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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.

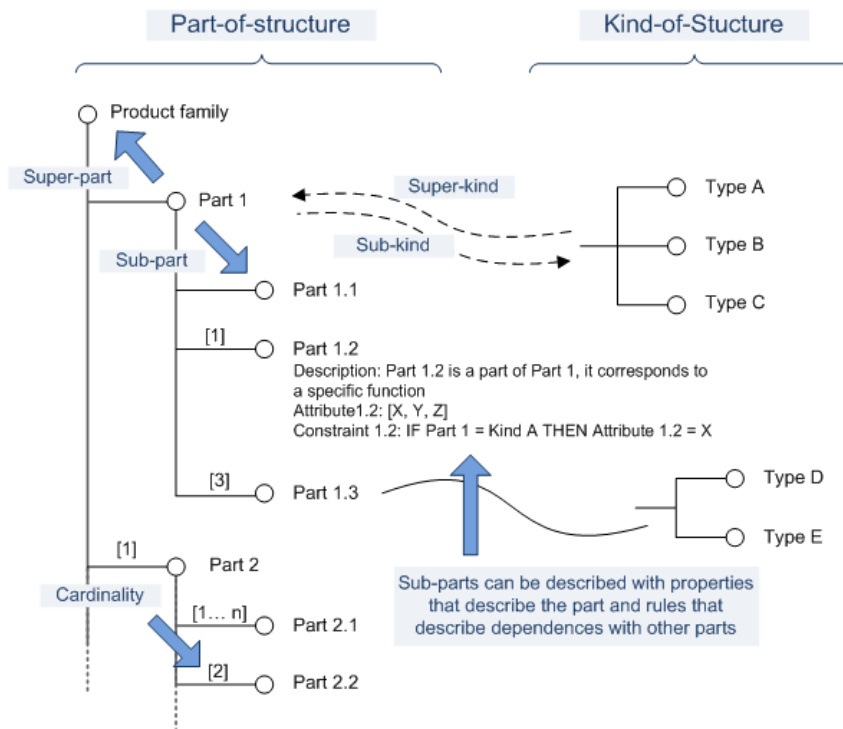


Figure 1: The structure of a PVM (Hvam et al., 2008).

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](http://www.imo.org), 2012). Since the ratification of the IMO Tier III criteria for NOx 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 NOx. The extent of the necessary measures for NOx reduction up to 80% for meeting the IMO NOx-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 ( $O_2$ ) with carbon dioxide ( $CO_2$ ) 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  $CO_2$  and the decreased amount of  $O_2$  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**

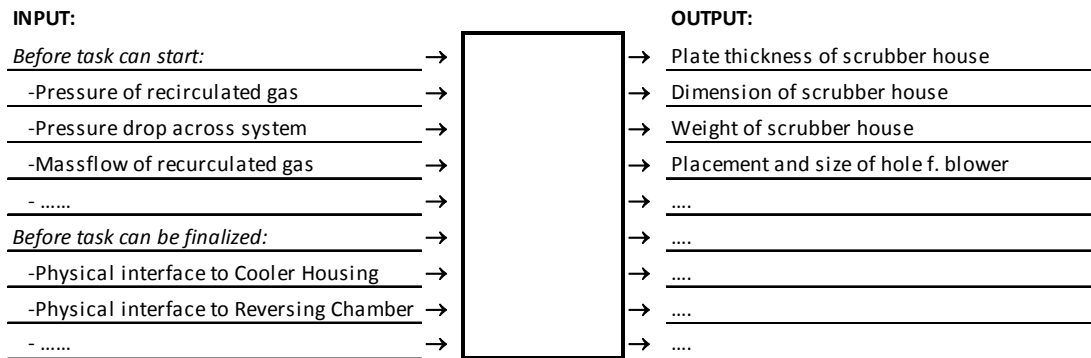
As initially stated MAN Diesel & Turbo has developed the technology needed to comply with IMO's new emission regulations. However, so far it is only in prototype versions for a limited segment of the product range. When the regulations become effective in 2016, marine diesel engines in all sizes will 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.

<b>Process step name:</b> Design Scrubber Housing	<b>Date:</b> DD.MM.YYYY	<b>Author:</b> Dr. Hansen	<b>Step no.</b> 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
.....	.....	.....

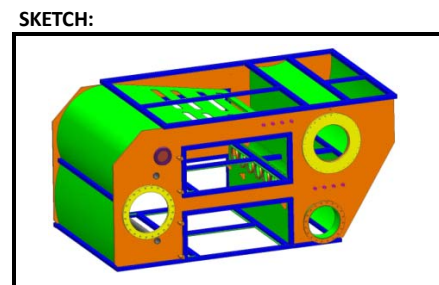


Figure 2: Task Clarification Card

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.

EGR-system	Used in Step:	
	Input	Output
<b>Performance Specification</b> 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
• ....		
<b>EGR-Cooler</b> For cooling of the EGR-gas		
• Dimensions of housing	7	4
• ....		
<b>Pre Scrubber</b> For removal of SO <sub>2</sub> in the exhaust gas		
• ....		
-----		
<b>Scrubber Housing</b> Contains the Scrubber Unit		
• Plate thickness of scrubber house		7
• Dimensions of scrubber house		7
• Weight of scrubber house		7
• .....		
• .....		
<b>Water Treatment System</b> For cleaning the scrubber water in the system.		
• .....		

Figure 3: 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.

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