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Modelling Product Families for Product Configuration Systems with Product Variant Master and CRC-cards

Niels Henrik Mortensen, Lars Hvam¹, Anders Haug²

Abstract. This article presents an evaluation of applying a suggested method for modelling product families for product configuration based on theory for modelling mechanical products, systems theory and object-oriented modelling. The modelling technique includes a so-called product variant master and CRC-cards for modelling and visualising the parts and properties of a complete product family. The modelling techniques include:

- Customer, engineering and part views on the product assortment to model the properties, functions and structure of the product family. This also makes it possible to map the links between the three views.
- Modelling of characteristics of the product variants in a product family
- Modelling of constraints between parts in the product family
- Visualisation of the entire product family on a poster e.g. 1x2 meters

The product variant master and CRC-cards are means to bridge the gap between domain experts and IT-developers, thus making it possible for the domain experts (e.g. engineers from product development) to express their knowledge in a form that is understandable both for the domain experts and the IT-developers.

The product variant master and CRC-cards have currently been tested and further developed in cooperation with several industrial companies. This article refers to experiences from applying the modelling technique in three different companies. Based upon these experiences, the utility of the product variant master and CRC-cards is evaluated.

Significance. Product configuration systems are increasingly used in industrial companies as a means for efficient design of customer tailored products. The design and implementation of product configuration systems is a new and challenging task for the industrial companies and calls for a scientifically based framework to support the modelling of the product families to be implemented in the configuration systems.

Keywords. Mass Customization, product architecture, product modelling, product configuration, object-oriented system development.

1. INTRODUCTION

Customers worldwide require personalised products. One way of obtaining this is to customise the products by use of product configuration systems (Tseng and Piller, 2003, Hvam et al 2008). A product configuration system is a knowledge-

integrated or intelligent product model, which means that the models contain knowledge and information about the products, and based on this is able to derive new specifications for product instances and their life cycle properties.

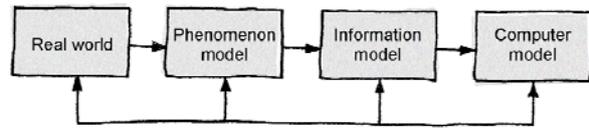


Figure 1. From Real world to an IT-system (Duffy et al, 1995)

A product configuration system is based on a model of the product portfolio. Figure 1 illustrates how to use the phenomenon model and the information model as means for modelling real world objects for an IT-system, in this case modelling a product family for a product configuration system. This article focuses on the phenomenon model and presents the experiences from using product variant master and CRC-cards for modelling product families. A product model can be defined as a model that describes a product's structure, function and other properties as well as a product's life cycle properties e.g. manufacturing, assembly, transportation and service (Krause, 1993, Hvam, 1999). A product model used as a basis for a product configuration system also includes a definition of the rules for generating variants in the product assortment (Hvam et al, 2008, Schwarze, 1996).

Experiences from a considerable number of industrial companies have shown that often these product configuration systems are constructed without the use of a strict modelling technique.

As a result of this, many of the systems are unstructured and undocumented, and they are, therefore, difficult or impossible to maintain or develop further. Thus, there is a need to develop a modelling technique which can ensure that the product configuration systems are properly structured and documented, so that the configuration systems can be continually maintained and developed further.

In order to cope with these challenges, a technique for modelling product families for product configuration has been developed - which makes it possible to document the product configuration systems in a structured way.

This article evaluates the experiences from applying the suggested method (product variant master and CRC-cards) for modelling product families for product configuration systems. The suggested method is based on three theoretical domains:

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- Object-oriented modelling (Bennett et al, 1999; Booch et al 1999; Felfernig; 2000, Hvam 1999)
- System theory (Skyttner 2005; Bertalanffy 1969)
- Modelling mechanical products (Hubka, 1988; Schwarze, 1996)

The theory for modeling mechanical products and systems theory are used for defining the structure in the PVM and the CRC-cards, and thereby the structure of the configuration system, reflecting the product families to be modeled and the user requirements of the configuration system.

2. MODELLING PRODUCT FAMILIES FOR PRODUCT CONFIGURATION SYSTEMS

2.1. The Product Variant Master

A company's product range often appears to be large and have a vast number of variants. To obtain an overall view of the products, the product range is drawn up in a so-called product variant master (Hvam et al 2008).

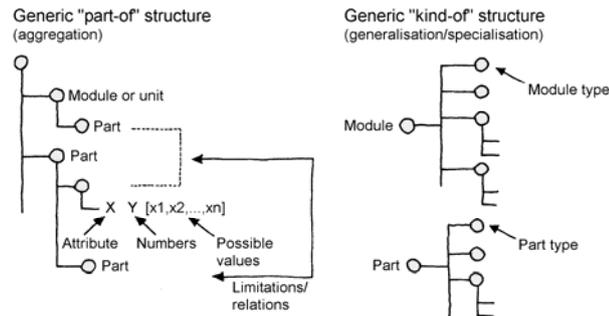


Figure 2. Principles of the Product Variant Master

A product variant master consists of two parts. The first of these, the "part-of" model (the left-hand side of the product variant master), contains those modules or parts which appear in the entire product family. For example, a car consists of a chassis, motor, brake system etc. Each module/part of the product range is marked with a circle. It is also possible to specify the number of such units used in the product - for example, 1 motor and 4 wheels in each car. The individual modules/parts are also modeled with a series of attributes which describe their properties and characteristics.

The other part of the product variant master (the right-hand side) describes how a product part can appear in several variants. A motor, for example, can be a petrol or diesel motor. This is shown on the product variant master as a generic structure, where the generic part is called the motor, and the specific parts are called petrol motor and diesel motor, respectively.

The two types of structure, "part of" and "kind of", are analogous to the structures of aggregation and specialization within object-oriented modelling.

The individual parts are also described with attributes, as in the part-of model. In the product variant master, a description is also given of the most important connections between modules/parts, i.e. rules for which modules/parts are permitted to be combined. This is done by drawing a line between the two modules/parts and writing the rules which apply for combining the modules/parts concerned. In a

similar manner, the life-cycle systems to be modelled are described in terms of masters that for example describe the production system or the assembly system.

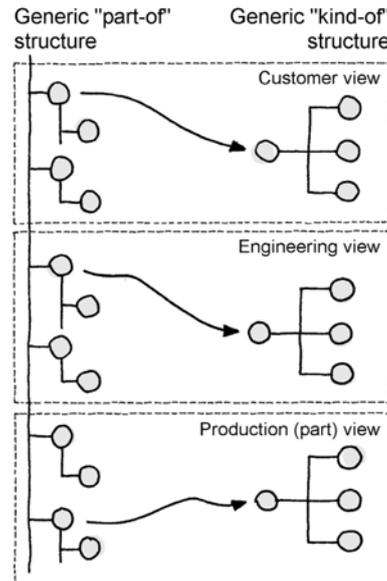


Figure 3. Structure of the Product Variant Master

The individual modules/parts in the product variant master are further described on so-called CRC cards, which are discussed in more detail in the next section.

It is normally possible to create the product variant master in such a way that the products are described from the customer's point of view at the top, followed by a description of the product range seen from an engineering point of view, while the products are described from a production point of view at the bottom as shown in figure 3.

2.2. The CRC-cards

In connection with the specification of the product variant master and the final object-oriented class model, CRC cards are used to describe the individual object classes (Bellin, 1997), (Hvam et al., 2003), (Hvam et al, 2008). CRC stands for "Class, Responsibility, and Collaboration". In other words, this is where a description is made of what defines the class, including the class' name, its possible place in a hierarchy, together with a date and the name of the person responsible for the class. In addition, the class' task (responsibility), the class' attributes and methods, and with which classes it collaborates (collaboration) are given.

Figure 4 shows an example of a CRC card. In connection with the modelling of products, a sketch of the product part is added, with a specification of the attributes of the product part.

The CRC cards are filled in gradually during the object-oriented analysis. The CRC cards can be associated with both the product variant master and the OOA model. The purpose of the CRC cards is to document detailed knowledge about attributes and methods for the individual object classes, and to describe the classes' mutual relationships. The CRC cards serve as documentation for both domain experts and system developers, and thus, together with the product variant master and the class diagram, become an important means of com-

municating and documenting knowledge within the project group.

A more detailed description of the individual fields on the CRC cards is as follows:

Class name:

The CRC card is given a name that is unique, so that the class can be identified in the overall structure.

Date:

Each card is dated with the date on which the card was created, and a date for each time the card is revised.

Author/ version:

The person who created the card and/or has the responsibility for revising the card and the card's version number.

Responsibilities:

This should be a short text describing the mission of the class. This makes it easier to get a rapid general view of what the class does.

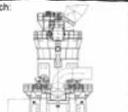
Class name: OK Mill		Date:	Author/version: LiHe												
Class responsibilities: The class' responsibilities are to determine the machine type from the capacities calculated in mass flow.															
Aggregation:		Generalisation:													
Supersparts: Cement grinding		Superclasses:													
Subparts:		Subclasses:													
Sketch: 															
Attributes: Power Blaine [0..1000] kW/ton Production (mass flow) [0..10.000] ton Power Mill [0..50.000] kW Production Mill [0..10.000] ton/hour Power Cement Mill			Class collaborates with:												
<table border="1"> <thead> <tr> <th>Type</th> <th>Power [kW]</th> </tr> </thead> <tbody> <tr> <td>OK 27.4</td> <td>1.636</td> </tr> <tr> <td>OK 30.4</td> <td>2.136</td> </tr> <tr> <td>OK 33.4</td> <td>2.970</td> </tr> <tr> <td>OK 36.4</td> <td>3.713</td> </tr> <tr> <td>OK 39.4</td> <td>4.554</td> </tr> </tbody> </table>				Type	Power [kW]	OK 27.4	1.636	OK 30.4	2.136	OK 33.4	2.970	OK 36.4	3.713	OK 39.4	4.554
Type	Power [kW]														
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OK 36.4	3.713														
OK 39.4	4.554														
System methods:															
Product methods: Power Mill (calc) = Production Mass Flow * Power Blaine Mill type is selected as the first mill in the Power Cement Mill table with a power large than the calculated power.															
Heat generator Heat generator only for cement grinding stations. Cement grinding stations in scope causes a heat generator to be selected by default.															
Gear Gear power >= mill power															
<table border="1"> <thead> <tr> <th>Gear</th> <th>Power [kW]</th> </tr> </thead> <tbody> <tr> <td>DMHG 18</td> <td>2.690</td> </tr> <tr> <td>DMHG 22</td> <td>4.100</td> </tr> <tr> <td>DMHG 25.4</td> <td>6.500</td> </tr> <tr> <td>ZxDMHG 22</td> <td>8.400</td> </tr> <tr> <td>ZxDMHG 25</td> <td>10.000</td> </tr> </tbody> </table>				Gear	Power [kW]	DMHG 18	2.690	DMHG 22	4.100	DMHG 25.4	6.500	ZxDMHG 22	8.400	ZxDMHG 25	10.000
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DMHG 18	2.690														
DMHG 22	4.100														
DMHG 25.4	6.500														
ZxDMHG 22	8.400														
ZxDMHG 25	10.000														
			Mass flow												

Figure 4. CRC-card

Aggregation and generalization:

The class' position in relation to other classes is described by specifying the class' place in generalization-specialization structures, respectively, or aggregation structures. This is done by describing which superclasses or subclasses are related to the class within either a generalization-specialization hierarchy or an aggregation hierarchy. Generalization categorises classes with common properties from general to specific classes in the so-called generalization-specialization hierarchies, also known as inheritance hierarchies, because the specialized classes further down in the hierarchy "inherit" general properties from the general (higher level) classes.

The other type of aggregation is a structure in which a higher-level class (the whole) consists of a number of subordinate classes (the parts). Using ordinary language, decomposi-

tion of an aggregation structure can be expressed by the phrase "has a" and aggregation by "is part of".

Sketch:

When working with product descriptions, it is convenient to include a sketch, which in a concise and precise manner describes the attributes included in the class. Geometric relationships are usually easier to explain by using a sketch/drawing than by using words.

Class attributes:

The various parameters such as height-interval, width-interval etc., which the class knows about itself, are described in the field "Attributes". Attributes are, as previously mentioned, described by their names, datatype (if any), range of values and units (for example, Length, [Integer], [1..10] mm). It is often convenient to express attributes in table form.

Class methods:

What the class does (for example, calculation of an area) is placed in the field of "Methods", which, as stated, can be divided into system methods and product methods.

Methods can be described in a natural language with the help of tables, with a pseudo code, by using a formal notation such as Object Constraint Language (OCL) (Warmer et al., 1999), which is a standard under UML, or by using the notation from individual items of configuration software.

3. CASE STUDY

3.1. The Industry Applications

The Product Variant Master has been applied in several manufacturing companies. In the following we shall give a brief introduction to three of those companies and their configuration projects, and we will discuss the experiences and lessons learned by using the product variant master and CRC-cards for modelling product families for product configuration systems. *Company A*

Company A is an engineering and industrial company with an international market leading position within the area of development and manufacturing of cement plants. The company has a turnover around 1 billion USD.

A modern cement plant typically produces 2-10,000 tonnes of clinkers per day (TPD), and the sales price for a 4,000 TPD plant is approx. 100 million USD. Every complete cement plant is customized to suit the local raw material and climatic conditions, and the lead-time from signing the contract to start-up is around 2½ years.

The company has initiated a project on the development of a product configuration system for the selection of the main machines of the factory and the overall determination of capacity, emissions etc. based on 2-300 input parameters on e.g. raw materials, types and qualities of finished goods, geographical conditions, energy supply etc. The configuration system is meant to be used in the early sales phase for making budget quotations, including an overall dimensioning of the cement factory, a process diagram and a price estimate.

In the product analysis, the cement factory was divided into 9 process areas. Based on the process areas the model was structured hierarchically, starting with scope list and mass flow leading to the selection of solution principles described

as arrangements and lists of machines. The product analysis was carried out by using the product variant master and the CRC-cards. The product variant master proved to be a useful tool for modelling the overall cement milling processes and machine parts of the cement factory. The product variant master was built up through a series of meetings between the modelling team and the product experts at the company. The detailed attributes and constraints in the model were described on the CRC-cards by the individual product experts.

The product variant master and the CRC-cards formed the basis for making a formal object-oriented model of the configuration system. Based on the product variant master an object-oriented class structure was derived and the CRC-cards were checked for inconsistency and logical errors. The product variant master was drawn by using MS-Visio, the CRC-cards were typed in MS-Word documents. The product configuration system was implemented in an object-oriented standard configuration software "iBaan eConfiguration Enterprise." The OOA model was derived by the programmer of the configuration system based on the PVM and the CRC-cards. The CRC-cards both refer to the product variant master and the object-oriented class model, which represents the exact structure of the product configuration system in the "iBaan eConfiguration Enterprise." The experiences are summarised in table 1 below.

Table 1. PVM and CRC-cards in company A

Modelling tool for domain experts – how the PVM was received by the domain experts	The domain experts were engineers from product design and project engineering. The domain experts could easily learn the modelling techniques for the purpose of evaluation of the models and input of information. The modelling was carried out by the configuration team and external consultants.
The possibilities for structuring product knowledge	The customer, engineering and part views have proved to be useful when modelling these products of high complexity. Structuring the PVM requires knowledge on domain theory for modelling mechanical products.
Visualisation and decision making on the product families in focus	The Product Variant Master proved to be able to capture and visualise the product assortment in this case on a high level of abstraction. Need to control the discussions to avoid non relevant details in the model. Important to involve the right domain experts in order to make decisions needed on the product variants to include in the configuration system.
PVM as a basis for programming the configuration system	Based on the PVM an OOA-model was set up to be used as a basis for implementing and maintaining the configuration software. Easy to transform the PVM to a formal OOA model.
PVM and CRC cards as documentation when maintaining and updating the configuration system	The PVM is only used in the analysis phase and is not maintained in the phase of running the configuration system. The OOA-model is currently being updated and used in the running phase of the system. The company has over the last 10 years increased the level of documentation and searched for IT-systems to manage the documentation task.

The product configuration system is currently being updated and further developed by a task force who is responsible for updating and further developing the model and the configuration system in cooperation with the product specialists. Maintaining the documentation in Visio and Word has proved to be a tedious work, as the same attributes and rules will have to be updated in several systems. In order to improve this, the company has during the last year implemented an IT-system for documentation, which means that the rules and attributes now only will have to be entered once into the documentation system.

The project at Company A has proven that the use of the three views in PVM can be useful when modelling complex products. Finally, the configuration system has been implemented in two different product configuration systems. The first configuration system was not object-oriented, while the second configuration system ("iBaan eConfiguration Enterprise") was fully object-oriented. Applying an object-oriented system made it considerably easier to implement and maintain the product configuration system.

3.1.1 Company B

Company B is an international engineering company that has a market leading position within the area of design and supply of spray drying plants. The company is creating approx. 340 mio. USD in turnover a year. The products are characterised as highly individualised for each product.

The configuration system was implemented in 2004 at company B and is in many ways similar to the configuration system at company A. The project focuses on the quotation process. During the development of the product model the need for an effective documentation system has emerged. Early in the project it was decided to separate the documentation system from the configuration software due to the lack of documentation facilities in the standard configuration systems. Lotus Notes Release 5 is implemented throughout the company as a standard application, and all the involved people in the configuration project have the necessary skills to operate this application. The documentation tool is, therefore, based on the Lotus Notes application.

The documentation system is built as a hierarchical file sharing system. The UI is divided into two main parts, the product variant master and the CRC cards. However, the product variant master is used in a different way. Only the whole-part structure of the product variant master is applied in the documentation tool. Main documents and responses are attached to the structure of the product variant master. The configuration system is implemented in Oracle Configurator. Since the standard configuration software does not provide full object orientation, the CRC cards described in section 2.2 have been changed to fit the partly object-oriented system. The fields for generalization and aggregation have been erased. The aggregation relations can be seen from the product variant master and generalization is not supported.

To ease the domain expert's overview, an extra field to describe rules has been added. In this way, methods (does) have been divided into two fields, does and rules. "Does" could be e.g. print BOM while "Rules" could be a table stating valid variants. The CRC Card is divided into three sections. The

first section contains a unique class name, date of creation and a plain language text explanation of the responsibility of the card. The second section is a field for sketches. This is very useful when different engineers need quick information about details. The sketch describes in a precise manner the attributes that apply to the class. The last section contains three fields for knowledge insertion and collaborations. Various parameters such as height, width etc., which the class knows about itself, are specified in the “knows” field. The “knows” field contains the attributes and the “rules” field describes how the constraints are working. The “does” field describes what the class does, e.g. print or generate BOM. Collaborations specify which classes collaborate with the information on the CRC card in order to perform a given action.

The documentation system has been in use throughout the project period. As mentioned, the documentation system was created by using standard Notes templates. This gives limitations according to functions of the application. Class diagrams are not included in the documentation tools. They must be drawn manually. Implementing class diagrams would demand a graphical interface, which is not present in the standard Lotus Notes application. Table 2 below lists the main findings from company A.

Table 2. PVM and CRC-cards in company B

Modelling tool for domain experts – how the PVM was received by the domain experts	The modelling is carried out by the configuration team and reviewed by the domain experts/ engineers. However, the domain experts contributed with parts of the model reflecting their special field of competence. Easy for the domain experts to learn to read and review the PVM and CRC-cards.
The possibilities for structuring product knowledge	The model includes complex and highly engineered products. The three views in the PVM were used to clarify the interdependencies between customer requirements, main functions in the products and the Bill of material (BOM) structure. These interdependences were expressed as rules and constraints in the configuration model.
Visualisation and decision making on the product families in focus	The PVM was used to determine the preferred solutions to enter into the configuration system. The links between the three views provided insight into the consequences of delimiting which customer requirements to meet main functions and the number of main BOM's to include in the configuration system. The sketches on the CRC-cards have proved to be very useful in the communication with the domain experts.
PVM as a basis for programming the configuration system	The PVM and the CRC-cards were used as documentation for programming the configuration system. No formal OOA model was made.
PVM and CRC cards as documentation when maintaining and updating the configuration system	The PVM was transferred into a file structure in the company's file share system (Lotus Notes). The CRC-cards are stored and currently updated in Lotus notes. Domain experts are responsible for updating the individual CRC-cards.

Lessons learned from the project at Company B were that an IT-based documentation tool is necessary in order to secure

an efficient handling of the documents in the product model (product variant master and CRC-cards). The configuration system is implemented in Oracle Configurator, which is not a fully object-oriented configuration system. This means that e.g. inheritance between object classes in the product configuration system is not possible. The company uses a variant of the product variant master, where only the whole part structure on the right side of the product variant master is applied. However, the experiences from the project are that the revised product variant master and the CRC-cards still secure a structure and documentation of the system.

3.1.2 Company C

Company C produces data centre infrastructure such as uninterruptible power supplies, battery racks, power distribution units, racks, cooling equipment, accessories etc. The total turnover is approx. 4 billion USD (2008). The company has applied the PVM and CRC-cards since 2000. Today, the company has 8-9 product configuration systems. The company has formed a configuration team with approx. 25 employees situated in Kolding, Denmark. The configuration team is responsible for development and maintenance of the product configuration systems, which are used worldwide.

Table 3. PVM and CRC-cards in company C

Modelling tool for domain experts – how the PVM was received by the domain experts	The PVM is used for modelling the product families in a cooperation between the configuration team and engineers from product development
The possibilities for structuring product knowledge	Relative to company A and B this company has a more “flat” structure in the PVM and configuration system, meaning that the level of structuring is lower than company A and B. The PVM and CRC-cards is set up by the configuration team and afterwards discussed with product development.
Visualisation and decision making on the product families in focus	The product configuration systems are set up after the product development project is completed. The PVM and CRC-cards lead to clarification of decisions on product variants that haven't been made in the development project.
PVM as a basis for programming the configuration system	The configuration system is programmed based on an object-oriented model made from the PVM and on the CRC-cards.
PVM and CRC cards as documentation when maintaining and updating the configuration system	Only the CRC-cards are used for maintenance and update of the product configuration systems. The CRC-cards are stored and currently updated in Lotus notes. The configuration team members are responsible for updating the individual CRC-cards.

The product assortment is modeled in a co-operation between the configuration team and the product development teams. The product variant master and the CRC cards are used in the modeling process and document the configuration systems throughout programming and maintenance of the product

configuration systems. Similar to Company B, company C has developed a Lotus Notes based documentation tool – called the CRC-card database - to handle the documentation of the models. The configuration systems are implemented in Cincom Configurator, which is a rule based configuration system.

Lessons learned from company C are that the need for an IT-based documentation tool is even bigger at this company, than at Company B. Running a configuration team with 25 employees, which have to communicate with product development teams around the world, requires a structured procedure for building the product configuration systems, as well as a Web-based documentation tool, which can be accessed by employees worldwide. At company C, a Notes based documentation tool has been developed similar to the Notes application at company B. The documentation system has now been running for 6 years. The experiences from running the documentation system is that the structure in the product variant master and the CRC-card database form a solid basis for communicating with e.g. product designers and for maintaining and further developing the product configuration systems. However, the fact that the documentation system is separated from the configuration software means that the attributes and rules have to be represented in both the documentation tool and in the configuration with only limited possibilities of relating the two systems to one another. This means that the configuration team at company C needs to be disciplined about updating the documentation system every time a change is made in the configuration system.

4. CONCLUSION

The proposed modelling techniques are based on well-known and proven theoretical elements; theory for modelling mechanical products, systems theory and object-oriented modelling. The aim of the product variant master and CRC-cards are to serve as a tool for engineers and programmers working with design, implementation and maintenance of product configuration systems. The experiences from applying the procedure in the above mentioned three industrial companies show that the product variant master and CRC-cards contribute to define, structure and document the product configuration systems. The product variant master and the CRC-cards make it possible to communicate and document the product assortment, including rules and constraints on how to design a customer tailored product.

The product variant master is developed based on the basic principles in object-oriented modelling and programming. However, only a very small part of the standard configuration systems based on rules and constraints and including an inference engine are fully object-oriented. In order to meet this actual situation the product variant master and the CRC cards have been changed to fit into configuration systems, which are not fully object-oriented. The experiences from applying the procedure in building configuration systems in non object-oriented systems are positive. However, structuring and maintaining configuration systems are considerably easier in an object-oriented standard configuration system. Furthermore, an integration of the documentation tool and the configuration systems would ease the work of design, implementation and maintenance of product configuration systems considerably.

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