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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, engineering change processes, product modelling, integrated modelling of product and process

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1 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.

2 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).

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. 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).

3 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.

4 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?

5 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 & Coghlan, 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 (Gummeson, 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.

6 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: 5 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 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.

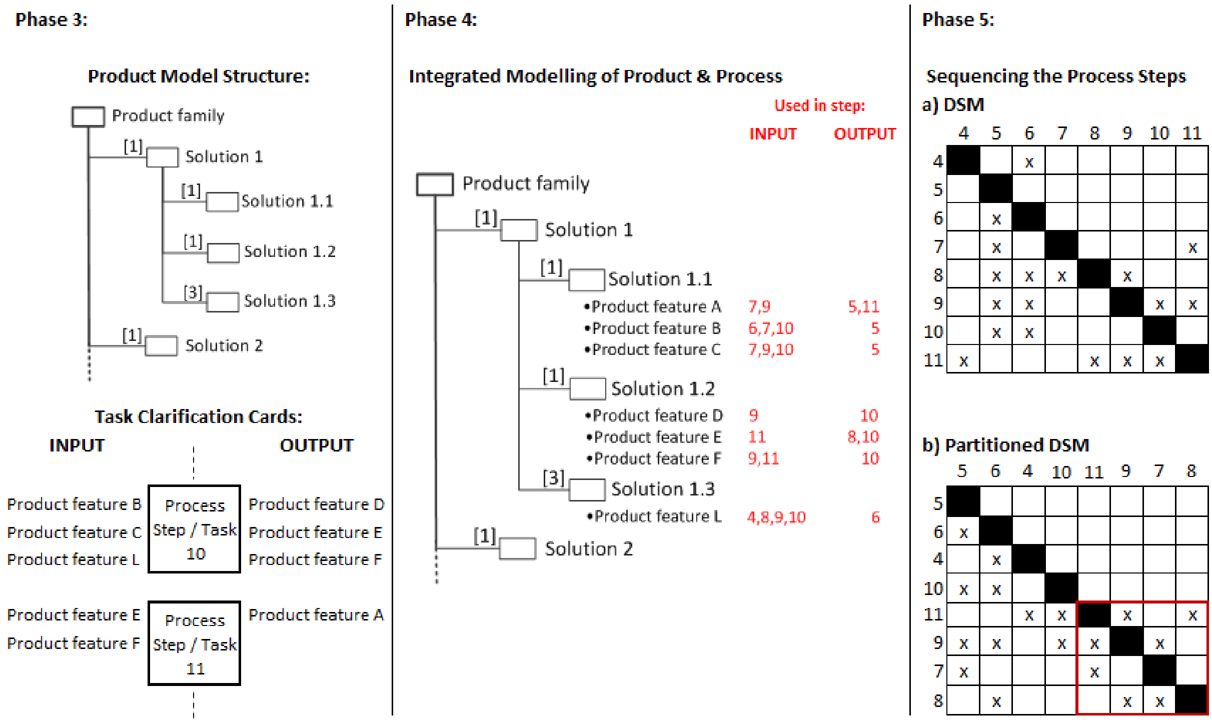

Figure 2: Phases 3 - 5

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.

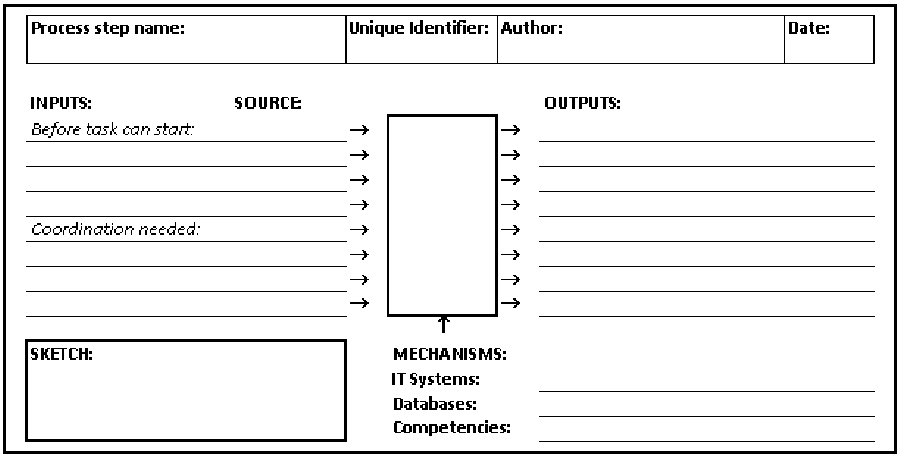

Figure 3: Task Clarification Card

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.

7 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 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. 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.

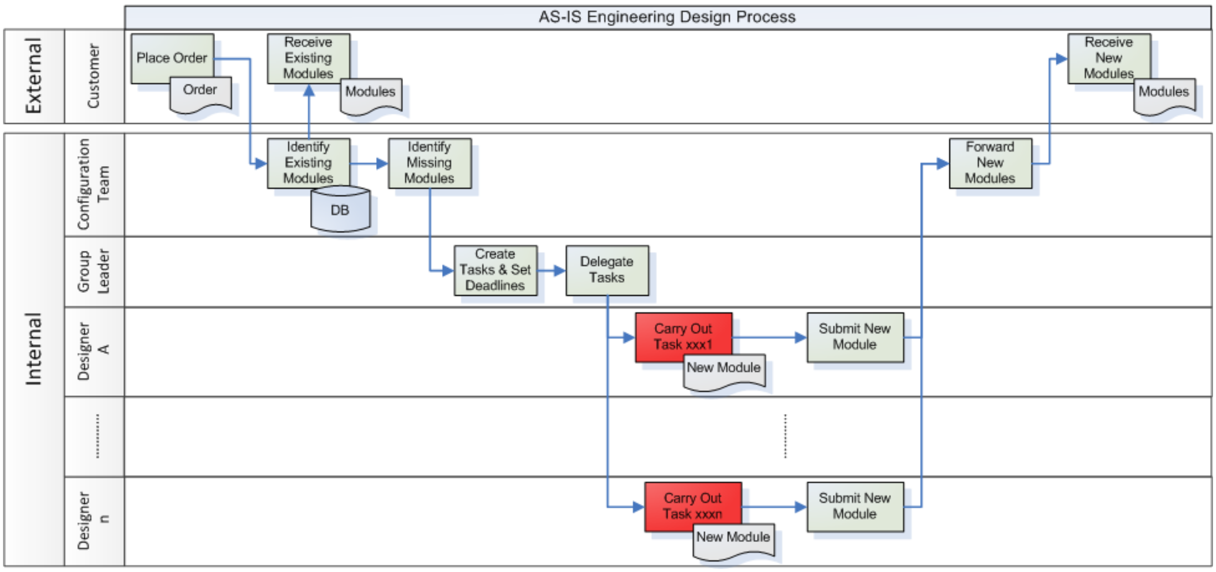

Figure 4: AS-IS Engineering Design Process

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 affect 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 futures 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 where then confirmed through a second round of interviews.
With the PVM outlining the product being engineering 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 Referenced 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. Be 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 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, fever resources and higher quality of the engineering work carried out.

8 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 & Coghlan, 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.

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