finally the procedure suggests using the Design Structure Matrix in conjunction with the tools provided by the IPPM- method. This will support sequencing and identifying whether process steps should be carried out in sequence, parallel and/or coupled together. Finally, the information gained from the applying the procedure can be utilized to create an improved TO-BE model of the engineering design process.

To the knowledge of the authors no current methods for redesigning and developing engineering design processes do explicitly take into account the product features to be used in every process step. We therefore believe that our research on this matter could provide a contribution to process development theories. Generating theory through action research is situation specific and incremental (Coughlan & Coughlan, 2002). This is also the case with the research at hand. However the belief is that a significant step from particular to general can be taken with this research, as the case company represents a typical engineering company. The authors therefore believe that the suggested modelling technique can support the development of engineering design processes in many companies.

References

- Coughlan, P. & Coughlan, D. (2002), "Action Research for Operations Management", *International Journal of Operations & Production Management*, vol. 22, no. 2, pp. 220-240.
- Eppinger, S. D., Whitney, D. E., Smith, R. P. & Gebala, D. A. (1994), "A model-based method for organizing tasks in product development", *Research in Engineering Design*, vol. 6, pp. 1-13.
- Eckert, C. & Clarkson, J. (2005), "The reality of design", in Eckert, C. and Clarkson, J. (Ed.), *Design Process Improvement – A review of current practice*, Springer-Verlag, London, pp. 1-29.
- Gummesson, E. (1991), *Qualitative Methods in Management Research*, Newbury Park, SAGE.
- Hvam, L., Mortensen, N. H. & Riis, J. (2008), *Product customization*, Springer-Verlag, Berlin.
- Harlou, U. (2006), *Developing product families based on architectures - Contribution to a theory of product families*, Dissertation, MEK, Technical University of Denmark.
- Jarratt, T., Eckert, C. & Clarkson, J. (2011), "Engineering Change: an overview and perspective on literature", *Research in Engineering Design*, vol. 22, pp. 103-124.
- Nielsen, J. B. & Hvam, L. (2012), "Developing Engineering Processes Through Integrated Modelling of Product and Process", *4th World Conference P&OM*, Amsterdam, 1-5 July 2012.

Pahl, G. & Bietz, W. (2007), *Engineering Design. A Systematic Approach*, 3rd Ed., Springer, London.

Steward, D. V. (1981), "The design structure matrix: a method for managing the design of complex systems", *IEEE Transactions on Engineering Management*, vol. EM-28, no. 3, pp.71-74.

Ulrich, K. T. & Eppinger, S. D. (2003), *Product Design and Development*, New York, McGraw-Hill.

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Assessing and Developing Engineering Design Processes

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Abstract

Engineering companies offering customised products face growing demands to design products faster and more efficiently. To meet these demands, efficient engineering design processes for specifying customised products need to be in place. A new engineering design methodology currently under development, called Integrated Product and Process Modelling (IPPM), analyses process and product models simultaneously in order to improve engineering design processes. The method provides detailed insight into the activities within an engineering design process by modelling the product features used in the process and by clarifying in which process step the specific product features are used. The insight gained by the IPPM-method can then be utilised to improve the process and identify inefficient elements that can be improved within the process flow. The methodology has been tested and further developed in an action research study carried out in collaboration with a major international engineering company.

Keywords: Engineering design, Engineering design processes, Product modelling, Process modelling, Complexity management, Integrated modelling of product and process, Knowledge management, Project management.

Introduction

In today's working environment most engineering companies face rapid technological developments and strong competition due to the growing international markets and increasing customer demand. The reality of this new working environment is the need to have efficient engineering design processes in place, so companies can design customised products faster and more efficiently. As engineering companies rely heavily on intellectual knowledge and human resources, the organisation of these key components is essential. The importance of addressing the engineering design processes within design companies has been given an increased attention in the recent years by authors such as (Jarratt et al. 2011) and (Veldman & Albas, 2012) to mention a few. This paper continues down that path.

Creating or re-engineering complex engineering design processes is not an easy and straightforward task. Most process modelling approaches today are too general in scope and prescriptive in nature for easy application (Eckert & Clarkson, 2005). The reason for this may lie in the fact that the scope of design is vast and engineers design everything from screwdrivers to aircrafts (Ulrich & Eppinger, 2003). Only at a very abstract level can the engineering design process of such different products be the same. Therefore, design methodology typically has looked at what is general in engineering design processes, ignoring factors such as how the product itself affects the process. And without understanding the link between the engineering design process and the product being engineered it becomes very difficult to understand and address the complexity inherent in engineering design processes. According to (Eckert & Clarkson, 2005), there is little theoretical understanding of how products affect the processes by which they are designed and vice versa. Furthermore it is not uncommon that companies with great confidence in their technical abilities are dismissive of their understanding of design processes. The companies can be world leaders in their respective technologies, yet they may not fully understand the process through which they generate their products, (Eckert & Clarkson, 2005). The potential benefits of understanding the relationship between product and process have been acknowledged by other scholars such as (Fixson, 2004) and (Albers & Braun, 2011), but to the knowledge of the authors no structured approach is explicitly aimed at understanding this link between the product and the process.

The authors therefore propose a new engineering design methodology, called Integrated Product and Process Modelling (IPPM). The methodology aims at analysing process and product models simultaneously in order to improve engineering design processes. The method provides detailed insight into the activities within an engineering design process by modelling the product features used in the process and by clarifying in which process step the specific product features are used. The insight gained by the IPPM-method can then be utilised to redesign the engineering design process in order to reduce lead time, improve quality, increase efficiency and improve ability to deliver on time.

The methodology has been tested and further developed within MAN Diesel & Turbo, which is a large international engineering company designing, among other things, customer specific two-stroke marine diesel engines.

Theoretical Background

The research at hand is rooted in the engineering design literature. The suggested modelling technique furthermore draws on theory on product modelling including the Product Variant Master method for modelling product families (Hvam et al., 2008). Also several process mapping theories are included.

Engineering Design

The concept of engineering design is rooted within product development. Product development can be described as the set of activities beginning with the perception of a market opportunity and ending in the production, sale and delivery of a product. The role of engineering design is then to define the physical form of the product to best meet customer needs (Ulrich & Eppinger, 2003). Engineering design is about applying scientific and engineering knowledge to the solution of a technical problem in form of a new product (Pahl et al., 2007).

Designing basically involves people, in form of a design team, with the appropriate expertise. They are then undertaking a process, which can be described as a sequence of activities arranged into phases and steps, to define a product (Eckert & Clarkson, 2005). For the members of the design team, it is knowledge that links everything together and enables them to take the actions and to make the decisions that direct the process and determine its outcome (Pahl et al., 2007).

Taking the above into consideration, engineering design processes can therefore be characterised as knowledge-intensive activities. Each step in the process involves members of the design team identifying the knowledge that defines a particular sub-task and then using their expertise to process that knowledge into a state that defines the selected sub-solution (Eckert & Clarkson, 2005). Engineering design processes are thereby significantly different from business administration processes. Where business administration processes are usually simple, well-defined and repetitive, engineering design processes are characterised by being ill-defined, iterative and complex (Maier & Störrle, 2011).

Academic design literature such as (Pahl et al., 2007) and (Ulrich & Eppinger, 2003) has traditionally had a strong focus on the development of new products. The modification of existing products has however been given an increased focus during recent years by (Jarratt et al. 2011), (Veldman & Alblas, 2012) and (Pasqual & de Weck, 2012) to mention some, and the significance of engineering change has eventually been quite recognised. This research continues down the path focusing on the challenges associated with developing the engineering design processes creating variants of existing products. (Jarratt et al. 2011) defines engineering change

as alterations made to parts, drawings or software that has already been released during the product design process. A change may encompass any modifications to the form, fit and/or function of the product as a whole or in a part, and may alter the interactions and dependencies of the constituent elements of the product.

It is important to acknowledge this difference between designing entirely new product and designing variants of existing products. Schwarze (1996) also describes this by distinguishing between the specification process and the development process of a product. A product development process is about generating knowledge and designing new components in a creative process. The specification process however is characterised by having low degrees of freedom and by utilising existing knowledge to specify and adapt existing components in a more routine manner. To detailed model a development process, which has a completely open solution space with high degrees of freedom, would have little value as the process might be significantly different for the next development project. Repeatability is a central criterion for creating value with the analysis at hand, and the authors believe that it is considered possible to model the products and processes in question as we are working within a closed world assumption, focusing on designing variants of existing products and not on developing new products.

Product Modelling

Many companies often face significant challenges when trying to get an overview of their entire product portfolio. Using product modelling techniques can be a mean to acquire this overview. By modelling your product range you will achieve a better understanding of the product portfolio and be able to control the complexity that exists within it. In general, product modelling can be interpreted as the logical accumulation of all relevant information concerning a given product range. But to do so you need a tool, such as the Product Variant Master, that can describe the complete product assortment in an efficient manner to all stakeholders. The Product Variant Master (PVM) modelling technique is a tool for modelling and visualising product families (Hvam, 2001) and (Hvam & Jensen, 2007). It provides an overview of the product range offered by a company and illustrate how the products can vary. The tool has its basis in object oriented modelling, and simply put, it can be said that a PVM contains a description of the company's product range and the associated knowledge (Harlou, 2006).

A PVM consists of two parts. The left hand side of the model describes the product's generic structure, and is called the 'part-of'-structure. It contains the modules, components and parts, generally referred to as classes, which appear in the entire product family. These classes are then modelled with a series of attributes and constraints which describe their properties as well as rules for how classes can be combined and how attributes are related. The right hand side of the PVM, called the 'kind-of'-structure, describes how the individual modules and parts can appear in several variants.

In this study we will solely apply the ‘part-of’-structure of the modelling technique as we are focused on how the product is constructed rather than how it varies. Further information on the PVM-method can be found in (Harlou, 2006) and (Hvam et al. 2005).

Process Modelling

Several tools for modelling processes have been developed in the course of time. The most well known tool for mapping processes is probably the Business Process Modelling Notation, BPMN. BPMN is a flowchart tool used to create graphical models of business processes. By using the tool you can create models that clarify which activities are performed by whom within the company. Furthermore it clarifies which communication is occurring between different departments and external stakeholders (White, 2004). The notation form is quite straightforward and easy to put into use which makes it a popular choice.

Another modelling approach applied in this study is the Design Structure Matrix, DSM (Steward, 1981). The DSM-modelling technique has a wide field of application as it is used for developing product, process and organisation architectures (Eppinger & Browning, 2012). In our research the DSM is applied for assessing the process architecture of the engineering design processes. The tool is especially suitable for engineering design projects, which involves specification of many interdependent variables which together define a product. The DSM is a matrix structure representation that captures the sequence and the technical relationships among different design tasks in a project. By using the modelling technique it becomes possible to find alternative sequences of the tasks and streamline the inter-task coordination (Eppinger et al., 1994). The relationships between the tasks are divided into dependent, independent and interdependent. The dependent relationships have to be performed sequentially, the independent can be performed in parallel whereas interdependent activities have to be coupled. A central strength of DSM is that it provides a concise visual format for representing processes. It becomes apparent how the individual activities affect the overall process and which activities that may trigger rework (O’Donovan, 2005). The DSM is well established and widely applied within the field of product development and engineering design, and is frequently referred to be academics such as (Li, 2010) and (Bilalis & Maravelakis, 2006).

Empirical Background

This article is based on empirical data collected in collaboration with the Low Speed business unit of MAN Diesel & Turbo. MAN Diesel & Turbo is a large international engineering company designing, among other things, customer specific two-stroke marine diesel engines. The Low Speed business unit has no physical production but is only developing and designing the products.

The unit of analysis in this article is a subset of the order process within the company. Based on an order from a customer it is analysed how a specific engineering department designs a solution fulfilling the customer request.

The company is using a modular based product platform, which allows for reuse of modules across specific orders. Thus when complying with a unique customer request, it doesn't necessarily mean that all modules are new. A manual configuration process is taking place every time an order is placed. During this configuration it is identified which modules can be reused and which have to be designed in accordance with the customer requests for the specific order. For every missing module an engineering design task is created, delegated and a deadline for the task is set. It has to be stressed that the orders considered are requests for customised variants of already existing products, and not requests for entirely new engine types. It is therefore the variant specification processes that are considered rather than the product development process which is far more comprehensive and complicated. Different modules are mutually interdependent but there is currently no clear mapping of these interdependencies.

Recently the department in question has experienced increasing lead time and efficiency problems due to lack of overview over these dependencies. Too often bottlenecks are identified which are caused by dependencies not taken into account when internal deadlines are set for the different engineering design tasks. The empirical objective for this study has therefore been to identify and map these interdependencies so they can be taken into account when setting deadlines for the engineering design tasks.

Research Objective

In order to obtain detailed insight into the engineering design process dealing with design of new modules it is our suggestion to model the product features used in the process and clarify in which steps of the engineering design process the specific product features are used.

The research questions for the project are:

- How to operationally model the product and identify the relevant features?
- How to model the engineering design process and the activities carried out within the process?
- How to operationally model products and processes in an integrated way?
- How to apply the modelling technique in developing engineering design processes in an engineering company?

Research Methodology

As no structured approach for doing integrated modelling of product and process has been identified, the research at hand must be characterised as exploratory research, with focus on theory development rather than theory testing. The aim is to assess which existing theories and concepts can be applied to the problem or whether new ones should be developed (Karlsson,

2009). It is a preliminary study where the focus is on gaining insights and familiarity with the subject area for more rigorous investigations at a later stage.

The research has been carried out using qualitative methods. A department with 10 designers as well as their group leader have participated in the development of the framework for improving the design processes. The methodology applied is action research where the aim is to enter a situation (the design of new modules for two-stroke marine diesel engines), attempt to bring about change and to monitor results (Collis & Hussey, 2003). The scope has not just been to observe what is happening but actually participate in solving a managerial problem while attempting to contribute to existing body of theory, which also characterises action research (Coughlan & Coughlan, 2002). A basic idea of action research is to experiment in the field rather than in a laboratory, which makes it well suited to work with practitioners and managers in large organisations. Action research is at one and the same time the investigation of action, implementation of investigation through action and the transformation of research into action, and is frequently used in intraorganisational problems (Kagan, Burton & Siddiquee, 2008).

The main source of data is semi-structured interviews with the designers who have provided insight into both processes and products. Additional product and process information has been found in information systems within the company.

Research Framework

The underlying proposition of the method introduced in this paper is that in order to understand an engineering design process it is necessary to understand the product being engineered. By recognising what product features are used, defined and modified in every process step, better understanding of the engineering activities will be acquired, which can then be utilised to improve the process. A product model containing relevant product features as well as the tasks in the engineering design process model will therefore be analysed simultaneously. This is done by linking together the product model and the process model, thereby revealing where and how specific product features are used in the process flow. This will allow us to improve the project flow leading to significant advances such as increased efficiency, reduced lead time, improved ability to deliver on-time and improved quality of the engineering work.

More detailed the IPPM-method can lead to an improved process flow by six means:

- By identifying when product information (parameters or product features) is entered into a process, i.e. in what process step information is defined and later modified. Knowing when information is defined and altered, the relationship of the process steps becomes clear. Then process steps can be organised so they can be carried out in sequences, parallel and coupled together depending on their relationship. If the right type of product information is not defined in the right place in the process it can lead to assumptions or a recurring need to go back and forth between process participants to clarify questions.

Such an engineering design process is inefficient, and will possibly produce faulty specifications.

- By clarifying how product information should be defined and presented in which process step. If product information is not conveyed in a manner so the recipient of that information can understand and utilise it, this can inhibit the recipient in carrying out his or her task optimally. This might cause misunderstandings and possibly the production of erroneous specifications.
- By identifying if the person defining or modifying product specifications possess the required competences. If product information is defined or modified by someone that does not have the required knowledge, specifications could need to be redone later in the process leading to increased resource consumption
- By identifying non-value adding process steps in a current process flow. Process steps that are identified as not producing specifications might be non-value adding and could therefore potentially be eliminated.
- By identifying if the same product information is being re-entered too often into different IT-systems. To manually re-enter data is a potential source of error affecting the quality of the specifications produced within the overall specification process.
- By increasing the insight into every single activity in the engineering design process, this can help identify whether the work break down structure of the overall design into tasks is suitable. If this is not the case a redefinition of the content of tasks should be carried out. If the definition of the tasks is closely linked to the product architecture of the product in question, it might also be relevant to assess whether a revision of the architecture should be conducted.

As pointed out initially the overall objective is to develop an operational modelling technique for achieving the benefits stated above through integrated modelling of product and process. For obtaining this, following 5-step procedure is proposed, see Figure 1.

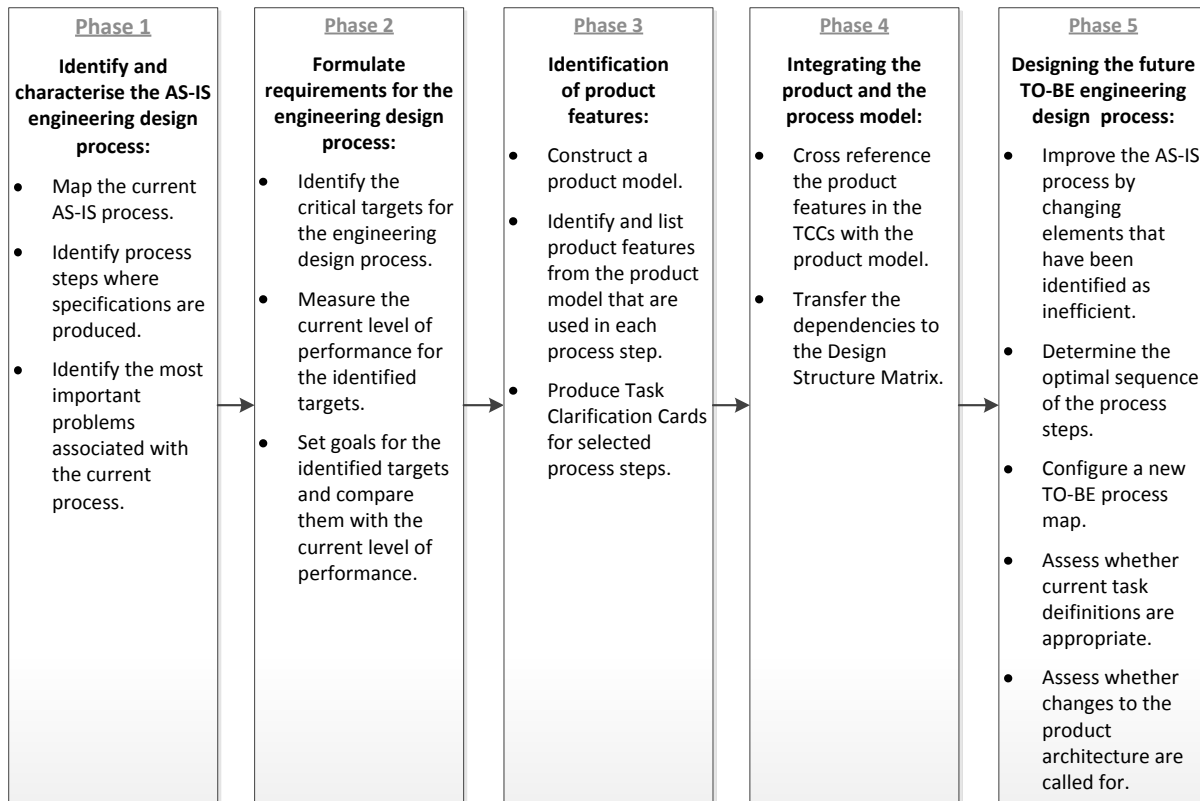


Figure 1: The procedure for developing engineering design processes through integrated modelling of product and process

Phase 1 – Identify & Characterize AS-IS Process

In order to develop engineering design processes, we need first to acquire an understanding of the existing process. The first step is therefore to map out the AS-IS process and identify the process steps where product information is being processed and specifications are produced. This can be done using numerous process mapping tools. In this study we have chosen the Business Process Modelling Notation as it is deemed suitable for the task at hand. At this stage we are interested in getting an overview of the existing process applying a widespread, easy-to-use and intuitive mapping tool. The tool does not need to provide us with an in-depth understanding of the process yet. The purpose of phase 1 is merely to get an overview of the process. The detailed insight into the individual process steps will be acquired in phase 3. Process steps that are identified as tasks where product features are specified are highlighted as they are of particular interest.

After having mapped the existing process it can be evaluated by identifying the most critical problems associated with the process. This will provide insight into which problems need to be addressed in the development of a new and improved process. Examples of problems could be too many transfers of responsibility, too many loops etc.

Phase 2 – Requirements for New Process

After having identified and characterised the existing engineering design process, the next step is to make clear what requirements are to be placed on the process. A starting point for the requirements is the company's current strategy plan and their commercial targets, such as profitability, product strategy, delivery time, etc. Based on this it is identified which targets are critical if the company is to meet its overall targets. (Hvam et al. 2008) points out following targets as typical appropriate measures for a company's specification process:

- Lead time for producing specifications.
- On time delivery for specifications.
- Resource consumption for producing specifications.
- Quality of specifications.

This should not be seen as a complete list. Other measures might be more relevant, and it has to be assessed when analysing the current AS-IS process, which measures are most important to address.

When quantifiable targets have been set, then the next step is to carry out a series of measurements to determine the current level of performance. Then the current level of performance and the target goals can be compared and the largest gaps can be identified. This will indicate where the greatest potential for improving the engineering design process will be.

Phase 3 – Identify Product Features

Phases 3 to 5 are closely interconnected as these are the phases in which the actual integrated modelling of product and process takes place. Figure 2 illustrates how these are interrelated and the figure will be used as reference for the rest of this chapter.

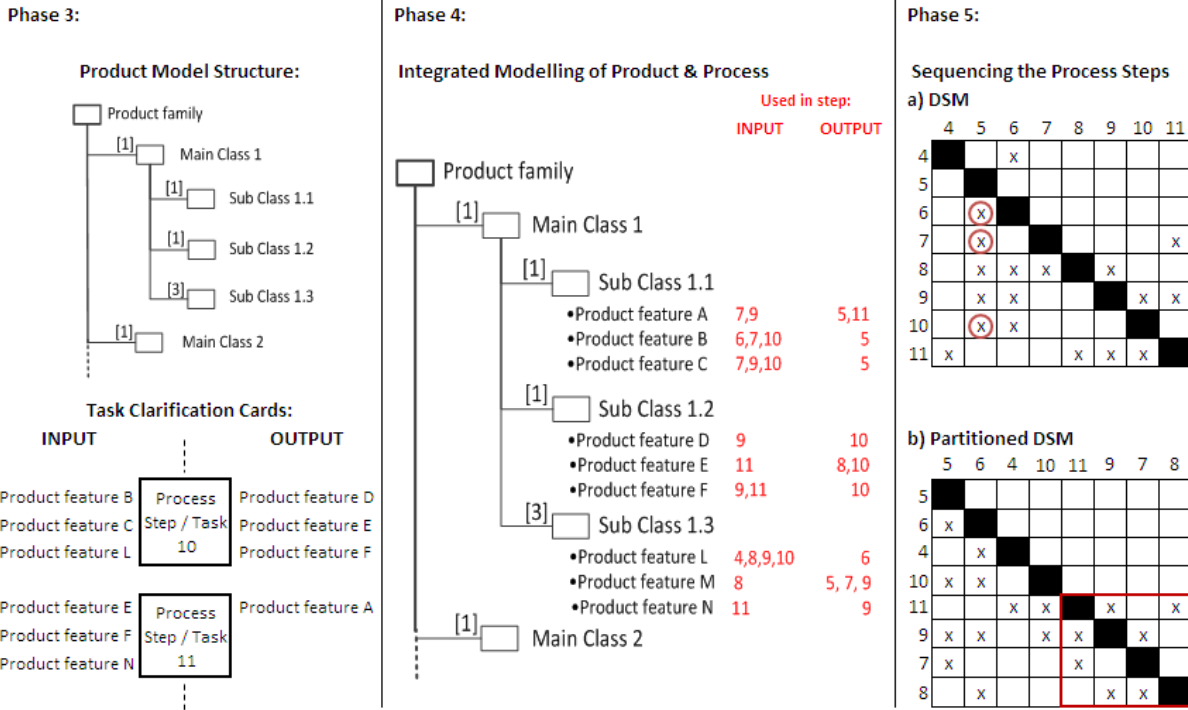


Figure 2: Phases 3 to 5

As stated earlier the basic proposition of this study is that it is necessary to understand the product being engineered in order to address the engineering design process. In phase 3 the first objective is therefore to construct a product model. The authors have applied the Product Variant Master as product modelling tool. The main reason for choosing this tool is that is straightforward to understand and to put in to use, while describing the product family in an efficient manner to all relevant stakeholders. The main focus of the product model at this point is to document the structure of the product, see upper left side of Figure 2. Normally when applying the Product Variant Master technique it is also part of the task to identify all features and constraints of the product. However this is neither necessary nor practical when modelling complicated products for the purpose of integrating the model with an engineering design process. Complicated products can consists of hundreds even thousands of product features. To assess the potential process implications of every product feature can therefore be very complex, time consuming and only add limited value. Earlier studies have confirmed this matter [Nielsen & Hvam, 2012]. It is therefore vital to identify the relevant product features that are decisive for the engineering design process and not waste time on less significant product features.

Identifying the right level of product detail to include in the PVM is one of the most critical issues that must be addressed when using the IPPM-method. Too much information will only lead to a time consuming process where the goal of the IPPM can potentially be lost in the amount of product detail. However, not enough detail can almost defeat the purpose of the IPPM-method as critical product relations may be missed. Identifying the relevant product features is mainly done through interviews with product experts, as they are the most likely to be

able to identify which product features are critical to the process. In order to support these interviews and document the knowledge provided by the designers we introduce the Task Clarification Card, TCC.

Basically the Task Clarification Card is a formalised description of an engineering activity. It supports clarification of which product features are critical for an activity to be carried out as well as characterisation of the process steps and identification of task interdependencies. Engineering activities are often complex tasks that are carried out by product experts. Therefore, such activities often end up as “black boxes” in a process map in known modelling techniques. Hence, the Task Clarification Card was developed to provide significant insight into the single activity of a process.

The Task Clarification Cards should only be made for process steps where engineering activities involving production of specifications take place. A template for a Task Clarification Card can be found in Figure 3.

Process step name:	Unique Identifier:	Author:	Date:
INPUTS:	SOURCE:	OUTPUTS:	
<i>Before task can start:</i> →	<div style="border: 1px solid black; width: 60px; height: 100px; margin: 0 auto;"></div>	→ _____	
→		→ _____	
→		→ _____	
<i>Coordination needed:</i> →		→ _____	
→		→ _____	
→		→ _____	
→		→ _____	
SKETCH:	MECHANISMS:		
<div style="border: 1px solid black; width: 180px; height: 80px; margin: 0 auto;"></div>	IT Systems: _____		
	Databases: _____		
	Competencies: _____		

Figure 3: Task Clarification Card

The Task Clarification Cards are primarily used to describe the engineering design task in terms of input and output product features with process significance. As part of the input declaration the source of the input is stated. The reasons for this will be elaborated below. The inputs are grouped into two. First product features that are needed before the task can start are stated. This means that the task acting as source and the task in question need to be performed in sequence with the source task first. The other inputs are product features that require some mutual coordination to other tasks. The tasks therefore need to be carried out in a coupled manner exchanging information. The Task Clarification Cards also contain the name of the engineering

design task, a unique identification number together with a date and name of the person responsible for the card.

The mechanisms-paragraph supports characterisation of the engineering design task, by clarifying with competencies are needed to complete the task as well as which IT-systems and databases should be used. The TCC thereby supports identifying whether the person responsible for the task possesses the required competencies and whether he or she has access to the needed information and IT-systems. If product information is defined or modified by someone that does not have the required expertise, specifications could need to be redone later in the process leading to increased resource consumption and longer lead time. Finally a sketch of the component in question is included. It can be convenient to include a sketch when working with product descriptions. Geometric relationships are usually easier to explain using a sketch rather than words. The introduction of the Task Clarification Card is inspired by the usage of so-called CRC-cards that are used within the area of product modelling, where each major product component is described in a predefined template (Hvam et al. 2003) and (Haug et al. 2010).

The basic idea is to conduct interviews with the employees who perform tasks identified as having process implications in the AS-IS diagram from Phase 1, using the TCCs as interview templates. For each interview the scope is to fill in all the information except the output column. Instead, after having conducted all interviews, the output columns are filled out tracing back the stated inputs using the source information. This way only product features having an impact on the engineering design process are included, ensuring a suitable level of detail. This is done as earlier studies (Nielsen & Hvam, 2012) resulted in an information overload in the output columns of the Task Clarification Cards. Back then the designers stated every nut and bolt which they specified as outputs. However these had no significance for the engineering design process and only added unnecessary complexity to the modelling task. The explicit declaration of the source of the product features is crucial for getting an overview of the interdependencies between the tasks.

Revealing interdependencies is however not the only benefit of the TCCs. The engineering design process for complicated functional products is very complex and there is a need to share information as well as to communicate it among the parties involved in the process (Lindström et al., 2012). The cards can also serve as a knowledge management tool, supporting knowledge sharing and preservation. The TCCs can also be considered as design manuals for how to perform tasks, serving as a check list which can be used by the design engineers when carrying out the individual tasks. This is especially valuable when aiding new designers to assimilate and digest design, as new designers often face significant challenges in fully comprehending complex design activities (Ding et al., 2011).

Phase 4 – Integrating the Product and the Process Model

In phase 4 the integration of the product features and the process steps takes place. The scope is to clarify where all product features are defined or modified. This is done by cross referencing the product features on the Task Clarification Cards with the PVM from phase 3. However, by using a PVM with the purpose of redesigning an engineering design process, some alterations of the PVM are called for. This is because some new features need to be incorporated to help fulfil its purpose. The PVM is therefore introduced in a revised version designated as the Cross Referenced PVM.

The Cross Referenced PVM is made by adding two columns to the PVM, an input and an output column. Then every time a product feature appears as an input or output on the Task Clarification Cards, the unique identifier of the card is noted on the Cross Referenced PVM next to the appropriate product feature in the designated input and output column, see Figure 2. Consider for example process step (task) 10 to understand better the link between the three phases. Phase three on the left hand side of the figure shows that product features B, C and L are inputs for the process step 10 and product features D, E and F are outputs. In phase four (the middle part of the figure) the number ten has been placed in the designated input and output columns beside the appropriate product features in the Cross Referenced PVM. Now consider the product feature B in the Cross Referenced PVM. It here becomes evident that the specification of product feature B takes place in process step 5 and the specification is used to produce other specifications in tasks 6, 7 and 10.

These cross references between the PVM and process steps provide valuable information on how to organise the sequence of the engineering design tasks. The IPPM-method also identifies the process steps that do not convey any new information i.e. do not produce specifications. These process steps indicate that they might be non-value adding and therefore they should possibly be eliminated to improve the process flow.

Phase 5 – Designing the TO-BE Process

The 5th and final phase is about designing the new improved engineering design process based on the insight acquired through the previous phases. The Cross Referenced PVM-tool introduced in phase 4 clearly displays the dependency relationships of the process steps. Nevertheless, engineering design processes are often complex, with numerous process steps. Thus, the interdependencies in such processes are often complex and intertwined, making the job of reorganising the process steps in an optimal order too difficult to do without some kind of algorithm. The authors have chosen the Design Structure Matrix as a tool for dealing with this complexity. The DSM modelling method uses a simple algorithm to organise elements based on their relationship dependencies and it is an ideal modelling tool to utilise in conjunction with the Cross Referenced PVM-tool.

The information from the Cross Referenced PVM is therefore transferred to the DSM with the output column controlling the columns in the matrix while the input column controls the rows.

Consider product feature B again, see Figure 2. The specification of the feature takes place in step 5 and is used as input in steps 6, 7 and 10. Therefore 'x's are placed in the DSM in rows 6, 7 and 10 under column 5, see red markings in upper right side of Figure 2. When this is done for all output values for all product features the DSM is filled. After the DSM is filled it is partitioned. The partitioning reveals the optimal sequence for the process steps based on minimizing feedback loops in the process. Using the information displayed in a partitioned DSM a new TO-BE process map can be configured for the engineering design process.

In summary, the five phases will reveal a detailed understanding of the single activities in a process, which then can be utilised to reorganise the sequence of process steps in an engineering design process. By applying the insight gained by the IPPM, an engineering design process can be redesigned leading lead to improvements in process efficiency, quality, lead time and on-time delivery.

Findings

The 5 phase-procedure proposed above has been applied within a design department in the Low Speed business unit of MAN Diesel & Turbo during the fall of 2012. The main objective was to develop the engineering design processes taking place every time an order for a customised engine is to be processes within the department in question. The department is not designing the full engine, but has the responsibility for approximately 100 modules within the overall product architecture. The design of each of these modules is a delimited design task assigned to a single design engineer. Several interdependencies exist between the modules though, but these are not explicitly mapped. In order to develop and improve the engineering design processes it is critical to get an overview over these interdependencies, and a critical aim is therefore to map those. The modules differ significantly in size as well as the corresponding workload required for designing it.

Phase 1 – Identify & Characterize AS-IS

As mentioned earlier a manual configuration process is taking place every time an order is placed. Here it is identified which modules can be reused and which that have to be redesigned in order to comply with the customer requests. The configuration team afterwards informs the group leaders of the different design departments which modules they need to design. The group leader then creates a task per module and delegates the task after having set a deadline for it. Finally the designers carry out the tasks and then submit them to the configuration team who then forwards the drawings to the customer. Due to the customisation it differs which modules are to be designed for each engine order. Accordingly, it then also differs which designers will be given a task. Therefore it is not possible to map a detailed generic process flow as the actors involved changes from order to order. However a simplified conceptual flow has been mapped in Figure 4.

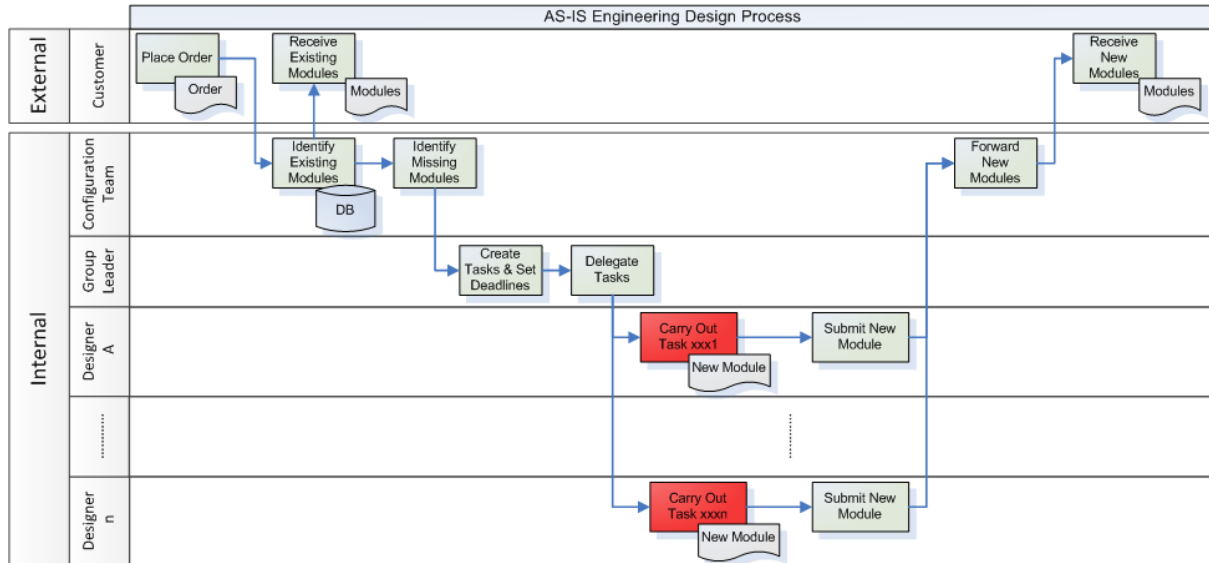


Figure 4: AS-IS Engineering Design Process

The tasks marked with red are those who will be given particular attention, as these are where product specifications are actually produced. These different design tasks are mutually interdependent but as mentioned earlier there is currently no mapping of these interdependencies. The group leader has some experience which is utilised when setting deadlines, but as the dependencies are numerous errors occur. For instance bottlenecks emerge when two interdependent tasks are scheduled displaced. This leads to increased lead times, failure to comply with delivery deadlines and a general drop in efficiency and quality.

Phase 2 – Requirements for New Process

As stated, bottlenecks have been identified in the current engineering design process causing problems with delivery deadlines and overall efficiency. These are therefore central targets that need to be improved. Furthermore, due to the lack of overview of interdependencies between design tasks, design work occasionally has to be redone. This affect the resource consumption and potentially the quality of the design work. The critical targets for the engineering design process in question are therefore on-time delivery of modules, resource consumption for producing specifications and the quality of the specifications.

In order to set up realistic requirements for the new process it is necessary to diagnose the existing performance of the engineering design process. Analyses based on interviews with designers as well as data from the company's PLM-system have been conducted to assess the performance for the critical metrics stated above. However, comprehensive data describing all of these matters had not been collected. It has therefore not been possible to quantify all metrics. For those parameters without concrete data a qualitative assessment based on interviews was conducted.

- On time delivery for specifications: Whenever an order is placed expected delivery dates for modules to be designed are set. These are registered centrally and can be extracted for analyses. However the delivery dates might change along the way in agreement with the customer and the individual design department. The new changed delivery date is not noted within the systems, and we can therefore not be sure whether the initially stated date is the actual deadline. Nevertheless, the objective is to comply with the expected delivery dates and the data describing these can therefore still be used for assessing the on-time delivery performance to some extent. But the nature of the measure needs to be taken into account. It is not realistic to aim for a 100 % compliance with expected delivery dates, which is why a target for 75% is set. The current performance is identified as 62%.
- Quality of specifications: Every time a critical flaw is identified for a module an action code is issued. This leads to a revision of the module and possible a recall of already dispatched modules. Currently the performance is that for every 100 modules that are designed, 1,27 needs a major revision. This number should be reduced 1 major revision per 100 designed modules.
- Resource consumption for producing specifications: Currently no data exists that can determine the exact performance of the resource consumption for producing specifications. However, at stated earlier, the designers have experienced several cases of modules needed to be redesigned due to conflicting interdependencies between modules. This is not acceptable, and the target is to make sure, that these situations will not occur in the future.

The targets, the current performance and the gap between those are compiled in Figure 5.

	Target	Current Performance	Gap
<u>On Time Delivery:</u> Modules Delivered in Accordance with Expected Delivery Date	Expected delivery date should be kept for 75 % of module deliveries	62 % of modules are delivered in accordance with expected delivery date	13 percentage point
<u>Ressource Consumption for Producing Specifications</u>	No resources should be needed for redoing engineering tasks	Several observations of redoing tasks	Not quantifiable due to lack of data
<u>Quality of Specifications:</u> Average no of Revisions per Module	1 major revision per 100 modules	1,27 major revision per 100 modules	0,27 major revisions per 100 modules

Figure 5: Requirements for the engineering design process

The objectives stated above are to be kept in mind when carrying out the remainder of the analysis. They can be considered as guidelines for how the futures engineering design process should be designed.

Phase 3 – Identify Product Features

The main objective of phase 3 is to identify those product features that are decisive for the engineering design process. First a structural product model covering the relevant subset of the engine is constructed without including any product features, see left hand side of Figure 6. This model basically provides us with the overall structure of the product in question, and served as a suitable starting point for the analysis. Next Task Clarification Cards for the highlighted engineering design tasks from Figure 4 are made based on interviews with product experts. In the specific case this means interviews with designers A to n concerning all tasks that they are responsible for. In order to create maximum value with the analysis Task Clarification Cards are made for all highlighted engineering design tasks and not only for tasks occurring in selected orders. Thereby a master mapping of all dependencies covering all potential order process flows regardless of customer requirements are included. Then when a specific order is placed only the dependencies for the engineering design tasks needed are included in the planning of the execution of the specific order. An example of a Task Clarification Card describing a specific engineering design task can be seen on the right hand side of Figure 6.

In terms of data collection phase 3 turned out to be an iterative process. First the structural product model was determined in collaboration with the entire department ensuring that consensus existed on how the product is constructed. Then through interviews with the

individual designers identified in the AS-IS process flow, inputs were added to the Task Clarification Cards alongside with the output sources for those inputs. The sources were then confirmed through a second round of interviews.

With the PVM outlining the product being engineered and the Task Clarification Cards describing the process steps producing product specifications, the integration of the product and process could now take place.

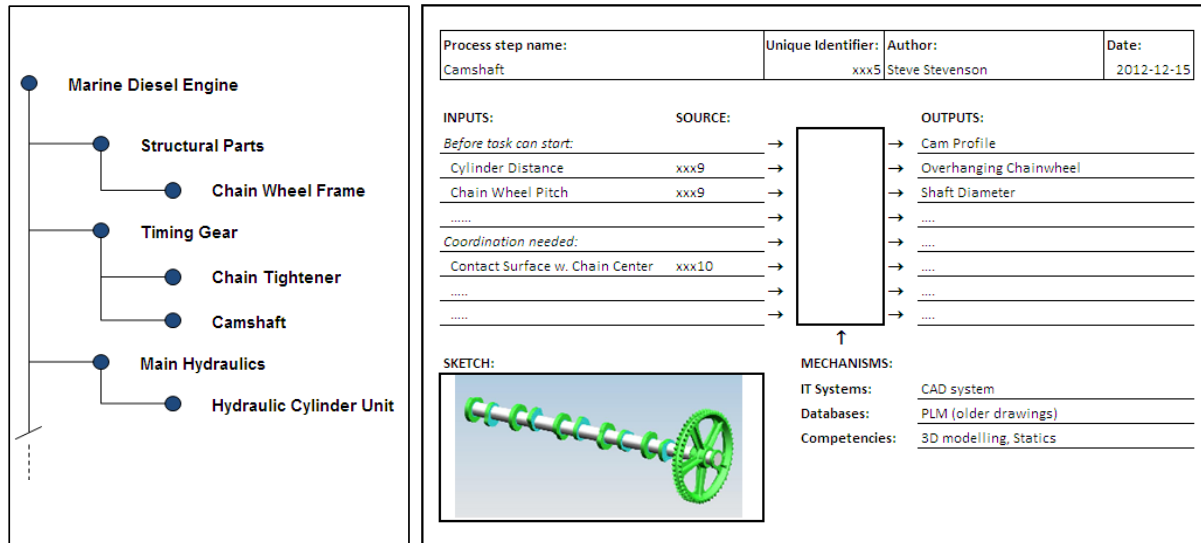


Figure 6: Identification of product features

Phase 4 – Integrating the Product and the Process Model

Phase 4 starts with the rather tedious task of compiling all information from the collected Task Clarification Cards into the structural PVM thereby creating the Cross Referenced PVM. This is basically the integration of the process and the product model. A subset of the Cross Referenced PVM can be seen in Figure 7.

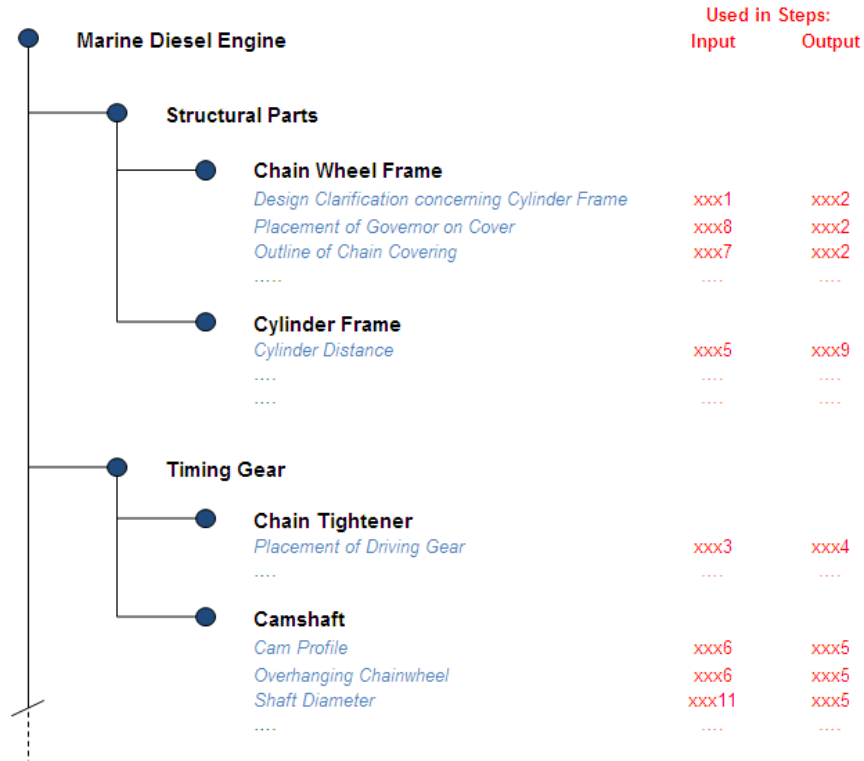


Figure 7: Subset of Cross Referenced PVM

The product model has been extended in two ways. First the specifications with process implications are added in the appropriate places in the model written in blue italic. These are all specifications explicitly stated within the Task Clarification Cards. Then cross references between the included specifications and the process steps in which they occur are stated on the right-hand side of the model with red writing. Consider for instance the Task Clarification Card for the design of the Camshaft from Figure 6. In the output field the features ‘Cam Profile’, ‘Overhanging Chainwheel’ and ‘Shaft Diameter’ are stated. The unique identifier for the engineering design task (xxx5) is then written in the output column next to same features in the Cross Referenced PVM. Correspondingly the unique identifier is added in the input columns next to the features stated as inputs to the task in the corresponding Task Clarification Card. For instance, for ‘Cylinder Distance’ in the Cross Referenced PVM, xxx5 is stated as input indicating that engineering design task xxx5 needs to know the feature ‘Cylinder Distance’ in order to be completed. Furthermore the source information for this product feature is added, stating that ‘Cylinder Distance is specified in engineering design task xxx9. If considered isolated this extract tells us, that task xxx9 needs to be carried out before task xxx5 which again should be performed before tasks xxx6 and xxx11. However this is only when considering these tasks solely. Many other cross references might also influence this sequence, and only by taking all interdependencies into account a complete understanding of sequence dependencies can be acquired.

Phase 5 – Designing the TO-BE Process

By integrating the information from the Task Clarification Cards with the product model an understanding of the process implications of each product feature is achieved. This insight can be used for redesigning the process. However the Product Variant Master modelling techniques is not suitable for handling extensive internal relations. Therefore the Design Structure Matrix is applied by feeding the information from the Cross Referenced PVM into the DSM. In the MAN Diesel & Turbo case this resulted in a large 104 x 104 master matrix containing all engineering design tasks producing specifications. However when partitioned the matrix revealed a substantial amount of interdependent coupled tasks. If we only had information on the dependencies between the different design tasks, this would be our final result. We would then have to deal with the coupled tasks and set suitable deadlines for these. But once again we could now benefit from the detailed information acquired in the Task Clarification Cards. In these we obviously have information on how tasks are related, but we also information on which specifications and product features that actually create the interdependencies between the engineering design tasks. Therefore we took out the cluster of coupled tasks from the DSM and exploded these tasks into specifications stated in the TCCs and made a new DSM. This way we went from a tasks DSM to a specification DSM. By partitioning the specification DSM, it was revealed that a few critical specifications really caused the major clustering of the engineering design tasks. An exemplification of the procedure is illustrated in Figure 8.

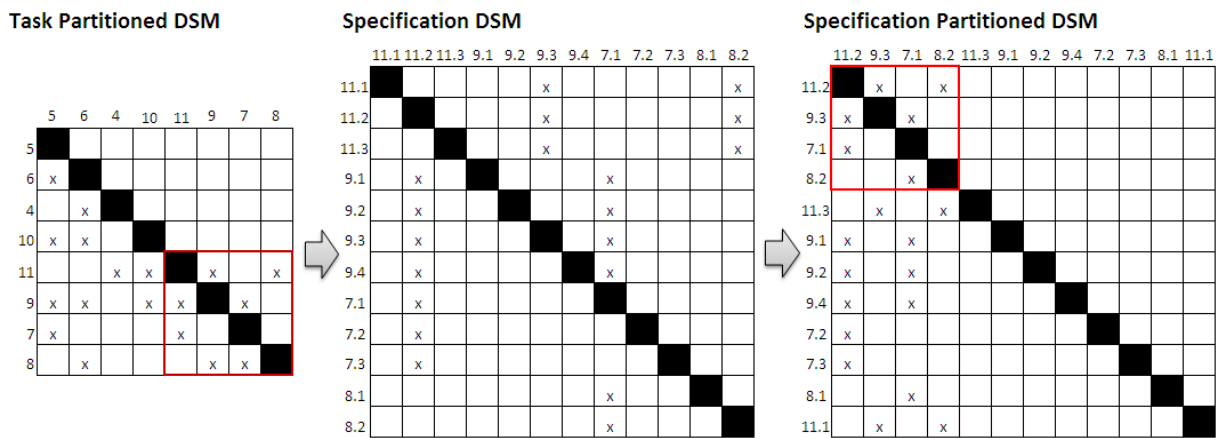


Figure 8: Partitioning the Task and the Specification DSM

The example above shows that four tasks (7, 8, 9 and 11) are coupled. However when addressing the specifications of these four tasks in a separate DSM it becomes clear, that it is only one specification from each task that creates the interdependencies. Therefore the designers responsible for these tasks should, if possible, determine these key specifications as early as possible, as this will induce a less coupled workflow.

The remaining issue is then how to create value utilising this insight. The proposition is, that every time an order is placed it is identified which design tasks that need to be performed. Based on the information acquired in the Task Clarification Cards and the Cross Referenced PVM, a

DSM is made containing the tasks needed for the specific order. The DSM should not be built from scratch every time it is to be applied. It should just be made by subtracting the subset of tasks relevant for the specific order from the master DSM containing information on all possible tasks. The DSM is then partitioned and if needed an additional specification based DSM is made and partitioned. This will provide the group leader from Figure 4 with a valuable decision support tool for setting deadlines and distributing the engineering design tasks.

As stated under phase 5 in Figure 1 it is now relevant to assess whether the current task definitions are appropriate as well as evaluate if changes to the current product architecture could be valuable. However, the analysis revealed a clear and well defined correlation between the product architecture within the company and the engineering design tasks. No further actions were therefore taken in this regard.

In summary, applying the 5-phase IPPM-procedure proposed in this paper has allowed us to map the existing engineering design process within the specific design department in MAN Diesel & Turbo and identify the most critical problems. Careful modelling of both the product being engineered as well as the engineering design process in an integrated manner provided us with a detailed insight into how the different product features were decisive for the performance of the engineering design process. By compiling all of this information into first a Cross Referenced PVM end thereafter a DSM we have created a decision support tool which the group leader can apply when delegating tasks and setting deadlines. As the testing of the tool is still in its initial phase, the effects cannot yet be quantified. It has therefore not been possible to determine whether the targets formulated in phase 2 will be achieved. However the participants within the project are confident in the potential outcome of employing the procedure. The belief is that applying the tool will cause fewer bottlenecks in the engineering design process leading to an improved ability to deliver on-time, a more efficient process and higher quality of the engineering work carried out. In order to produce maximum value with the procedure, other design departments should obviously be included in the analysis. Many interdependencies exist between design activities across design departments, and these also affect the overall performance of the engineering design processes. Inclusion of all departments has however not been within the scope of this analysis, but the integrated modelling of product and process is expected to be carried out for all departments during 2013.

Discussion & Conclusion

As the main objective of this study is to develop engineering design processes one could question why not applying the DSM right away, saving us a lot of effort in making the product model and the Task Clarification Cards. The authors believe that it is rarely possible to fully comprehend all interdependencies inherent within the engineering design process without prior analyses of the engineering design process as well as the product being engineered. The Product Variant Master modelling technique provides us with an easy applicable tool to thoroughly map a product's structure, features and behaviour. And the Task Clarification Cards support the

identification of features that are decisive for the performance of the engineering design process. Using these tools in unison helps identifying what to actually add to the DSM. However the PVM-modelling technique has its limitations. When relations between the elements in the model increase in numbers, the PVM is inadequate in dealing with those relations. As this is where the DSM is particularly strong the authors recommend combining the strengths of the modelling techniques as it is done in the 5-phase procedure introduced in this paper.

In conclusion, it is believed that the IPPM-approach has potential to become an effective method to sequence and improve complex engineering design processes. It can create insight into the complex activities within a process that are usually unanalysed in most known process modelling approaches. By utilising the insight gained through the IPPM approach, processes can be specifically configured to suit the product being engineered, thereby creating an optimal process flow for that specific product.

The 5-phase procedure presented is an operational tool for how engineering design processes can be developed in a structured and systematic way. By analysing the product and process models together it becomes possible to identify relationship dependencies between the tasks. Finally the procedure suggests using the Design Structure Matrix in conjunction with the tools provided by the IPPM- method. This will support sequencing and identifying whether process steps should be carried out in sequence, parallel and/or coupled together. The information gained from applying the procedure can be utilized to create an improved TO-BE model of the engineering design process.

To the knowledge of the authors no current methods for redesigning and developing engineering design processes do take into account the product features to be used in every process step. We therefore believe that our research on this matter could provide a contribution to process development theories, especially within the field of engineering design. Generating theory through action research is situation specific and incremental (Coughlan & Coughlan, 2002). This is also the case with the research at hand. However the belief is that a significant step from particular to general can be taken with this research, as the case company represents a typical engineering company. The authors therefore believe that the suggested modelling technique can support the development of engineering design processes in many companies, and we will continue our efforts on this matter in the years to come.

References

- Albers, A. and Braun, A. (2011), "A generalised framework to compass and to support complex product engineering processes", *International Journal of Product Development*, vol. 15, no. 1-3, pp. 6-25.
- Bilalis, N. and Maravelakis, E. (2006), "Analysing the dependencies between the Innovation Attributes in NPD using Design Structure Matrix – the I-DSM tool", *International Journal of Product Development*, vol. 3, no. 3/4, pp. 432-446.

- Collis, J. and Hussey, R. (2003), *Business Research. A practical guide for undergraduate and postgraduate students*. 2nd edition. Palgrave Macmillan, New York.
- Coughlan, P. and Coughlan, D. (2002), "Action Research for Operations Management", *International Journal of Operations & Production Management*, vol. 22, no. 2, pp. 220-240.
- Ding, L., Matthews, J. and Mullineux, G. (2011), "Capturing constraint evolution: a technique to preserve and handle design knowledge", *International Journal of Product Development*, vol. 15, no. 1/2/3, pp. 135-155.
- Eppinger, S. D. and Browning, T. R. (2012), *Design Structure Matrix Methods and Applications*, Massachusetts Institute of Technology.
- Eppinger, S. D., Whitney, D. E., Smith, R. P. and Gebala, D. A. (1994), "A model-based method for organizing tasks in product development", *Research in Engineering Design*, vol. 6, pp. 1-13.
- Eckert, C. and Clarkson, J. (2005), "The reality of design", in Eckert, C. and Clarkson, J. (Ed.), *Design Process Improvement – A review of current practice*, Springer-Verlag, London, pp. 1-29.
- Fixson, S. K. (2004), "Product architecture assessment: a tool to link product, process, and supply chain design decisions", *Journal of Operations Management*, vol. 23, pp. 345-369.
- Harlou, U. (2006), *Developing product families base on architectures - Contribution to a theory of product families*, Dissertation, MEK, Technical University of Denmark.
- Haug, A., Hvam, L. and Mortensen, N. H. (2010), "A layout technique for class diagrams to be used in product configuration projects", *Computers in Industry*, vol. 61, no. 5, pp. 409-418.
- Hvam, L. (2001), "A Procedure for the Application of Product Modelling", *International Journal of Production Research*, vol. 39, no. 5, pp. 873-885.
- Hvam, L. and Jensen, K. R. (2007), "A multi perspective approach for the development of visual configuration systems", *Computers & Industrial Engineering*, vol 53, no. 3, pp. 401-419.
- Hvam, L., Mortensen, N. H. and Riis, J. (2008), *Product customization*, Springer-Verlag, Berlin Heidelberg.
- Hvam, L., Pape, S. and Riis, J. (2005), "Development and maintenance of product configuration systems: Requirements for a documentation tool", *International Journal of Industrial Engineering*, vol 12, no.1, pp. 79-88.
- Hvam, L. Riis, J. and Hansen, B. (2003), "CRC-cards for product Modelling", *Computers in Industry*, vol 50, no. 1, pp. 57 – 70.
- Jarratt, T., Eckert, C. and Clarkson, J. (2011), "Engineering Change: an overview and perspective on literature", *Research in Engineering Design*, vol. 22, pp. 103-124.
- Kagan, C., Burton, M., and Siddiquee, A. (2008), "Action research", in C. Willig & W. Stainton-Rogers (Eds.), *The SAGE Handbook of Qualitative Research in Psychology* (pp. 32–53).
- Karlsson, C. (2009), "Researching Operations Management", in Karlsson, C. (Ed.), *Researching*

Operations Management, Routledge, New York and London.

- Koh, E. C. Y., Caldwell, N. H. M. and Clarkson, J. (2012), "A method to assess the effects of engineering change propagation", *Research in Engineering Design*, vol. 23, pp. 329-351.
- Li, S. (2009), "Matrix-based decomposition algorithms for engineering applications: the survey and generic framework", *International Journal of Product Development*, vol. 9, no. 1/2/3, pp. 78-110.
- Lindström, J., Löfstrand, M., Karlberg, M. and Karlsson, L. (2012), "Functional product development: what information should be shared during the development process?", *International Journal of Product Development*, vol. 16, no. 2, pp. 95-111.
- Maier, A. M. and Störrle, H. (2011), "What are the characteristics of engineering design processes?", *18th International Conference on Engineering Design (ICED)*, Copenhagen, 15-18 August 2011.
- Nielsen, J. B. and Hvam, L. (2012), "Developing Engineering Processes Through Integrated Modelling of Product and Process", *4th World Conference P&OM – Serving the World*, Amsterdam, 1-5 July 2012.
- Pahl, G. and Bietz, W. (2007), *Engineering Design. A Systematic Approach*, 3rd Ed., Springer-Verlag, London.
- Pasqual, M. C. and de Weck, O. L. (2012), "Multilayer network model for analysis and management of change propagation", *Research in Engineering Design*, vol. 23, pp. 305-328.
- Steward, D. V. (1981), "The design structure matrix: a method for managing the design of complex systems", *IEEE Transactions on Engineering Management*, vol. EM-28, no. 3, pp.71-74.
- Schwarze, S. (1996), *Configuration of multiple-variant products*, Dissertation, Swiss Federal Institute of Technology Zürich, Zürich.
- Ulrich, K. T. and Eppinger, S. D. (2003), *Product Design and Development*, New York, McGraw-Hill/Irwin.
- Veldman, J. and Alblas, A. (2012), "Managing design variety, process variety and engineering change: a case study of two capital good firms", *Research in Engineering Design*, vol. 23, pp. 269-290.
- Yang, F. and Duan, G. (2012), "Developing a parameter linkage-based method for searching change propagation paths", *Research in Engineering Design*, vol. 23, pp. 353-372.
- White, S.A. (2004), *Introduction to BPMN*, IBM Cooperation, BP Trends.

PAPER 4 - APPLICABILITY AND EVALUATION OF IPPM – INTEGRATED PRODUCT AND PROCESS
MODELLING

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Applicability and Evaluation of IPPM – Integrated Product and Process Modelling

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Abstract

Engineering design processes are often ill-defined, iterative and complex, and can therefore be difficult to model and develop. With the objective of creating the highest level of efficiency within an organisation by planning and controlling the engineering design process, the authors have developed a new modelling technique called IPPM – Integrated Product and Process Modelling. The idea is to integrate a model of the product features used in the engineering design process and clarify in which steps of the process the features are used. This will provide an additional understanding of what actually takes place within the engineering design process. This paper presents three rather different cases where IPPM has been applied and evaluates the outcome of each case. Seven characteristics are identified as having significant impact on the applicability of IPPM, and it is evaluated how to maximize the value of applying the modeling technique.

Keywords: Engineering Design Processes, Product Modelling, Process Modelling, Planning and Scheduling, Design Management.

1. Introduction

Understanding an engineering design process fully requires understanding of the product being engineered. This means that if you are to develop an engineering design process you will benefit from understanding how the product itself affects this process. What product features are used in which process step and how are these steps interrelated? Current methods for developing engineering design processes do not take into account the product features to be used in every process step, and because of that it can be difficult to obtain a detailed understanding of the activities in the processes and to come up with significant improvements.

A new engineering design methodology called Integrated Product and Process Modelling (IPPM) aims at analysing process and product models simultaneously in order to improve engineering design processes (names deleted to maintain the integrity of the review process). By integrating a product model in the design of engineering processes, a better understanding of the engineering activities will be acquired. Furthermore, insight into how different decisions on product features affect the engineering process will be achieved. Making use of this insight will allow us to plan and schedule the engineering activities in a more optimal way and thereby increase the efficiency, reduce lead time, improve ability to deliver on-time and improve the quality of the engineering work carried out. We are thereby aiming at creating the highest level of efficiency within an organisation by planning and controlling the process of converting labour into goods and services, which is a central objective within operations management.

The IPPM-methodology is a 5-phased procedure for assessing, modelling and developing engineering design processes in a structured and systematic way. The procedure supports mapping and diagnosing of an existing process and it creates insight into the complex activities within a process that are usually unanalysed in most known process modelling approaches. By utilising the insight gained through the IPPM-approach, processes can be specifically configured to suit the product being engineered. This way it is possible to create an optimal process flow for that specific product and enable better planning and scheduling of design tasks.

In the period 2011-2012 the IPPM-methodology was applied three times by the authors on rather different engineering design cases within the engineering company MAN Diesel & Turbo. The cases differed significantly in terms of number of actors involved in the engineering design process, the maturity level of the product being engineered and the level of detail included in the analysis. The results from these three case studies provided valuable insight into the applicability of IPPM, and enabled the authors to list what characteristics that should be in place in order to get maximum value from applying IPPM.

2. Theory

The research at hand operates in the cross section between product and process modelling theories on the one side and engineering design theory on the other. This paragraph will briefly

introduce some of the key concepts and techniques applied in the study.

2.1. Product Modelling

To get an overview of a product range can be challenging. A way of dealing with this challenge is to make use of product modelling techniques. By modelling your product range you will achieve a better understanding of the product portfolio and be better equipped to control the complexity that exists within it. In general, product modelling can be interpreted as the logical accumulation of all relevant information concerning a given product range. But to do so you need a tool, such as the Product Variant Master, that can describe the complete product assortment in an efficient manner to all stakeholders. The Product Variant Master (PVM) modelling technique is a tool for modelling and visualising product families (Hvam, 2001; Hvam & Jensen, 2007). It provides an overview of the product range offered by a company and illustrate how the products can vary. The tool has its basis in object oriented modelling, and simply put, it can be said that a PVM contains a description of the company's product range and the associated knowledge (Harlou, 2006).

2.2. Process Modelling

Several tools for modelling processes have been developed in the course of time. Process modelling is a central part of process management and is used for many different purposes such as aiding decision making, process planning, supporting problem solving and providing a common platform for communication (Maier & Störrle, 2011). The most well known tool for mapping processes is probably the Business Process Modelling Notation, BPMN. BPMN is a flowchart tool used to create graphical models of business processes. By using the tool you can create models that clarify which activities are performed by whom within the company. Furthermore it clarifies which communication is occurring between different departments and external stakeholders (White, 2004). The notation form is quite straightforward and easy to put into use which makes it a popular choice.

Another modelling approach applied in this study is the Design Structure Matrix, DSM (Steward, 1981). The DSM-modelling technique has a wide field of application as it is used for developing product, process and organisation architectures (Eppinger & Browning, 2012). The tool is especially suitable for engineering design projects, which involves specification of many interdependent variables which together define a product. The DSM is a matrix structure representation that captures the sequence and the technical relationships among different design tasks in a project. By using the modelling technique it becomes possible to find alternative sequences of the tasks and streamline the inter-task coordination (Eppinger et al., 1994). A central strength of DSM is that it provides a concise visual format for representing processes. It becomes apparent how the individual activities affect the overall process and which activities that may trigger rework (O'Donovan, 2005).

2.3. Engineering Design Processes

Engineering design processes are significantly different from business administration processes. Business administration processes are usually simple, well-defined and repetitive whereas engineering design processes are characterised by being ill-defined, iterative and complex (Maier & Störrle, 2011). The tasks within engineering design processes furthermore require specialist knowledge (Eckert & Clarkson, 2005). The individual process steps within the overall process therefore easily end up being black boxes when applying conventional process mapping techniques, as they are not able to deal with and express this complexity in a suitable way. This is among other things due to the complex nature of the product being engineered as well as the complexity of the process. Several scholars such as (Fixson, 2004) and (Albers & Braun, 2011) acknowledge that these factors are highly interdependent, and that it is very difficult to distinguish the cause and effect relationships between them. But no structured modelling approach is explicitly aimed at understanding this link between the engineering design process and the product being engineered.

Most process modelling approaches today are too general in scope (Eckert & Clarkson, 2005). The reason for this may lie in the fact that the scope of design is vast and engineers design everything from screwdrivers to aircrafts (Ulrich & Eppinger, 2003). Only at a very abstract level can the engineering design process of such different products be the same.

3. Empirical Background

The three cases that form the foundation of this article are conducted in collaboration with the Low Speed business unit of MAN Diesel & Turbo. MAN Diesel & Turbo is a large international engineering company designing, among other things, customer specific two-stroke marine diesel engines. The Low Speed business unit has no physical production but is only developing and designing the products.

The company is the market leader within their industry and the primary strategic goal is to maintain this position. In order to fulfil this goal the company strives to win every order by delivering customer specific, high quality products on time, even if it requires significant development and engineering work. However, within the last years the market has gotten more diverse and more unique customer requests occur. The consequence has been a steep increase in the number of very customer specific product variants offered by the company. This is clearly reflected in the product program, which today is approximately twice the size as it was just 5 years ago. The engineering departments are thereby experiencing increased pressure as they are required to design considerably more new variants than earlier. In order to deal with this increased pressure the company has initiated several initiatives aiming at optimising and improving the engineering design processes. One of these initiatives is the development and application of IPPM.

The article at hand is based on the application of IPPM in three separate case studies. The three cases all had the scope of improving specific engineering design processes, but they had quite different characteristics, in terms of number of designers involved, maturity level of product being engineered, etc. Throughout these cases it was realised that the applicability of IPPM and the outcome of the analysis differed significantly dependent on the characteristics of the cases. Listing and assessing these decisive characteristics is the main outcome of this paper.

4. Research Methodology

The research has been carried out using qualitative methods. The methodology applied is action research where the aim is to enter a situation (the design of new components for two-stroke marine diesel engines), attempt to bring about change and to monitor results (Collis & Hussey, 2003). The scope has not just been to observe what is happening but actually participate in solving a managerial problem while attempting to contribute to existing body of theory, which also characterises action research (Coughlan & Coughlan, 2002). A basic idea of action research is to experiment in the field rather than in a laboratory, which makes it well suited to work with practitioners and managers in large organisations. Action research is at one and the same time the investigation of action, implementation of investigation through action and the transformation of research into action, and is frequently used in intra-organisational problems (Kagan, Burton & Siddiquee, 2008).

The research proposition has been tested in three case studies, which is often considered quite few. Having only a few cases can affect the validity, reliability and generalising potential of the study. Context-dependent knowledge gives this type of science a basic limitation when generalising the conclusions made on the basis of a single experiment (Smith, 2006). However (Gummesson, 1991) contends it is possible to generalise from a very few cases if the analysis has captured the characteristics of the phenomena being studied.

The authors have had free access to detailed data within the company allowing an in depth analysis. The internal validity, which concerns the extent to which the research findings accurately represent what is really happening, is therefore assessed to be high. A tendency that often gets even stronger when considering single case studies (Voss et al. 2002). A clear limitation of this article is that the findings are based on data from one company only. We therefore need to be cautious when concluding whether the findings can be generalised. If similar tendencies can be found in other companies, the external validity of the findings will be improved considerably (Karlsson, 2009). The authors do however believe that the case company represents a typical engineering company designing customer specific products, which supports the validity of the findings. Furthermore, the free access to detailed data provided to the authors also strengthens the validity.

Reliability is concerned with the findings of the research and whether anyone would get the same

results as you if they were to repeat the research. This is quite unlikely in the research at hand due to acknowledgement of the influence of social factors both from the subjects being studied and also the researchers self. However the requirements for reliability are usually interpreted somewhat differently when talking about qualitative research (Collis & Hussey, 2003). Qualitative research traditionally focuses more on validity as described above.

The main source of data is semi-structured interviews with the designers who have provided insight into both processes and products. Additional product and process information has been found in information systems within the company.

5. Research Questions

The applicability and outcome of IPPM seems to be dependent on the characteristics of the specific setting in which the methodology is to be applied. The process modeller should therefore carefully asses whether the engineering design process to be scrutinised constitutes a suitable case for IPPM. The scope of this article is to support the process modeller in this task by investigating what characteristics are critical for a successful application of IPPM.

The research questions for the paper are:

- What characteristics are decisive when assessing the suitability of IPPM?
- What comprise a good case for applying IPPM?
- How to create maximum value of applying IPPM?

6. Analysis

The IPPM-methodology has been developed over the last three years in an industrial PhD-project in collaboration with the Low Speed Department in MAN Diesel & Turbo. Three larger case studies have been conducted and the methodology has continually been adapted according to the experience gained by the researchers. This paragraph will shortly introduce the IPPM-methodology followed by the three case studies and the outcome of these.

6.1. IPPM-Methodology

The overall objective of the IPPM-methodology is to assess and develop engineering design processes. It comprises the five phases illustrated in Figure 1.



Figure 1: IPPM

6.1.1. Phase 1 – Identify & Characterize AS-IS Process

In order to develop engineering design processes, it is necessary to acquire an understanding of the existing process. The first step is therefore to map out the AS-IS process and identify the process steps where product information is being processed and product features and specifications are produced. The purpose of phase 1 is merely to get an overview of the process. The detailed insight into the individual process steps is acquired in phase 3.

6.1.2. Phase 2 – Requirements for New Process

After having identified and characterised the existing engineering design process, the next step is to make clear what requirements are to be placed on the process. Typical requirements could be reducing lead time for producing specifications, improving on time delivery for specifications, minimise resource consumption, increasing quality of specifications, etc.

When quantifiable targets have been set, the next step is to carry out a series of measurements to determine the current level of performance. Then the current level of performance and the target goals can be compared and the largest gaps can be identified. This will indicate where the greatest potential for improving the engineering design process will be.

6.1.3. Phase 3 – Identify Product Features

Phases 3 to 5 are closely interconnected as these are the phases in which the actual integrated modelling of product and process takes place, see Figure 2.

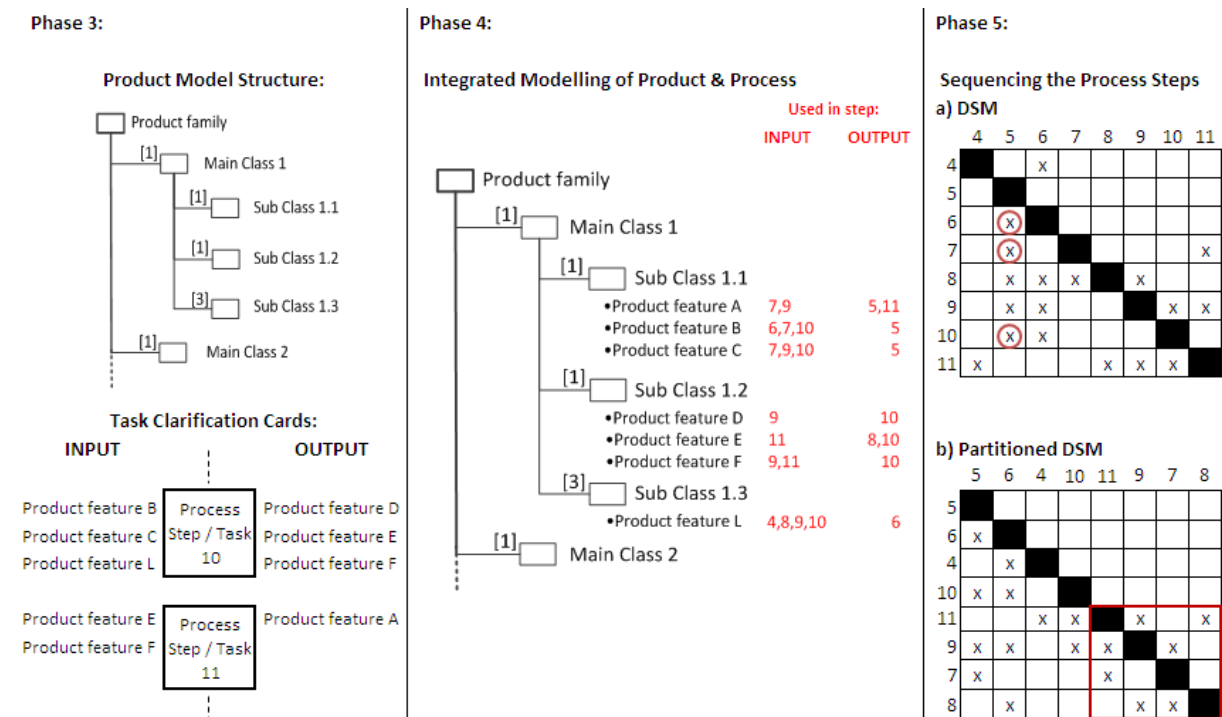


Figure 2: Phases 3 to 5

As stated earlier the basic proposition of this study is that understanding the product being engineered will enable you to acquire additional insight into the engineering design process and support you in improving the overall efficiency of the process. In phase 3 the first objective is therefore to construct a product model. Focus is put on identifying the relevant product features that are decisive for the engineering design process and not waste time on less significant product features. Identifying the relevant product features is mainly done through interviews with product experts, as they are the most likely to be able to identify which product features are critical to the process. In order to support these interviews and document the knowledge provided by the designers, an interview template called Task Clarification Cards are applied. The Task Clarification Cards clarify what engineering activities actually take place within the individual task. The cards are basically used for identifying what product features are used and produced in every significant engineering task. With this information it is possible to identify product feature dependencies between engineering tasks. Revealing interdependencies is however not the only benefit of the Task Clarification Cards. The engineering design process for complicated functional products is very complex and there is a need to share information as well as to communicate it among the parties involved in the process. The cards thereby also serve as a knowledge management tool, supporting knowledge sharing and preservation.

6.1.4. Phase 4 – Integrating the Product and the Process Model

In phase 4 the integration of the product features and the process steps takes place. The scope is to clarify where all product features are defined or modified. This is done by cross referencing the product features on the Task Clarification Cards with the product model from phase 3. The cross references between the product model and process steps provide valuable information on how to organise the sequence of the engineering design tasks.

6.1.5. Phase 5 – Designing the TO-BE Process

The 5th and final phase is about designing the new improved engineering design process based on the insight acquired through the previous phases. The cross referenced product model established in phase 4 clearly displays the dependency relationships of the process steps. Nevertheless, engineering design processes can be complex, with numerous process steps. Thus, the interdependencies in such processes are often complex and intertwined, making the job of reorganising the process steps in an optimal order too difficult to do without some kind of algorithm. The authors have therefore chosen the Design Structure Matrix, DSM, as a tool for dealing with this complexity. After the DSM is filled it is partitioned. The partitioning reveals the optimal sequence for the process steps based on minimising feedback loops in the process. Using the information displayed in a partitioned DSM a new TO-BE process map can be configured for the engineering design process.

In summary, the five phases reveal a detailed understanding of the single activities in a process, which can be utilised to reorganise the sequence of process steps in an engineering design process. By applying the insight gained by the IPPM, an engineering process can be redesigned

leading to improvements in process efficiency, quality, lead time and on-time delivery. More detailed information on the IPPM-methodology can be found within (names deleted to maintain the integrity of the review process).

6.2. Application of IPPM

In the period 2011-2012 the IPPM-methodology was applied three times on rather different engineering design cases. The experiences gained provided valuable insight into the applicability of IPPM, and it has enabled the authors to list what characteristics that should be in place in order to get maximum value from applying IPPM. Table 1 introduces and describes the characteristics that were found to be especially relevant to consider when applying IPPM.

Characteristic	Description
Actors Involved	How many people are involved in the engineering design process? The more people the higher is the need for coordination.
Cross-Disciplinary	Does the engineering design process spread over several departments and different disciplines?
Level of Detail Included	What level of detail is included in the modelling of the product and process? Too much will make the analysis overwhelming while too little will make it worthless.
Maturity Level of Product	What is the maturity level of the product being modelled? Is it prototype or variant creation of well-known products? The more open the solution space is, the more difficult is it to model the product.
Resource Consumption	What is the resource consumption for specifying the product in question? The more resources the more interesting is it to investigate whether improvements can be made.
Frequency	What is the frequency of engineering design process? Processes occurring more frequently might possess a higher improvement potential in total.
Process Nature	Is the process dynamic or static in nature? Dynamic processes can be hard to map as they evolve over time.

Table 1: Decisive characteristics for application of IPPM

The three cases will be presented below and evaluated according to the stated characteristics.

6.2.1. Case 1 – Drowning in Detail

The first case revolved around the ongoing customisation of a specific main component within the engine, called the hydraulic power supply (HPS). Customers often wanted the component adapted and optimised for their specific needs causing a small group of designers to continually adapt the component. The engineering design process exhibited no critical problems. However the actors involved had a wish to get the process scrutinised in order to establish whether the process flow could be improved.

The hydraulic power supply is a component that has been included in engine design for many years. The technology is quite fixed and the engineering work carried out can therefore be

characterised as variant creation of existing products. The team designing the HPS consisted of four persons, all possessing a rather detailed understanding of the components involved, even though they had separate areas of responsibility related to specifying the HPS. This meant that whenever coordination was necessary, every single actor most often knew exactly who to address to ensure a successful coordination. The engineering design process could therefore not be characterised as cross-disciplinary. In order to attempt to uncover knowledge that might not be apparent to the actors involved, the authors constructed a product model containing very detailed product knowledge.

As the design team was rather small, and since they were also responsible for the design of several other components, the resource consumption for designing the HPS was relatively low. The frequency on the other hand was quite high as approximately 75 % of the engines ordered needed to have a hydraulic power supply specified. The engineering design process was very fixed and static and was conducted by and large the same way every time.

What was especially time consuming in case 1 was the high level of detail included in the product modelling. Every nut and bolt was carefully included only with the outcome that the authors realised that the value of including them was very limited. In case one designer made alterations on very specific part level it rarely affected the design tasks of the other designers. And in case it did, the team only consisted of four people so the coordination was straightforward and quite uncomplicated. The somewhat discouraging conclusion of applying IPPM on case 1 was therefore that the effort put into the analysis by far exceeded the yield gained.

6.2.2. Case 2 – New Technology Development

The second case was the introduction of new emission technology to be incorporated into all engines. The company had developed the emission technology on prototype level but it had not yet been adapted to comply with the entire product range. The designers therefore faced the task of developing a complete set of engineering design processes for specifying their products including the new emission technology. The product being in an early development phase meant that no formal engineering design processes for creating customer specific variants of the product with the new emission technology was established. The actors to be involved in this future specification process therefore had a need to acquire an overview of interdependencies between different design tasks.

As the product was on prototype level and still quite immature, the engineering design processes were still very dynamic. There were a lot of iterative loops of redesigning and rethinking solutions, which required many resources from the staff involved. One thing the designers were much occupied with was to create an emission system that could cover several engines with the same design. This way they could reduce the engineering efforts needed and keep the frequency

of designing the emission system low. The engineering design team to be involved in designing the emission technology as part of the overall products consisted of 8 people, scattered across different departments and engineering disciplines. The need for coordination between designers was therefore somewhat higher compared to case 1.

As a lesson learned from case 1 was to be careful when choosing the level of detail to include, the authors were cautious when establishing the product model. The designers were encouraged only to include what they considered to be relevant product features when filling in the Task Clarification Cards.

To model a product being still on prototype level was however difficult as fundamental design changes and reprioritisations occurred frequently. This resulted in constant revisions of the product model as well as the Task Clarification Cards. Thereby the modelling task never really came to an end and the benefits of applying the IPPM could not be fully harvested.

6.2.3. Case 3 – Creating Variants in Large Design Team

The third case was an analysis of a subset of the order process within the company. Based on an order from a customer it was analysed how a specific engineering department designed a solution fulfilling the customer request. The engineering design tasks to be performed within the department were highly interdependent and also dependent on engineering work carried out in other departments. The overall process was therefore characterised as being highly cross-disciplinary. The department in question was experiencing increasing lead time and efficiency problems due to lack of overview over dependencies between engineering design tasks both within and outside their own department. Too often bottlenecks were identified which were caused by dependencies not taken into account when internal deadlines were set for the different engineering tasks.

The design team, consisting of 11 people, was occupied with adapting existing engine components in accordance with specific customer requests. They were not involved in fundamental redesign of the product but rather on creating variants of well-known components. The frequency of the process was high as it was conducted every time the company received an order. The process nature was therefore also quite static even though it differed exactly which components were to be customised for the individual order. The resource consumption was high also due to the fact that the scope of the engineering design process was wider. Whereas case 1 and 2 focused on specific components, case 3 included many components to be specified by the department in question.

As earlier applications of IPPM caused substantial problems related to the level of detail to include in the analysis, the authors put effort into minimising the level of detail. In stead of asking the designers to inform both inputs and outputs from their individual design tasks when

filling in the Task Clarification Cards, they were only to provide information on which inputs were needed to conduct the task. This way only product features that were decisive for the engineering design process were included, keeping the level of detail low without losing valuable information.

By applying the IPPM on case 3 the authors were actually able to thoroughly model the product and process in an integrated way creating valuable insight into product feature dependencies between the engineering design tasks. By utilising this insight it will be possible to develop the engineering design process and improve the performance of the department in question.

6.3. Summary

In summary, the application of the IPPM-methodology was conducted on three cases which exhibited quite different characteristics. Table 2 restates the characteristics identified as especially crucial for the application of IPPM and summarises how the three cases relates to those characteristics.

Case	Actors Involved	Cross-Disciplinary	Level of Detail Included	Maturity Level of Product	Resource Consumption	Frequency	Process Nature
1	4	No	High	Variant Creation	Medium	Medium	Very Static
2	8	Yes	Medium	Prototype Level	High	Low	Dynamic
3	11	Yes	Low	Variant Creation	High	High	Quite Static

Table 2: Characteristics of case studies

In terms of outcome of applying the IPPM it was clear that case 3 was the most appropriate case. Case 1 drowned in detailed product modelling, providing only limited value in a process setting that was quite simple and easy to cope with. Considering a product on a low maturity level was the main reason for the problems experienced in case 2. But case 3 seemed to possess a more appropriate mix of characteristics making the application of IPPM suitable and provided valuable insight.

7. Discussion & Conclusion

Engineering design processes are very often ill-defined, iterative, complex and very knowledge intensive. They can therefore be difficult to model in such a way that adequate insight into the processes is acquired. By integrating a product model into the development of engineering design processes, the authors believe a better understanding of the engineering activities will be acquired. This is the background for developing and applying the IPPM-methodology.

However, to conduct interviews with several designers for all engineering tasks within an overall process is beyond doubt a time-consuming activity. And because of that it is important that

process modellers do some thorough considerations before applying a tool such as the IPPM. The IPPM provides valuable insight into what is actually taking place within engineering design processes by integrating a product model with the process model. But it also requires a substantial amount of resources to conduct such a study. By doing a preliminary assessment of an engineering design process with regards to the characteristics identified in this paper, the process modeller can significantly enhance the output of applying the IPPM.

Based on the case studies conducted it has been possible to identify seven characteristics that have significant impact on the applicability of IPPM: Actors involved in process, whether the process is cross-disciplinary, level of detail included in analysis, maturity level of product, resource consumption within process, frequency of process and the nature of the process. In order to create maximum value when applying IPPM it is crucial to make sure the process is worthwhile putting effort into optimising. This is ensured if the frequency as well as resource consumption is high. Also it is essential that the coordination challenges are substantial, which is indicated by a high number of actors as well as whether the engineering tasks in question spread over several disciplines and departments. Furthermore, the process modeller should make sure that the maturity level of the product is rather high. Products on prototype level are hard to model as they continually develop causing the modelling task to extend significantly. Similarly, one should only address processes that are rather static. If the process flow is too unsettled the process modelling task can be too tedious. Finally it is very important to find an appropriate level of detail too include in the modelling task. Process modellers should be careful too capture what is decisive but also be cautious of not including too much detail as this might cause the analysis too drown in irrelevant information.

To the knowledge of the authors no current methods for redesigning and developing engineering design processes do take into account the product features to be used in every process step. We therefore believe that our research on this matter could provide a contribution to process modelling theories, especially within the field of engineering design. Generating theory through action research is situation specific and incremental (Coughlan & Coughlan, 2002). This is also the case with the research at hand. However the belief is that a significant step from particular to general can be taken with this research, as the case company represents a typical engineering design company.

8. References

- Albers, A. and Braun, A. (2011), "A generalised framework to compass and to support complex product engineering processes", *International Journal of Product Development*, vol. 15, no. 1-3, pp. 6-25.
- Collis, J. and Hussey, R. (2003), *Business Research. A practical guide for undergraduate and postgraduate students*. 2nd edition. Palgrave Macmillan, New York.

- Coughlan, P. and Coghlan, D. (2002), "Action Research for Operations Management", *International Journal of Operations & Production Management*, vol. 22, no. 2, pp. 220-240.
- Eckert, C. and Clarkson, J. (2005), "The reality of design", in Eckert, C. and Clarkson, J. (Ed.), *Design Process Improvement – A review of current practice*, Springer-Verlag, London, pp. 1-29.
- Eppinger, S. D. and Browning, T. R. (2012), *Design Structure Matrix Methods and Applications*, Massachusetts Institute of Technology.
- Eppinger, S. D., Whitney, D. E., Smith, R. P. and Gebala, D. A. (1994), "A model-based method for organizing tasks in product development", *Research in Engineering Design*, vol. 6, pp. 1-13.
- Fixson, S. K. (2004), "Product architecture assessment: a tool to link product, process, and supply chain design decisions", *Journal of Operations Management*, vol. 23, pp. 345-369.
- Gummesson, E. (1991), *Qualitative Methods in Management Research*, Newbury Park, SAGE
- Hvam, L. (2001), "A Procedure for the Application of Product Modelling", *International Journal of Production Research*, vol. 39, no. 5, pp. 873-885.
- Hvam, L. and Jensen, K. R. (2007), "A multi perspective approach for the development of visual configuration systems", *Computers & Industrial Engineering*, vol 53, no. 3, pp. 401-419.
- Harlou, U. (2006), *Developing product families base on architectures - Contribution to a theory of product families*, Dissertation, MEK, Technical University of Denmark.
- Kagan, C., Burton, M., and Siddiquee, A. (2008), "Action research", in C. Willig & W. Stainton-Rogers (Eds.), *The SAGE Handbook of Qualitative Research in Psychology* (pp. 32–53).
- Karlsson, C. (2009), "Researching Operations Management", in Karlsson, C. (Ed.), *Researching Operations Management*, Routledge, New York and London.
- Maier, A. M. and Störrle, H. (2011), "What are the characteristics of engineering design processes?", 18th *International Conference on Engineering Design*, Copenhagen, 15-18 August 2011.
- O'Donovan, B., Eckert, C., Clarkson, J. and Browning, T. R. (2005), "Design planning and modelling", in Eckert, C. and Clarkson, J. (Ed.), *Design Process Improvement – A review of current practice*, Springer-Verlag, London, pp. 1-29.
- Smith, M. L. (2006), "Overcoming theory-practice inconsistencies: Critical realism and information systems research", *Information and Organization*, vol. 16, no. 3, pp. 191-211.
- Steward, D. V. (1981), "The design structure matrix: a method for managing the design of complex systems", *IEEE Transactions on Engineering Management*, vol. EM-28, no. 3, pp.71-74.

Ulrich, K. T. and Eppinger, S. D. (2003), *Product Design and Development*, New York, McGraw-Hill/Irwin.

Voss, C., Tsiriktsis, N., and Frohlich, M. (2002), "Case research in operations management", *International Journal of Operations & Production Management*, vol. 22, no. 2, pp. 195-219.

White, S.A. (2004), *Introduction to BPMN*, IBM Cooperation, BP Trends.

PAPER 5 - PRODUCT COMPLEXITY IMPACT ON QUALITY AND DELIVERY PERFORMANCE

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Product Complexity Impact on Quality and Delivery Performance

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Abstract

Existing literature on product portfolio complexity is mainly focused on cost related aspects. It is widely acknowledged that an increase in a company's product portfolio will lead to an increase in complexity related costs such as order management, procurement and inventory. The objective of this article is to examine which other factors that might be affected when a company is expanding its product portfolio, if initiatives are not taken to accommodate this increase. Empirical work carried out in a large international engineering company having a market leader position confirms that cost is increased, but it is not the only factor affected. We can document that there is a tendency towards increasing lead times as well as a drop in on time delivery and quality for newly introduced product variants. This means that the company experiences a reduced ability to deliver on time while also receiving more quality related complaints for the product variants, seldom engineered and produced.

1. Introduction

Increases in variance are important for many reasons. It supports companies in attracting new customers and in creating differentiation from competitors' products. The challenge is to offer the correct variance and how to control the variance. Too little variance will obstruct companies in developing their business, while too much variance will threaten to undermine the efficiency.

When introducing new variants into a product portfolio it will most likely generate an increase in turnover. But it will at the same time lead to an increase in complexity related costs as multiple functions within the company such as development, engineering, production planning, sales and marketing need to deal with more variants. But cost might not be the only factor at stake. When complying with unique customer requests the company will have to initiate an engineering process, for which the lead time and quality of the outcome cannot be determined beforehand.

It will be of significant value to document whether there exists a dependency between an expanding product program and increases in lead time as well as reduced on time delivery and quality, if initiatives are not taken to comply with the increasing product program.

Companies whose main strategic focus is on market share might choose to launch new variants knowing that they will not be profitable, because by doing so they will maintain their market share and create market barriers for new competitors who wish to enter the market. In other words, cost is a price they are willing to pay. But if it can be documented that the lead time and quality are affected by increased complexity the company might need to reconsider. The price of delivering products too late which at the same time fail to meet customer expectations will probably lead to loss of customers and thereby a reduction of market share. It is therefore important that companies consider how to accommodate variance in their product portfolio.

The scope of this article is narrowed to focus on whether there is interdependency between increases in product portfolios and cost, lead time, on time delivery and quality. Later work will then focus on how to accommodate increases in product portfolio.

Data analysis has been carried out in a large international engineering company to investigate whether an expanding product program can lead to longer lead times, poor on time delivery and lower quality. The company is designing one-of-a-kind customer specific products and it is market leader within its industry.

2. Theory

Several theories have relevance for this study, and the most central will be presented shortly below.

2.1 Mass customization

In the world of today's competitive business there is an increasing demand for customized products, driving companies to constantly expand their offered product variety, often with the effect of introducing more complexity into the product families (Pine, 1993). Many companies are thereby experiencing increasing demands from their customers for the delivery of customized products that have almost the same delivery time, price and quality as mass-produced products. (Hvam, Mortensen and Riis, 2008). One way of complying with this is by engaging in mass customization. Mass customization is based on combining the efficiency of mass production with the differentiation possibilities of customization (Tseng and Piller, 2003).

Recent research suggests that in order to achieve full benefits from mass customization a company needs to develop three key capabilities. An ability to identify the product attributes along which the customer needs diverge, an ability to reuse or recombine existing organizational and value chain resources, and an ability to help customers identify or build solutions to their own needs (Salvador, De Holan and Piller, 2009).

2.2 Product architecture and modularization

Many different definitions of a product architecture exists in literature. (Sanchez, 2000) argues that a product architecture is created when a new product design has been decomposed into its functional components and interface descriptions have been fully specified. The types of interfaces range from attachment-, transfer-, control and communication-, spatial-, to environmental interfaces. (Meyer and Lehnerd, 1997) describes the architecture as being the combination of subsystems and interfaces. They argue that every product has an architecture, and that the goal is to make that architecture common across many variants. (Ulrich, 1995) has the comprehension, that a product architecture is the scheme by which the functions of the product is mapped towards the physical components, thus defining the product architecture as the arrangement of functional elements, the mapping from functional elements to physical components and the specification of interfaces among these. (Harlou, 2006) describes a product architecture as a structural description of a product assortment, product family or a product. It consists of design units, standard designs and interfaces, where design units are characterized by being unique to each product, and standard designs characterized by being reused between one or several product families. In this definition a clear emphasis is put on the decision of reuse, adequate documentation and organizational ownership.

Product modularity is closely related to the architecture term as well as mass customization. (Worren, Moore and Cardona, 2002) defines a modular architecture as a special form of product design in which loose coupling is achieved through standardized component interfaces, which enables the production of a large number of end items. In short, product modularity can be defined as the use of standardized and interchangeable components or units that enable configuration of a wide variety of end products (Jacobs, Vickery and Droge, 2007).

2.3 Product complexity

Product complexity describes the variety of and within the products or services you offer your customers. In general too much variety will be a burden both for the customers and the company, while too little variety will decrease the competitive advantage it can be to offer variety. It is often very difficult to find the right level of complexity and many companies suffer from the fear of having too little. Variety in products offering customers something they are willing to pay for is good complexity; variety that they will not pay for, or pay enough for is bad complexity. (Wilson, et al., 2010). Many firms are convinced that they maximize the fit between product offerings and customer desires when they increase their product variety, and that this allows them to maintain or even increase their market share. This might be the case but at the same time companies often experience lower performance of its internal operations when product variety increases (Salvador, Forza and Rungtusanatham, 2002)

When creating variants of an existing product you achieve greater differentiation compared to your competitors. This might result in growth in sales but at the same time it will increase the product portfolio complexity as it is necessary to manage another product variant. It is therefore a balance, and the task of finding an optimal level of product complexity is difficult. The optimal level of complexity in a product portfolio can be described as achieved when the combination of diminishing sales return and increasing costs due to complexity are taken equally into account (Closs, Jacobs, Swink and Webb, 2008).

2.4 Performance Measurement

Performance measurement can be defined as the process of quantifying the efficiency and effectiveness of actions, while a performance measure can be defined as a metric used to quantify the efficiency and/or effectiveness of an action (Neely, Gregory and Platts, 2005).

There are numerous reasons for using performance measurement, but common for all is that individual feelings and perceptions should be replaced with facts. Without performance measures, managers cannot really understand how their business work, the problems within them, and whether their attempts to improve performance is working as planned (Kaydos, 1999). Performance measurement can therefore be seen as an important precondition for making improvements. (Harbour, 1997) even claims that you cannot improve what you cannot or do not measure.

Recent investigations carried out by (Davenport & Harris, 2007) showed that a consistent use of analytics and performance measurement have a great impact on business and financial performance. High performers are 5 times more likely to use analytics strategically compared to low performers.

3. Hypothesis

The hypothesis in this paper is that when expanding the product program it will lead to an increase in cost and lead time as well as a drop in quality for the new variants. The company will then experience a reduced ability to deliver on time while also receiving more complaints related to the new product variants. Or put differently, companies will experience lower costs, lower lead times, improved ability to deliver on time as well as higher quality for product variants that have been frequently designed.

4. Introduction to Case Company

The research for this article is carried out in a large international engineering company designing one-of-a-kind customer specific products. The company has no physical production but is only designing the products. They are the market leader within their industry and the primary strategic goal is to maintain this position. In order to fulfill this goal the company strives to win every order, even if it requires significant development and engineering work. They thereby also acknowledge that their profit on the short run might be reduced, but it is believed that if the market share is kept high potential competitors will have great difficulties in entering the market, which will secure high profit in the long run. This cannot be substantiated but the company has chosen this strategy and accepted the uncertainty that exists in terms of cost. The objective is then to win every order by delivering customer specific, high quality products on time.

Within the last years the market has gotten more diverse and more unique customer requests occur. This is reflected in the product program, which today is approximately twice the size as it was just 5 years ago. This has resulted in an increased pressure on the engineering departments as they are required to design considerable more new variants than earlier. The consequence has been a steep increase in the number of very customer specific product variants in the product program. Sales statistics show that more than 40 % of the product variants sold to the market has only been designed once or twice within the last decade. Nevertheless, the company strategy of complying with every customer request no matter how unique remains the same.

It is a characteristic for the company that the sales department is quite decoupled from the engineering departments. The sales department is counseling and negotiating contracts with potential customers without showing too much consideration for potential engineering constraints and challenges. As mentioned above the company strives to win every order, regardless of how unique the request is from the customer. The belief is that the best way to satisfy the customer is to offer the most technically advanced solution or to comply with the customer's request without trying to sway the customers towards choosing a product variant that is more frequently designed. The company fears that if an alternative variant is suggested to the customer, the customer will instead address a competitor and place the order there.

At current time the customer is therefore not consistently informed of how unique the variant being requested is, and how often it is actually designed. The uncertainties that might exist

concerning development time and level of quality for new product variants are therefore not known by the customer. This means that the customer ordering a unique product variant is not given the opportunity of reconsidering whether another frequently designed variant should be selected instead.

The company is using a modular based product platform. When introducing a new variant it doesn't necessarily mean that all modules are new. On the other hand, two variants with the same designation are not completely alike either, as the products are specified in accordance with specific customer requests. Two customers asking for the same product might have different preferences requiring modification of the original design, thus resulting in design of new modules. When a substantial amount of orders has been made for a specific product there is a larger basis for reuse of modules for the specific product variant. So the more often a variant has been designed, the less new modules are needed in average to fulfill a new customer request. The modules differ significantly in size as well as the corresponding workload required for designing it. This analysis takes into account which new modules are designed for each specific order.

5. Definition of Measurements

In order to illuminate the hypothesis stated above, analysis has been carried out for following six measures:

5.1 Number of design specifications made according to each product variant

A design specification is a complete design of a product variant each consisting of approximately 100-200 modules depending on which product variant is chosen. Two instances of the same product variant can have the same designation without all the modules are the same. But the functional properties remain the same and that is why the same designation is used. There are today 158 different active product variants in the product program. An active variant here signifies that a specific design of the variant has been made within the last decade. The measure will illustrate the diversity in the company's product program according to how many variants are offered to the market as well as how often each of these variants are actually designed.

5.2 Average % new modules made per design specification according to each product variant

As mentioned above, a design specification consists of 100-200 modules. This measure tells in average how many of these modules are new in the design specification according to each product variant. The remaining modules are then reused from earlier design specifications.

5.3 Average costs associated with designing new design specifications according to each product variant

The costs associated with designing a new design specification is dependent on the number of new modules that need to be designed. But the kind of modules that need to be designed also

have great influence on the costs. This measure tells the average cost of working out design specifications according to each product variant.

5.4 Average on time delivery of modules according to each product variant

The modules in each design specification are delivered successively and there are different delivery deadlines for the different modules in each design specification. The measure reports how many modules in average are not delivered on time according to each product variant.

5.5 Average lead time for new design specifications according to each product variant

The lead time is here defined as the amount of engineering and development time that goes into designing the new modules needed for each design specification. The measure is dependent on how many new modules that need to be designed for the design specification as well which types of new modules are required. The lead time for designing new modules is then grouped according to which product variant they are intended for. The measure therefore tells us the average lead time for making a complete design specification according to each product variant.

5.6 Average complaint related costs according to each product variant

This measure is chosen as indicator for the quality of the designs made. The more complaint related costs that occur for a specific design specification the lower quality is the design specification assumed to have. The measure reports the average complaint related costs that occur per design specification according to each product variant.

The approach for testing the hypothesis is now to relate the first measure, ‘Number of design specifications made according to each product variant’, according to the remaining five measures. It can thereby be tested whether it can be rendered probable that lower costs, lower lead time, improved ability to comply with delivery deadlines and higher quality occur for product variants, that have been designed frequently compared to the rarely designed product variants.

6. Research method

The data upon which the findings are based is drawn from the company’s PLM and ERP systems as well as internal company databases. The findings are therefore mainly quantitatively based. Some sources have existed for many years and contain data that has been registered elaborately for more than a decade. But other sources have not been established until 3 years ago. It has therefore not been possible to acquire data that could describe every single product variant with regards to all six parameters under investigation for a period of 10 years. This especially becomes evident when considering product variants that are rarely designed. If one design has been made only a few times within the last decade, it has in some cases not been possible to identify data describing the same variant in terms of for example on-time delivery. But nevertheless each finding is based on a significant amount of data including approximately 2.500

complete design specifications each including a set of modules, more than 45.000 newly designed modules and close to 7.500 complaints.

A clear limitation for this article is that only data for one company has been analyzed. It is therefore only possible to investigate whether the hypothesis can be substantiated for the case company. In order to generically test the hypothesis, similar data analysis should be carried out in several other companies.

7. Empirical data

As mentioned above the data for this research is drawn from several systems. This paragraph will elaborate on the data foundation for each of the six measures used. The number of design specifications as well as the number of new modules made per design specification according to each product variant is based on data from the company PLM-system. For every module delivered to customers it is checked whether the module has figured in earlier design specifications. If not, the module is assumed to be a new module.

The costs associated with design according to each variant are based on expenses registered as design costs from the company ERP-system. Each design department has declared their resource consumption for each design task. By grouping the design costs associated with each specific design specification across all departments, it has been possible to estimate the average costs associated with working out new design specifications according to each product variant.

On time delivery of modules is based on internal task management databases containing customer expectations concerning lead times for different modules. This data is cross referenced with PLM-data stating when a design specification has been created and when the different modules are actually sent to the customers. The module is assumed to have been delivered on time, if the period between the creation of the design specification and the delivery date of the modules within the specification is shorter than stated in the task management databases.

The average lead time for new design specifications according to each product variant is also based on PLM-data. Lead time for all modules has been registered as the period between the creation and the release time of the module. For each design specification it is then summed up what the total lead time is for all new modules figuring in the relevant design.

The final measure, complaint related costs according to each product variant, is based on expenses registered in the ERP-system by warranty and maintenance employees in the company.

8. Analysis

Based on the data gathered it is possible to test the hypothesis of the article.

Each of the following plots has the same horizontal axis as well as primary vertical axis, to the left, designated 'Designs made'. Along the horizontal axis, each product variant is shown arranged after how often the specific variant has been redesigned, with the most frequent furthest to the left. Along the primary vertical axis is then the actual number of redesigns illustrated by the blue columns for each product variant.

The plots then differ with respect to the secondary vertical axis, to the right, where the following five parameters are outlined; average cost per design, average number of new modules per design, % of modules not delivered on-time, average lead time per design and average complaint related cost per design. For each parameter a linear tendency line is depicted in accordance with simple linear regression. These tendency lines will give indications of whether the hypothesis can be substantiated. Most numbers along the secondary axes have been indexed of confidentially reasons.

Finding 1 basically shows the relation between how often a product variant is designed and what the average cost of designing the variant is. As an example of how to read the plots consider product variant 61, marked with a circle. It has been redesigned 7 times, which can be read from the primary vertical axis to the left, and the cost index is approximately 60, as indicated on the secondary vertical axis to the right. As expected, there is a tendency stating that product variants that are rarely designed are more expensive to design.

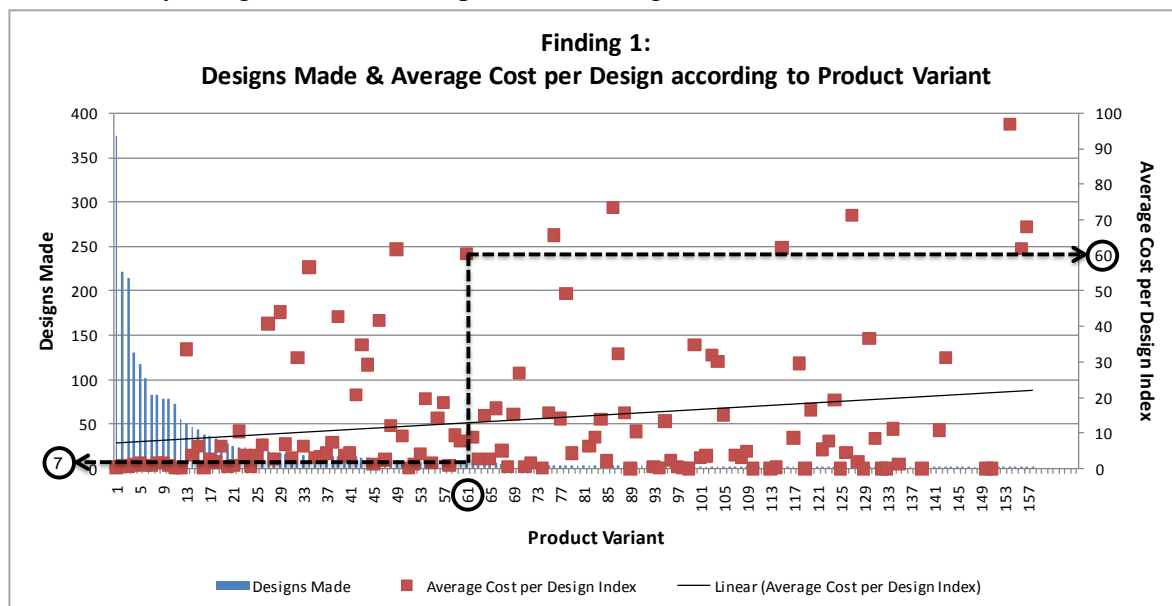


Figure 1: Designs made and average cost per design according to product variant

Finding 2 illustrates how many new modules that in average are made each time a product variant is designed. It therefore states how good the company is to reuse modules for every product variant. As expected, only few new modules are required for product variants that are often designed. The tendency is very clear and it is worth noticing that the dispersion of data is

bigger for rarely designed variants. This indicates that the uncertainty concerning how much design work that needs to be put into designing a product variant is greater for the infrequent variants.

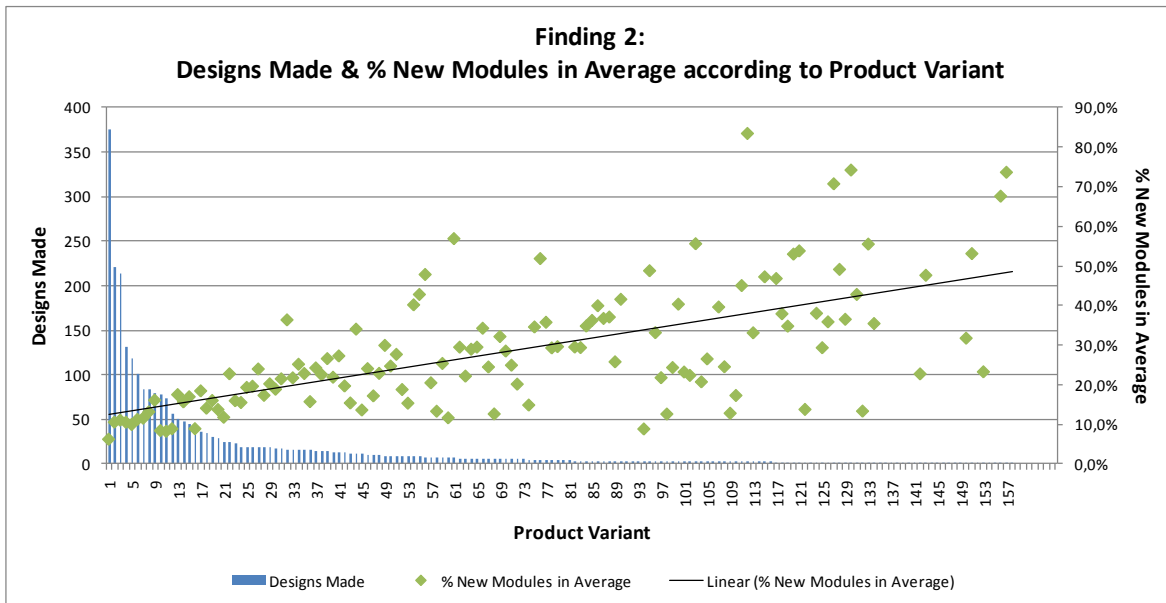


Figure 2: Designs made and % new modules in average according to product variant

Finding 3 is showing the relationship between how often a variant has been designed and how many modules fail to meet the intended delivery deadline for each variant. The data is somewhat scattered but there is a tendency towards reduced ability to deliver modules on time for product variants that are rarely designed. As the data for the company's ability to deliver on time has only been registered for 3 years there are some holes in the empirical foundation. It would be very interesting to repeat this analysis when more data has been gathered to see if the tendency will continue. Nevertheless finding 3 shows a quite clear tendency and it can be rendered probable that the ability to deliver on time is improved the more often a product variant has been designed which supports the hypothesis.

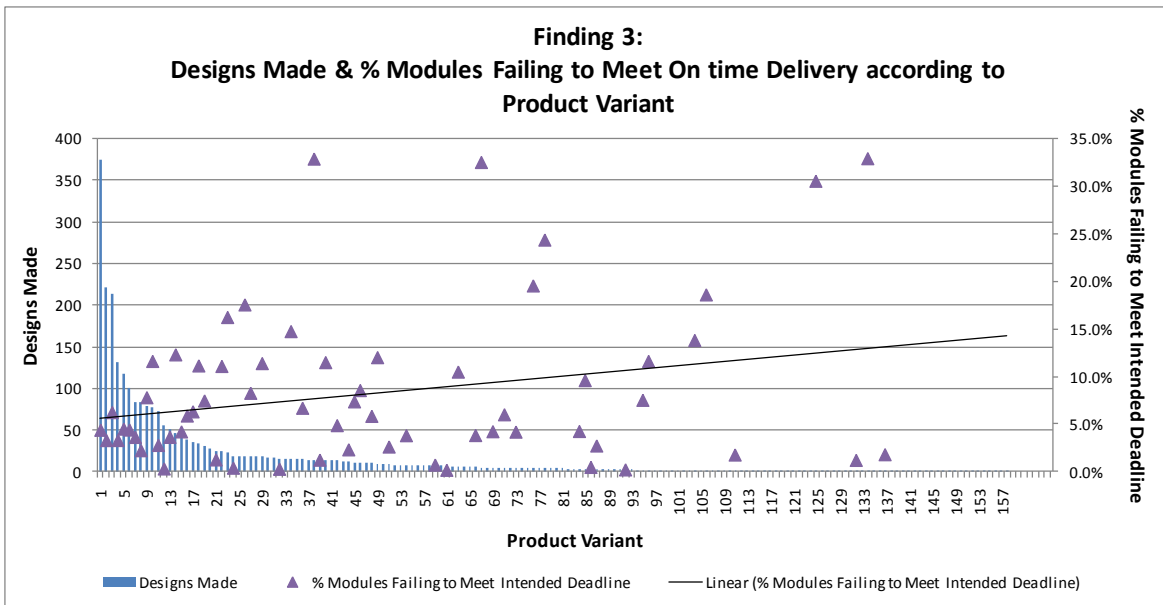


Figure 3: Designs made and % modules failing to meet intended deadline according to product variant

By combining the data foundation for finding 2 and 3 it becomes evident that there is a clear connection between the two. Analysis concerning on time delivery for new modules shows that 47 % of the modules are not delivered on time, whereas modules that have been used before only fail to meet intended delivery in 16 % of the cases. The customer ordering a unique or rarely designed product variant will therefore have a considerably different perception of the company’s reliability compared to the customer ordering a frequently designed product variant. The reason for this deviation is that at current time the number of new modules needed for a specific order is not taken into account when determining delivery agreements. This is an undesirable situation and the company might need to reconsider their procedures on this matter.

Finding 4 addresses the lead time according to each product variant. Again a rather clear tendency can be spotted indicating that product variants that are rarely designed have a significantly longer lead time compared to frequently designed variants. The reason for this can be found by again referring to finding 2 showing the amount of new modules needed for each product variant. Data analysis shows that for approximately 86 % of the module types, new modules have a longer lead time compared to reused modules. Thus, ordering a rare product variant leads to a larger requirement for new modules which again leads to a longer lead time.

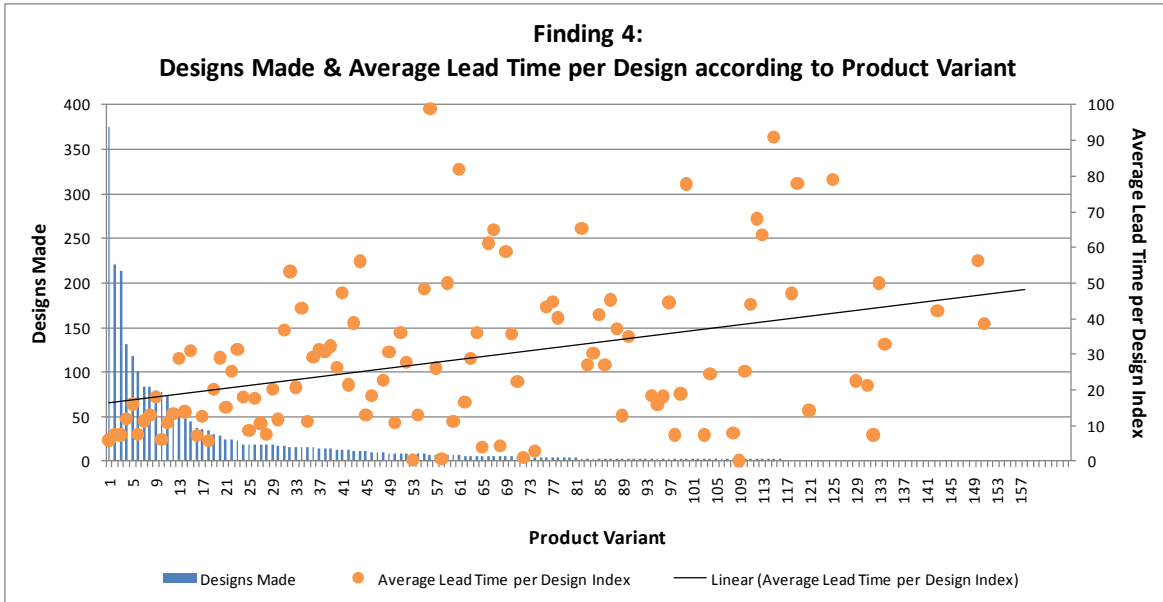


Figure 4: Designs made and average lead time per design according to product variant

This means that the customer ordering a more unique variant will experience a considerable later time of delivery. As it was noted earlier the delivery agreements are by default not influenced by which variant the customer is ordering. Therefore a customer will most likely have the same expectation concerning delivery time every time he or she is ordering a new product. But as finding 4 shows, the lead time differs from variant to variant, and the customer might experience ordering a product and then receive it significantly later compared to the last product ordered. This is unfortunate and will undoubtedly affect the customer's perception of the company's reliability in a negative direction. The hypothesis is thereby supported as lead time is higher for product variants rarely designed.

The final finding addresses the complaint related costs according to each product variant. Again the hypothesis is substantiated as the gathered data shows a tendency towards increased complaint related costs for product variants that are rarely designed. For these variants the company will experience increased costs in rectifying errors in the design while at the same time the customer will lose confidence in the company.

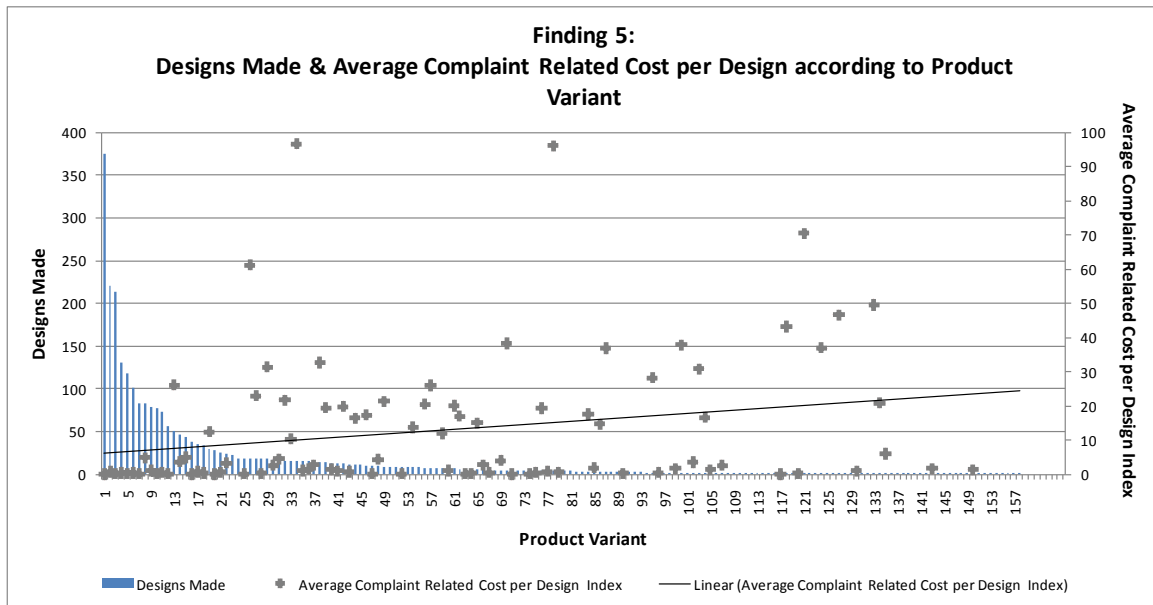


Figure 5: Designs made and average complaint related cost per design according to product variant

All in all the plots show the same tendency. Product variants that are rarely designed are likely to be more expensive to design, to require more new modules, to have a longer lead time, to exhibit a more frequent failure to meet delivery deadlines and to result in increased complaint related costs.

9. Conclusion

Based on the findings the initial hypothesis can be substantiated. It is found that there are tendencies showing that the more often a product variant is designed the lower is the cost and lead time for designing it, the ability to deliver on time is improved and the complaint related cost for the given product variant is lower.

As the situation is today the company strives to win every order by designing exactly the product the customer is requesting delivered on time and in highest quality. But finding 3-5 reveals that they are not completely successful in doing so. The belief is that by complying with every unique customer request the company will get the most satisfied customers. But if the customer experience a longer lead time and a poorer quality, the customer is unlikely to be completely satisfied.

The company's main objective of maintaining or expanding the market share is understandable. But the company should be careful that they in their pursuit of fulfilling every unique customer request, do not undermine the very same thing they are trying to achieve. They should therefore consider distinguishing between product variants that can be regarded as standard products and variants which are more unique. When customers then order product variants that are rarely designed the company can still choose to accept the order. But before doing so, they can inform

the customer of the consequences, in terms of lead time and quality that are likely to occur. If the customer has been presented to these issues up front, the level of dissatisfaction occurring if modules are delivered late and are in inadequate quality, is likely to be considerably lower. Another scenario could be that the customer decides to choose a different more common product variant, if lead time and quality is of highest importance. This will also be beneficial for the company as the cost of designing these frequently occurring variants are shown to be lower.

As mentioned earlier there are many product variants that have only been designed once or twice within the last decade. A potential error in this research is that characteristics for the period in which the design is made, is not taken into consideration. One design might have been made at a time where the overall workload in the company has been very high. A long lead time will then not necessarily mean that a lot of working hours has been put into designing the variant. It could just be an expression of general bustle where many orders are processed at the same time.

A clear limitation of this article is that the findings are based on data from one company only. It can therefore not be concluded whether the findings can be generalized. The plan is to expand the study to include at least five more comparable companies to test the hypothesis on a wider scale. If similar tendencies can be found, the validity of the findings will be improved considerably. Another aim of the future work will also be to get insight into how engineering companies could actually deal with increases in their product programs. Are they aware of the consequences and how do they try to minimize the undesirable outcomes? Three dimensions will then be evident to address; people, processes and tools. Could the solution be to simply hire more people? Or should processes be improved to better comply with the increasing portfolio? Would it for example be suitable for companies to divide their design processes into at least two main tracks? One track to take care of the standard requests and typical design work and another track dealing with very customer specific and unprecedented requests. Or would it be better to apply new tools and technology to assist the companies in accommodating and controlling the increasing variance? And how are the opportunities for combining these? These are all questions that are highly relevant, and which will be addressed in our future research.

References

- Closs, D.J., Jacobs, M.A., Swink, M. and Webb, G.S. (2008), "Toward a theory of competencies for the management of product complexity: Six case studies", *Journal of Operations Management*, 26: 590-610.
- Davenport, T. and Harris, J. (2007), *Competing on Analytics. The New Science of Winning*, Harvard: Harvard Business School Press.
- Harbour, J. L. (1997), *The Basics of Performance Measurement*, New York: Quality Resources.

- Harlou, U. (2006), *Developing Product Families based on Architectures*, Department of Mechanical Engineering, Lyngby: Technical University of Denmark.
- Hvam, L., Mortensen, N.H. & Riis, J. (2008), *Product Customization*, Berlin: Springer.
- Jacobs, M., Vickery, S. & Droge, C. (2007), "The effects of product modularity on competitive performance", *International Journal of Operations Management*, vol. 27, no. 10: 1046-1068.
- Kaydos, W. (1999), *Operational Performance Measurement. Increasing Total Productivity*, Florida: Taylor & Francis Group.
- Meyer, M. H. and Lehnerd, A.P. (1997), *The Power of Product Platforms*, New York: Free Press
- Neely, A., Gregory, M. and Platts, K. (2005), "Performance measurement system design", *International Journal of Operations & Production Management*, vol. 25, no. 12, pp. 1228-1263.
- Pine, B.J. (1993), *Mass Customization: The new frontier in Business Competition*, Harvard: Harvard Business School Press.
- Salvador, F., Forza, C. and Rungtusanatham, M. (2002), "Modularity, product variety, production volume and component sourcing: theorizing beyond generic prescriptions", *Journal of Operations Management*, vol. 20, pp. 549-575.
- Salvador, F., De Holan, P. M. and Piller, F. (2009), "Cracking the code of Mass Customization", *MIT Sloan Management Review*, vol. 50, no. 3.
- Sanchez, R. (2000), "Modular architectures, knowledge assets and organizational learning: new management processes for product creation", *International Journal of Technology Management*, vol. 19, no. 6.
- Tseng, M. M. and Piller, F. (2003), *The Customer Centric Enterprise. Advances in Mass Customization and Personalization*, Berlin: Springer.
- Ulrich, K. (1995), "The role of product architecture in the manufacturing firm", *Research Policy*, vol 24, pp. 419-440.
- Wilson, S. A. and Perumal, A. (2010), *Waging War on Complexity Costs. Reshape Your Cost Structure, Free Up Cash Flows and Boost Productivity by Attacking Process, Product and Organizational Complexity*, U.S.A.: McGraw-Hill.
- Worren, N., Moore, K. and Cardona, P. (2002), "Modularity, strategic flexibility, and firm performance: a study of the home appliance industry", *Strategic Management Journal*, vol. 23, no. 12, pp. 1123-1140

**PAPER 6 - THE COST OF CUSTOMISING – ASSESSING THE PERFORMANCE OF A MODULAR
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The Cost of Customising

Assessing the Performance of a Modular Product Program

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Abstract

Introducing modularity in product development as a mean for dealing with increasing levels of variance within product portfolios has been widely and successfully applied by many companies. It is however important to acknowledge that challenges related to product portfolio variance will not disappear after introducing modularity. A new type of variance on modular level is likely to develop over time.

Empirical work carried out in a large international engineering company designing customer specific products confirms that increasing levels of variance within module portfolios can lead to reduced performance according to crucial key performance indicators. The findings illustrate the importance of recognising the potential trade-off when continually complying with unique customer requests. The paper contributes with a detailed insight into a company's competitive performance trade-off on a modular level after introducing mass customisation. The paper also adds a dimension to existing survey-based findings on the potential trade-offs.

Keywords: Product Modularity, Product Architecture, Mass Customisation, Product Portfolio Analyses with Respect to Modularity, Product Development, Metrics for Modularity, Performance Measurement, Complexity Management, Trade-Off.

Introduction

Many companies are currently experiencing increasing demands from their customers for the delivery of customised products that have almost the same delivery time, price and quality as mass-produced products. This puts pressure on the companies and often results in significant increases in product variants offered by those companies. To offer the right level of variance and to control it, is however a challenge. Too little variance will obstruct companies in developing their business, while too much variance will threaten to undermine the efficiency.

Mass customisation and product modularity have often been seen as a way of complying with such increases in variance. By establishing a modular product range, customised products can be made by selecting and combining different standard modules in various ways. Thereby, companies can increase the externally offered product variance without increasing the internal variance equally (Hvam et al, 2008). But this does not mean that the internal variance is static. While internal variance might develop at a slower pace for a modular product program compared to a non-modular, it is important to acknowledge that internal variance will still increase, if the company continues to comply with increasingly unique customer requests.

Several scholars have claimed that introducing mass customisation will eliminate the trade-off between customisation and other competitive priorities (Pine et al, 1993; Tu et al, 2001). Jacobs et al. (2007) also state that modularity positively affects competitive performance for parameters such as cost, flexibility and cycle time. However, in recent years more studies have started to emphasise that introducing mass customisation is not free, and companies are likely to experience a trade-off in performance related to parameters such as lead-time and cost. Squire et al. (2006) found that increasing levels of customisation negatively impacts the manufacturing costs and delivery times, whereas quality and delivery reliability were not significantly affected. Åhlström and Westbrook (1999) found major trade-offs to be costs and on time delivery performance and (Filippini et al, 1998) more generally concluded that trade-offs between different types of performance will occur with increasing customisation. This paper joins that research stream in examining the trade-offs or costs of customising.

In order to comply with the continuing demand for customised variants, the product architecture, upon which the modular product range is based, might need to be expanded with new module classes to be able to fulfil the ever increasing functionalities required by the market. This rise in module classes is likely to increase over time and it is important to acknowledge that introducing a modular product program does not completely remove the limit for how much variance a company can control. It merely pushes it. Instead of product portfolio complexity companies will experience module portfolio complexity.

Within the area of product portfolio complexity management there has in recent years been an increasing focus on streamlining the offered product range by critically assessing the variance

that is not contributing to profit. It is still however quite unexplored how to assess different dimensions of competitive performance of modular product programs (Jacobs et al, 2007).

When introducing new modules and module classes it will be possible to offer new customised configurations of a product, which will most likely generate an increase in turnover. But at the same time it might lead to an increase in complexity related costs as multiple functions within the company such as development, engineering, production planning, sales and marketing need to deal with more module variants. And cost might not be the only factor at stake. When complying with unique customer requests the company will have to initiate a development process, for which the lead time and quality of the outcome cannot be determined beforehand. Previous analyses carried out by (Nielsen and Hvam, 2011) revealed that an expanding product portfolio led to increases in cost and lead time while reducing the quality as well as the on time delivery performance for very customer specific product variants being rarely sold. Such occurrences can be very unfortunate for companies seeking to attract customers by complying with unique requests. Obviously it will increase the customers feeling of satisfaction when unique requirements are met by the company. However, it is likely that this satisfaction will decrease significantly if the end product is delivered too late and in a poor quality.

It will be of significant value to document whether the same tendencies also exist on modular level. Can it be documented whether an expanding modular product program leads to increases in cost, lead time as well as reduced on time delivery and quality, if initiatives are not taken to comply with the increasing amount of module classes? The scope of this article is therefore to analyse product portfolios with respect to modularity and to suggest metrics for assessing the performance of a modular product program.

This paper contributes with increased empirical research in the area of mass customisation within operations management, as called for by scholars such as (Tu et al, 2001) and (Squire et al, 2006). The paper also contributes to the ongoing discussion of whether trade-offs exist between customisation and performance. It more specifically supplements the current body of literature exploring the trade-off which is mainly based on surveys (Jacobs et al, 2007; Squire et al, 2006; Åhlström and Westbrook, 1999; Filippini et al, 1998). Squire et al. (2006) explicitly call for longitudinal work as well as triangulation between quantitative and qualitative in the area. The findings in this paper are based on actual data found in the case company's PLM-system, and are not subject to subjective interpretation from respondents. The level of detail within this paper is also very high as it is not just assessing the overall performance of a company. It addresses the performance of the individual module classes within the product architecture applied by the case company.

Data analysis has been carried out in a large international engineering company to investigate whether an expanding module portfolio can lead to higher costs, longer lead times, poor on time

delivery performance and lower quality. The company is designing one-of-a-kind customer specific products and is applying a well-established modular product architecture.

Literature Review

The study at hand is positioned in the cross field between modularity and mass customisation on the one side and complexity management and performance measurement on the other. Linking these theories allows for assessment of performance and complexity related issues when introducing modularity into product portfolios.

Mass Customisation

Mass Customisation basically means producing goods and services to best meet individual customer needs with near mass production efficiency (Zhang & Tseng, 2007; Bettig & Gershenson, 2010). The objective is to combine the efficiency of mass production with the differentiation possibilities of customisation (Tseng & Piller, 2003). Mass Customisation is therefore often considered suitable for complying with the increasing demands for customised products, which drives companies to constantly expand their offered product variety (Pine, 1993). However, in recent years more studies have started to emphasise that introducing mass customisation is not free, and companies are likely to experience a trade-off in performance related to parameters such as lead-time and cost (Squire et al, 2006; Åhlström and Westbrook, 1999).

Mass Customisation is based on two central principles (Hvam et. al., 2008). The product range being offered should be modular so customised products can be offered by combining the modules in different ways. The other principle is that configuration systems should be used to support the tasks involved in the customer-oriented business processes related to the specification of the products.

Product Architecture & Modularisation

Understanding the architecture of a product is key for introducing modularity, as it basically describes the product's structure and composition, and will support the process of decomposing the product into modules. Many different definitions of product architecture exist in literature. Sanchez (2000) argues that a product architecture is created when a new product design has been decomposed into its functional components and interface descriptions have been fully specified. The types of interfaces range from attachment-, transfer-, control and communication-, spatial-, to environmental interfaces. Meyer and Lehnerd (1997) describe the architecture as being the combination of subsystems and interfaces. They argue that every product has an architecture, and that the goal is to make that architecture common across many variants. Ulrich (1995) has the comprehension, that a product architecture is the scheme by which the functions of the product is mapped towards the physical components, thus defining the product architecture as the arrangement of functional elements, the mapping from functional elements to physical

components and the specification of interfaces among these. Harlou (2006) describes a product architecture as a structural description of a product assortment, product family or a product. It consists of design units, standard designs and interfaces, where design units are characterised by being unique to each product, and standard designs characterised by being reused between one or several product families. In this definition a clear emphasis is put on the decision of reuse, adequate documentation and organisational ownership.

A product architecture can be visualised by applying the Product Variant Master modelling technique, PVM, (Hvam, 2001; Hvam and Jensen, 2007). The technique provides an overview of the product range offered by a company and illustrate how the products can vary. The tool has its basis in object oriented modelling, and simply put, it can be said that a PVM contains a description of the company's product range and the associated knowledge (Harlou, 2006).

A PVM consists of two parts, see Figure 1.

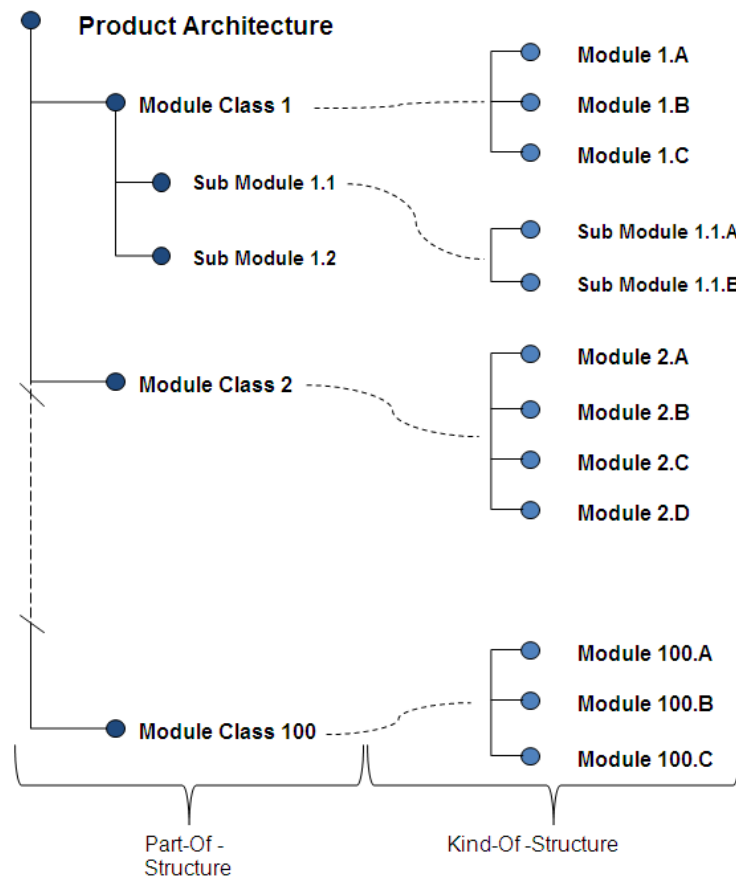


Figure 1: Product Variant Master

The left hand side of the model describes the product's generic structure, and is called the 'part-of'-structure. It contains the modules, components and parts, generally referred to as module classes, which appear in the entire product family. The right hand side of the PVM, called the

‘kind-of’-structure, describes how the individual modules and parts can appear in several variants. The ‘part-of’ and ‘kind-of’-structures are analogous to the structures of aggregation and generalisation/specialisation within object oriented modelling. Further information on the PVM-method can be found in (Harlou, 2006; Hvam et al. 2005).

Product modularity is closely related to the term product architecture as well as to mass customisation. Worren, Moore and Cardona (2002) defines a modular architecture as a special form of product design in which loose coupling is achieved through standardised component interfaces, which enables the production of a large number of end items. In short, product modularity can be defined as the use of standardised and interchangeable components or units that enable configuration of a wide variety of end products (Schilling, 2000).

Complexity Management

Complexity management typically has a strong focus on the management of product variants. It describes the variety of and within the products or services you offer your customers. In general too much variety will be a burden both for the customers and the company, while too little variety will decrease the competitive advantage it can be to offer variety (Tanner, 2009). It is often very difficult to find the right level of complexity and many companies suffer from the fear of having too little. Wilson et al. (2010) argues that variety in products offering customers something they are willing to pay for is good complexity. Bad complexity is however variety that customer will not pay for, or pay enough for. Many firms are convinced that they maximise the fit between product offerings and customer desires when they increase their product variety, and that this allows them to maintain or even increase their market share. This might be the case but at the same time companies often experience lower performance of its internal operations when product variety increases (Salvador et al. 2002).

When creating variants of an existing product you achieve greater differentiation compared to your competitors. This might result in growth in sales but at the same time it will increase the product portfolio complexity as it is necessary to manage another product variant. It is therefore a balance, and the task of finding an optimal level of product complexity is difficult. Closs et al. (2008) argues that the optimal level of complexity in a product portfolio can be described as achieved when the combination of diminishing sales return and increasing costs due to complexity are taken equally into account.

Focusing on costs and on the product as the only source of complexity is however somewhat narrow. Increasing complexity within a product portfolio is likely to induce complexity into the processes dealing with the products. Adopting a wider perspective on complexity is suggested by other scholars such as (Albers & Braun, 2011) who emphasise the need for researching the complex relationship that exists between product and process. Lindemann et al. (2009) also

introduces the term structural complexity management, which places a holistic perspective on the mutual complexity that exists between the market, product, process and organisation.

Performance Measurement

Performance measurement can be defined as the process of quantifying the efficiency and effectiveness of actions, while a performance measure can be defined as a metric used to quantify the efficiency and/or effectiveness of an action (Neely et al. 2005).

There are numerous reasons for using performance measurement, but common for all is that individual feelings and perceptions should be replaced with facts. Without performance measures, managers cannot really understand how their business work, the problems within them, and whether their attempts to improve performance is working as planned (Kaydos, 1999). Performance measurement can therefore be seen as an important precondition for making improvements. (Harbour, 1997) even claims that you cannot improve what you cannot or do not measure.

Making use of performance measurement has great potential. Recent investigations carried out by (Davenport and Harris, 2007) showed that a consistent use of analytics and performance measurement have a great impact on business and financial performance. High performers are 5 times more likely to use analytics strategically compared to low performers.

Within the area of New Product Development scholars such as (Graner and Mißler-Behr, 2012) have been researching how to improve performance of a company's ability to innovate. However, the effects of product modularity on various dimensions of competitive performance do not seem to have been thoroughly investigated (Jacobs et al, 2007).

Research Setting

The research for this article is carried out in a large international engineering company designing one-of-a-kind customer specific products within the heavy engineering industry. The company has no physical production but is only designing the products. Other companies then acquire a licensee to manufacture the products being designed by the case company. They are the market leader within their industry and the primary strategic goal is to maintain this position. In order to fulfil this goal the company strives to win every order by delivering customer specific, high quality products on time, even if it requires significant development and engineering work. The belief is that the best way to satisfy the customer is to offer the most technically advanced solution or to comply with the customer's request without trying to sway the customers towards choosing a product variant that is more frequently designed. The company fears that if an alternative variant is suggested to the customer, the customer will instead address a competitor and place the order there.

Furthermore, within the last years the market has gotten more diverse and more unique customer requests occur. The consequence has been a steep increase in the number of very customer specific product variants offered by the company. This is clearly reflected in the product program, which today is approximately twice the size as it was just 5 years ago.

The strategic choice of complying with every unique customer request combined with a growing diversification of market requests drive the company to increase the variance offered to the market, which again enhances the complexity-related challenges faced by the company. It is not thoroughly investigated what the price is for this increasing complexity. The engineering departments have however experienced an increased pressure as they are required to design considerably more new variants than earlier.

The company has implemented a modular based product architecture, which allows for reuse of modules across specific orders. Every time an order is placed a configuration process is taking place. During this configuration it is identified which modules can be reused and which have to be designed in accordance with the customer requests for the specific order. Thus when complying with a unique customer request, it rarely means that all modules are new. The modules are delivered successively to the licensee companies whenever they are fully designed. The architecture currently consists of 71 module classes each containing a library of already made modules from previous orders. The number of existing modules in each module class differs for several reasons. For one, the requirements for variance within each class are different. In some classes modules can be used for several product variants, whereas for other classes each product variant needs a unique module. Furthermore, all classes are not necessarily present in all product variants. Some variants may contain a module from all 71 classes, whereas other variants might be composed of only 60 modules, or even less. One explanation of this is the size and complexity of the individual customised product. Some products are simply larger or more advanced and therefore more modules are needed to specify the full product. Another explanation is that the product architecture at times is expanded to be able to cover new product variants and features required by the market.

A simple conceptual illustration of the product architecture using the PVM-modelling technique can be seen in Figure 2.

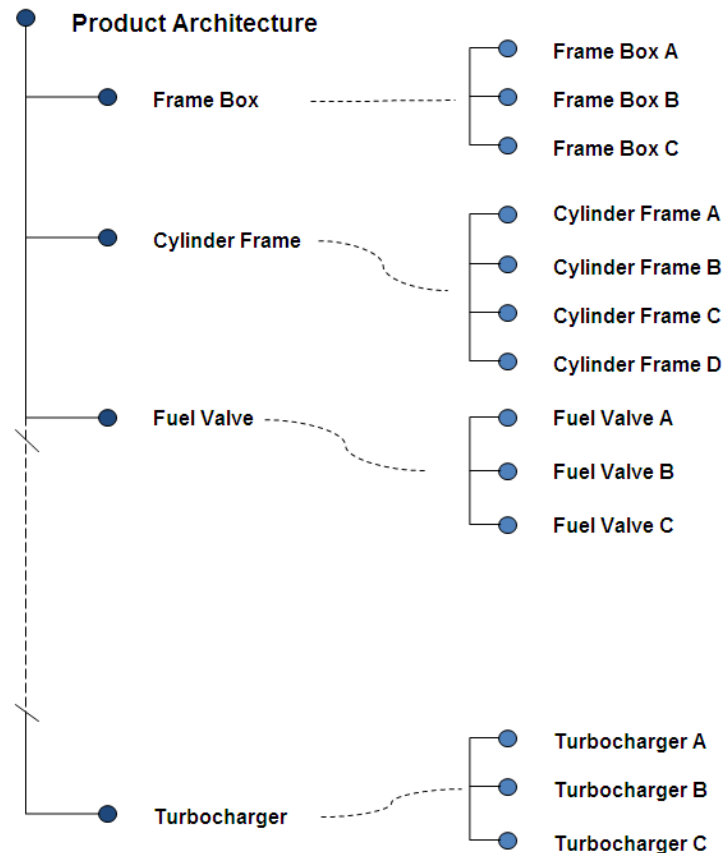


Figure 2: Subset of the case-company product architecture

When a substantial amount of similar products has been designed there is a larger basis for reuse of modules for the specific product variant. So the more often a product variant has been designed, the less new modules are needed in average to fulfil a new customer request. However as stated earlier the company is experiencing an increasing demand for customer specific variants urging them to continually design new modules and expand the product architecture.

Research Method

The data upon which the findings are based is drawn from the company's PLM-system as well as internal company databases. The findings are therefore mainly quantitatively based. Some sources have existed for many years and contain data that has been registered elaborately for more than a decade. But other sources have not been established until a few years ago. It has therefore not been possible to acquire sufficient data that could describe every single module class with regards to all parameters under investigation. But nevertheless the findings are based on a significant amount of data including approximately 23.000 modules.

The research is carried out as a single case study, which can affect the validity, reliability and generalising potential of the study. Context-dependent knowledge gives this type of science a basic limitation when generalising the conclusions made on the basis of a single experiment

(Smith, 2006). However (Gummesson, 1991) contends it is possible to generalise from a very few cases, or even a single case, if the analysis has captured the characteristics of the phenomena being studied.

The authors have had free access to detailed data within the company allowing an in depth analysis. The internal validity, which concerns the extent to which the research findings accurately represent what is really happening, is therefore assessed to be high. A tendency that often gets even stronger when considering single case studies (Voss et al. 2002). As the empirical data is drawn from the company PLM-system, the study is quite objective. The reliability concerning whether anyone would get the same results as you if they were to repeat the research in the same setting is therefore considered high. The authors furthermore believe that the case company represents a typical engineering company designing customer specific products. However, it is a clear limitation that only data for one company has been analysed. The external validity of the findings, which concerns whether the results are valid in a similar setting outside the studied objects, is therefore more questionable (Karlsson, 2009).

Hypotheses

Modularity has for many companies been a means of dealing with increasing variance in a product portfolio. By applying the principles of mass customisation companies have sought to improve their process efficiency and reduce lead time and costs for delivering customised products (Bare & Cox, 2008). However it might also be valuable to consider which level of modular variance to offer. By measuring the performance of the modular product program we will get further insight into how much variance we can offer without reducing our performance. Four hypotheses, H1-H4, each addressing the performance indicators cost, quality, lead-time and on-time delivery are therefore developed.

H1: Expanding the number of module classes will lead to an increase in cost.

H2: Expanding the number of module classes will lead to a drop in quality.

H3: Expanding the number of module classes will increase the lead-time.

H4: Expanding the number of module classes will lead to a drop on-time delivery performance.

The included metrics have been chosen for two reasons. Much of the trade-off literature focuses on exactly these competitive priorities (Da Silveira and Slack 2001). Several other trade-offs exist, but the chosen ones are widespread in literature and therefore deemed of particular interest. The other reason for choosing those metrics is that they are crucial for the case company's overall objectives.

Measurements

In order to illuminate the hypotheses stated above, analysis has been carried out for following five measures:

Number of modules designed according to each module class

As stated earlier there are today 71 different active module classes in the product architecture. Within each class it differs how many modules that have been designed. It depends on whether the module class represents a fundamental building block of the product which is included in every variant, or whether it represents a more peripheral component or functionality only included in certain product variants. The measure therefore illustrates how many classes that exist in the product architecture as well as how many modules within each of these classes that have actually been designed.

Average costs associated with designing new modules according to each module class

The modules differ significantly in size as well as the corresponding workload required for designing it. This measure tells the average internal cost of designing modules according to each module class.

Module revisions per module design according to module class

This measure is chosen as indicator for the quality of the design of the individual modules. Every time a critical flaw is identified for a module a so-called action code is issued. This leads to a revision of the module and possible a recall of already dispatched modules. The more revisions that occur for a specific module class the lower is the average quality of the modules belonging to this class assumed to be. This measure reports the average number of revisions made per module released according to each module class.

Average lead time for new modules according to each module class

The lead time is the time from the company receives the order until a module is sent to the customer. The case company sends the different modules whenever they are done. The lead time for a single module is therefore not equal to the lead time of the complete order. This measure tells the average lead time for every module according to each module class.

Average on time delivery of modules according to each module class

As stated above, the modules for each order are delivered successively and there are different delivery deadlines for the different modules. The measure reports how many modules in average that are not delivered on time according to each module class.

The approach for testing the hypotheses is now to relate the first measure, '*Number of modules designed according to each module class*', to the remaining four measures. This basically means to relate the module class index (ranging from 1 to 71) to the remaining four measures. It can thereby be tested whether and to which extent lower costs, lower lead time, improved ability to comply with delivery deadlines and higher quality occur for modules within classes appearing frequently compared to the module classes that are rare and only occur in very customer specific product variants.

Analysis

Based on the data gathered it is possible to test the hypotheses of the article. Each of the following plots has the same horizontal axis as well as primary vertical axis, to the left, designated ‘Modules Designed’. Along the horizontal axis, every module class is shown arranged after how many modules that has been designed within each class, starting with the most frequent furthest to the left. Along the primary vertical axis is then the actual number of modules designed illustrated by the blue columns for every module class.

The plots then differ with respect to the secondary vertical axis, to the right, where the following four parameters are outlined; average cost per module, module revisions per module design, average lead time per module and modules not delivered on-time. The data for these parameters are represented by the square data points. For each parameter a linear tendency line is depicted in accordance with simple linear regression. These tendency lines will give indications of whether the trade-offs addressed in the hypotheses are occurring. Please note that all numbers along the secondary axes have been indexed because of confidentiality. Regression coefficients for the tendency lines as well as correlation coefficients for the variables included in the analysis can be found in Table 1. Two-tailed statistical significance tests were conducted and associated p-values can also be found in Table 1.

Variable	Regression Coefficient, α	Correlation Coefficient, r
Cost	0.18	0.17 *
Revisions (Quality)	0.67	0.47 ***
Lead Time	0.16	0.20 **
On Time Delivery	0.18	0.19 *

* P < 0.2 ** P < 0.1 *** P < 0.01

Table 1: Regression and correlation coefficients

Finding 1 (see Figure 3) basically shows the relation between every module class (and implicitly how many modules that have been designed within each class) and what the average cost of designing a module variant within the class. As an example of how to read the plots consider module class 27, marked with a circle. Modules within this class have been designed 222 times, which can be read from the blue column above the number 27 and the primary vertical axis to the left. The cost index, equal to 33, is indicated by the red square data point above the number 27, and the value can be found on the secondary vertical axis to the right. The tendency line here reveals that there is a rather slight tendency ($\alpha=0.18$) towards that modules within classes appearing less frequently are more costly to design. The correlation coefficient equal to 0.17 does however suggest that the strength of the linear relationship between module class and cost is rather weak. Furthermore the correlation is significant at the level $p < 0.2$ suggesting some uncertainty concerning reliability.

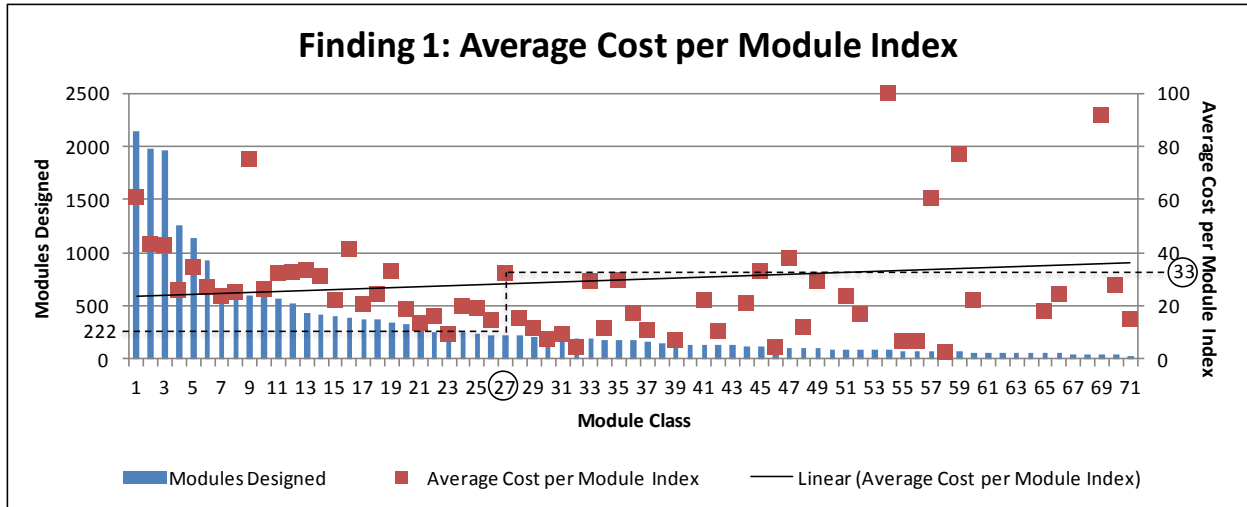


Figure 3: Module Class vs. Average Cost per Module Index

Finding 2, see Figure 4, illustrates an index for the number of module revisions that are made per module designed according to each module class. For instance consider the last module class 71. For the modules in this class the index is approximately 100 indicating that the company is having problems designing modules in sufficient quality within this class. The regression coefficient equal to 0.67 reveals that considerable more revisions are needed for module classes being rarely included in the product. A correlation coefficient value of 0.47 ($p < 0.01$) furthermore suggests a rather strong linear dependency between module class and the revision index. As expected, only few revisions per module design are occurring for classes with modules that are frequently designed. The tendency is very clear and it is worth noticing that the dispersion of data is bigger for rarely designed modules.

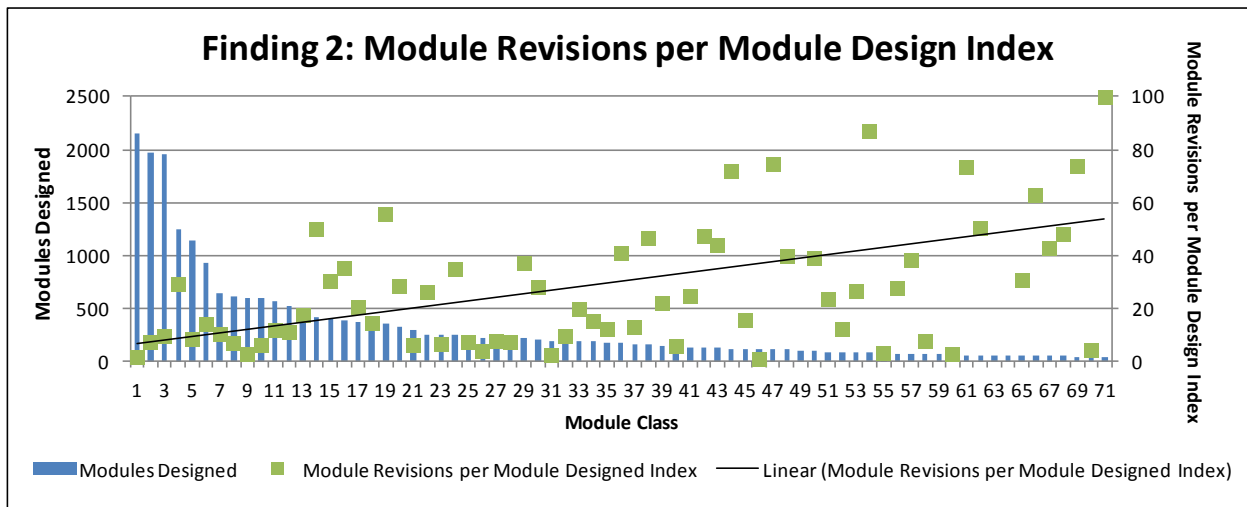


Figure 4: Module Class vs. Module Revisions per Module Design Index

Finding 3 can be found in Figure 5. The plot addresses the lead time for modules according to module class. As with costs only a slight tendency ($\alpha=0.16$) can be spotted indicating that

modules in classes that are rarely designed, in average only have slightly longer lead time compared to modules in classes frequently designed. The correlation between the two variables ($r=0.20$, $p < 0.1$) is also low suggesting a rather weak linear dependency between module class and lead time.

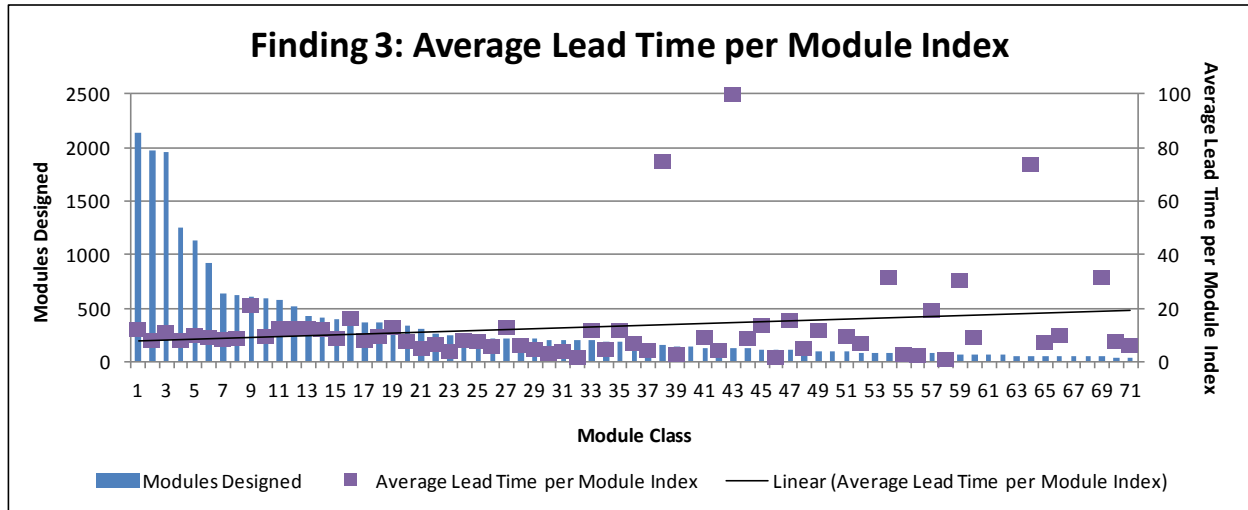


Figure 5: Module Class vs. Average Lead Time per Module Index

Finding 4 in Figure 6 is showing the relationship between module class and how many modules that fail to meet the intended delivery deadline for each class. The data is quite scattered ($r=0.19$, $p < 0.2$) and the positive regression coefficient ($\alpha=0.18$) of the tendency line is primarily due to three module classes for which the company has severe delivery performance issues. It is evident that there are a few holes in the data for this finding. The reason for this is that the on time delivery performance has only been registered for 1 year. For some classes modules have simply not been designed within that year, leaving holes in the empirical data which becomes apparent in the plot. Nevertheless, there is a slight tendency towards reduced ability to deliver modules on time for modules in classes that are rarely designed.

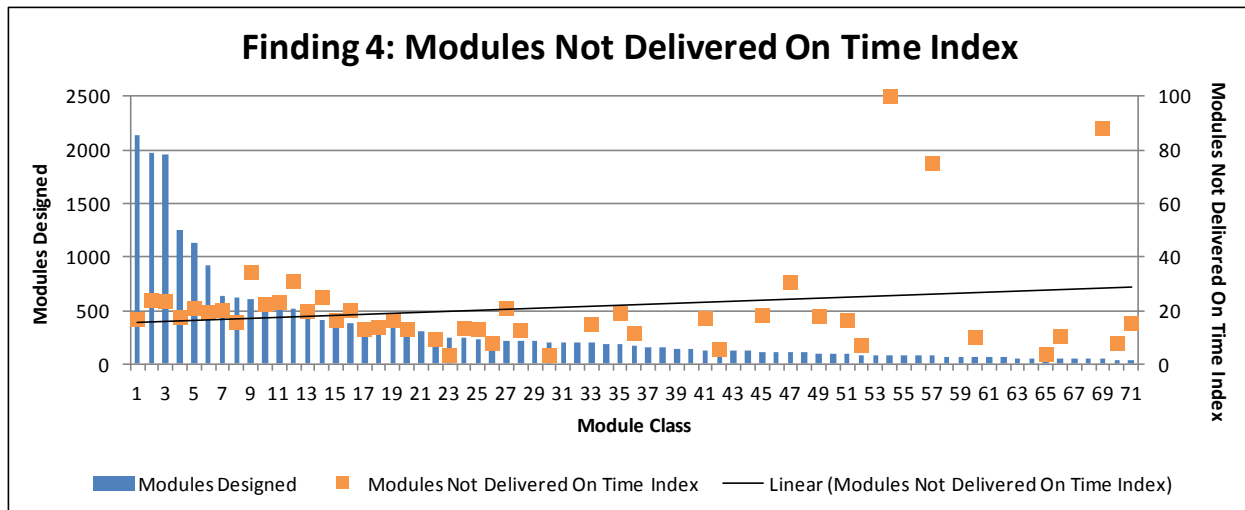


Figure 6: Module Class vs. % Modules Not Delivered On Time Index

All in all the plots all exhibit an increasing tendency. Module classes containing fewer modules are likely to be more costly to design, to be of poorer quality, to have a longer lead time and to exhibit a more frequent failure to meet delivery deadlines. All four hypotheses can therefore to some extent be substantiated. However the regression and correlation coefficients for the parameters cost, lead time and on time delivery, addressing hypotheses H1, H3 and H4, are rather low suggesting a somewhat weak relation between the variables with quite low negative impact. The statistical significance levels for these findings are also somewhat high adding some uncertainty to the findings related to those parameters. The findings related to the quality parameter are rather significant, though. The analyses suggest that there exist a dependency between module classes being rarely included in the product and the number of revisions needed for modules designed in those classes, which provides rather strong support for hypothesis H2.

Discussion & Conclusion

Based on the findings the hypotheses can only be substantiated to some extent. It is found that there are tendencies showing that modules in classes that are rarely designed in average have a higher cost and lead time for designing them while the ability to deliver on time is reduced and the number of revisions per module design is increasing. Especially the quality performance parameter is showing a strong tendency, while performance related to cost, lead time and on time delivery seem somewhat less affected.

The findings thereby support similar trade-off studies in the claim that customisation is not free. Companies are likely to experience a trade-off in performance related to parameters such as lead-time and cost when increasing their customisation even through a modular based product program. The specific results do however deviate somewhat as earlier studies pointed out costs and lead time as the performance parameters experiencing the most significant negative impact (Squire et al, 2006; Åhlström and Westbrook, 1999). This findings in this paper confirms a

negative impact but of smaller magnitude. Instead the level of quality is found to be the biggest trade-off.

The company strategy is to win every order by customising their products in accordance with the customer requests and to deliver those products on time and in highest quality. But the findings reveal that they are not completely successful in doing so. The belief is that by complying with every unique customer request the company will get the most satisfied customers. But if the customer experiences a longer lead time and a poorer quality, the customer is unlikely to be completely satisfied. The company's main objective of maintaining or expanding the market share is understandable. But the company should be careful that they in their pursuit of fulfilling every unique customer request, do not undermine the very same thing they are trying to achieve. Mass customisation and the introduction of modular product programs are by many considered efficient strategies for dealing with increasing levels of variance within product portfolios. However the research at hand indicates that increasing levels of variance within module portfolios also can lead to reduced performance according to crucial key performance indicators. This does by no means suggest that modularisation is a poor strategy. But it implies that we should be aware that challenges related to product portfolio variance do not simply disappear after implementing product modularity. A new type of variance on modular level is likely to develop over time, and this development should be monitored as it will enable companies to comprehend the consequences of expanding their modular product program.

In order to ensure high performance among all module classes within the modular product program one could choose to fix the product architecture and be cautious about expanding and adapting it to emerging market needs. This can however be strategically unwise as continual adaptation to customer needs might be critical for continual success. How to deal with the increasing variance should be carefully assessed by every company ensuring accordance with overall objectives. And this research suggests that an evident support for the assessment could be obtained through performance measurement of the modular product program.

The paper at hand is a contribution to the literature on trade-offs between customisation and performance. It triangulates the findings made by several survey-based studies with a concrete quantitative and detailed analysis of the performance of a modular product program. Especially the level of detail included in this paper adds to the existing body of literature as the study is not just assessing the overall performance of a company. It actually addresses the performance of the individual module classes within the product architecture applied by the case company.

A clear limitation of this article is that the findings are based on data from one company only. We therefore need to be cautious when concluding whether the findings can be generalised. If similar tendencies can be found in other companies, the external validity of the findings will be improved considerably. The authors do however believe that the case company represents a

typical engineering company designing customer specific products, which supports the validity of the findings. Furthermore, the free access to detailed data provided to the authors strengthens the validity of the findings.

The scope for this article has been to illustrate the value of carrying out performance analyses for product portfolios with respect to modularity. An evident suggestion for further work would then be to investigate how companies could actually deal with increases in variance in their modular product programs. This is however outside the scope of this article and will not be addressed further here.

References

- Åhlström, P. and Westbrook, R. (1999), "Implications of mass customization for operations management. An exploratory study", *International Journal of Operations & Production Management*, vol. 19, no. 3, pp. 262-274.
- Albers, A. and Braun, A. (2011), "A generalised framework to compass and to support complex product engineering processes", *International Journal of Product Development*, vol. 15, no. 1-3, pp. 6-25.
- Bare, M and Cox, J. J. (2008), "Applying principles of mass customization to improve the empirical development process", *Journal of Intelligent Manufacturing*, vol. 19, no. 5, pp. 565-576.
- Bettig, B. and Gershenson, J. K. (2010), "The representation of module interfaces", *International Journal of Product Development*, vol. 10, no. 4, pp. 291-317.
- Closs, D.J., Jacobs, M.A., Swink, M. and Webb, G. S. (2008). "Toward a theory of competencies for the management of product complexity: Six case studies", *Journal of Operations Management*, vol. 26, no. 5, pp. 590-610.
- Da Silveira, G. and Slack, N. (2001), "Exploring the trade-off concept", *International Journal of Production Management*, vol. 21, no. 7, pp. 949-964.
- Davenport, T. and Harris, J. (2007). *Competing on Analytics. The New Science of Winning*. Harvard: Harvard Business School Press.
- Filippini, R., Forza, C. and Vinelli, A. (1998), "Trade-off and compatibility between performance: definitions and empirical evidence", *International Journal of Production Research*, vol. 36, no. 12, pp. 3379-3406.
- Graner, M. and Mißler-Behr, M. (2012), "The use of methods in new product development – A review of empirical literature", *International Journal of Product Development*, vol. 16, no. 2, pp. 158-184.
- Gummesson, E. (1991), *Qualitative Methods in Management Research*, Newbury Park, SAGE
- Harbour, J. L. (1997), *The Basics of Performance Measurement*. New York: Quality Resources.

- Harlou, U. (2006), *Developing Product Families based on Architectures*, Department of Mechanical Engineering, Lyngby: Technical University of Denmark.
- Hvam, L. (2001), "A Procedure for the Application of Product Modelling", *International Journal of Production Research*, vol. 39, no. 5, pp. 873-885.
- Hvam, L. and Jensen, K. R. (2007), "A multi perspective approach for the development of visual configuration systems", *Computers & Industrial Engineering*, vol 53, no. 3, pp. 401-419.
- Hvam, L., Mortensen, N.H. & Riis, J. (2008), *Product Customization*, Berlin: Springer.
- Hvam, L., Pape, S. and Riis, J. (2005), "Development and maintenance of product configuration systems: Requirements for a documentation tool", *International Journal of Industrial Engineering*, vol 12, no.1, pp. 79-88.
- Jacobs, M., Vickery, S. & Droge, C. (2007), "The effects of product modularity on competitive performance", *International Journal of Operations Management*, vol. 27, no. 10, pp. 1046-1068.
- Karlsson, C. (2009), "Researching Operations Management", in Karlsson, C. (Ed.), *Researching Operations Management*, Routledge, New York and London.
- Kaydos, W. (1999), *Operational Performance Measurement. Increasing Total Productivity*, Florida: Taylor & Francis Group.
- Lindemann, U., Maurer, M. and Braun, T. (2009), *Structural Complexity Management. An Approach for the Field of Product Design*. Springer-Verlag, Berlin Heidelberg.
- Meyer, M. H. and Lehnerd, A.P. (1997), *The Power of Product Platforms*, New York: Free Press
- Neely, A., Gregory, M. and Platts, K. (2005), "Performance measurement system design", *International Journal of Operations & Production Management*, vol. 25, no. 12, pp. 1228-1263.
- Nielsen, J. B. and Hvam, L. (2011), "Product Complexity Impact on Quality and Delivery Performance", *The 2011 World Conference on Mass Customization, Personalization, and Co-Creation (MCPC 2011): Bridging Mass Customization & Open Innovation*, San Francisco, November 15-19, 2011.
- Pine, B.J. (1993), *Mass Customization: The new frontier in Business Competition*, Harvard: Harvard Business School Press.
- Salvador, F., Forza, C. and Rungtusanatham, M. (2002), "Modularity, product variety, production volume and component sourcing: theorizing beyond generic prescriptions", *Journal of Operations Management*, vol. 20, no. 5, pp. 549-575.

- Sanchez, R. (2000), "Modular architectures, knowledge assets and organizational learning: new management processes for product creation", *International Journal of Technology Management*, vol. 19, no. 6, pp. 610-629.
- Schilling, M. A. (2000), "Toward a general modular systems theory and its application to interfirm product modularity" *Academy of Management Review*, vol. 25, no. 2, pp. 312-334.
- Smith, M. L. (2006), "Overcoming theory-practice inconsistencies: Critical realism and information systems research", *Information and Organization*, vol. 16, no. 3, pp. 191-211.
- Squire, B., Brown, S., Readman, J. and Bessant, J. (2006), "The impact of mass customisation on manufacturing trade-offs", *Production and Operations Management*, vol. 15, no. 1, pp. 10-21.
- Tanner, H. R. (2009), "Complexity Management in a Nutshell", *Complexity Management Journal*, vol. 2, pp. 19-23.
- Tseng, M. M. and Piller, F. (2003), *The Customer Centric Enterprise. Advances in Mass Customization and Personalization*, Berlin: Springer.
- Tu, Q., Vonderembse, M. and Ragu-Nathan, T. A. (2001), "The impact of time-based manufacturing practices on mass customization and value to customer", *Journal of Operations Management*, vol. 19, no. 2, pp. 201-217.
- Ulrich, K. (1995), "The role of product architecture in the manufacturing firm", *Research Policy*, vol. 24, no. 3, pp. 419-440.
- Voss, C., Tsikriktsis, N., and Frohlich, M. (2002), "Case research in operations management", *International Journal of Operations & Production Management*, vol. 22, no. 2, pp. 195-219.
- Wilson, S. A. and Perumal, A. (2010), *Waging War on Complexity Costs. Reshape Your Cost Structure, Free Up Cash Flows and Boost Productivity by Attacking Process, Product and Organizational Complexity*, U.S.A.: McGraw-Hill.
- Worren, N., Moore, K. and Cardona, P. (2002), "Modularity, strategic flexibility, and firm performance: a study of the home appliance industry", *Strategic Management Journal*, vol. 23 no. 12, pp. 1123-1140.
- Zhang, M. and Tseng, M.M. (2007), "A product and process modeling based approach to study cost implications of product variety in mass customization", *IEEE Transactions on Engineering Management*, vol. 54, no. 1, pp. 130-144.