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Model-Based Consistency for Design for Variety and Modularization

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Abstract: Methods for developing modular product families contain a lot of information and data that are not always consistent. Consistent data modeling enables simple changes across all affected tools while developing modular product families. Redundant information can be identified and eliminated, and networking between different data is enabled. Inconsistency in variant management is analyzed and addressed with a data model that supports consistency at different hierarchical levels. The data model is modeled with the Cameo Systems Modeler in SysML and is used in a case study for a Design for Variety and modularization with DSM on a vacuum cleaner robot.

Keywords: Model-based approach, Design for Variety, Modularization, Consistency, Data model

1 Introduction

Methods for developing modular product families are characterized by the use of a large amount of information and data, which can include numerous components, their links, and the resulting modules. Product development processes such as variant management (for example, in the method Design for Variety) are often inconsistent because they are carried out in a document-centered manner in companies. Methodological tools do not relate to each other or to available company information. A way to create and document different stages of development is also not provided. Inconsistencies can occur and networked information cannot be understood, which hinders the development process of modular product families. Consistency is important to ensure changes throughout all relevant documents and networking between the pieces of information, as well as to avoid redundant information. (Albers and Lohmeyer 2012, Krause et al 2014, Bursac 2016)

This paper addresses the problem using a model-based approach in which the data is modeled in a consistent data model to counteract inconsistencies that have occurred in product development to date. Variant management and the development of modular product families are modeled on a Design Structure Matrix (DSM). Tools from Model-Based Systems Engineering (MBSE) are used, because they aim for better document management.

Methods for variant management and the current state of research in MBSE are explained. Then the consistent data model and its implementation in Cameo Systems Modeler are shown. The resulting model is used to reduce internal variety in the example of vacuum cleaner robots.

2 Methods of Variant Management and Terms of MBSE

This section presents methods for reducing internal variety and some relevant terms of MBSE.

2.1 Methods for reducing internal variety

High external variety results from a multitude of variant products being offered by a company and leads to high internal variety. Variants could be managed using the method unit Design for Variety from the Integrated PKT-Approach. Its aim is to change the product structure to achieve the ideal of a variety-oriented product structure. This method is supported by some visualization tools (Figure 1).

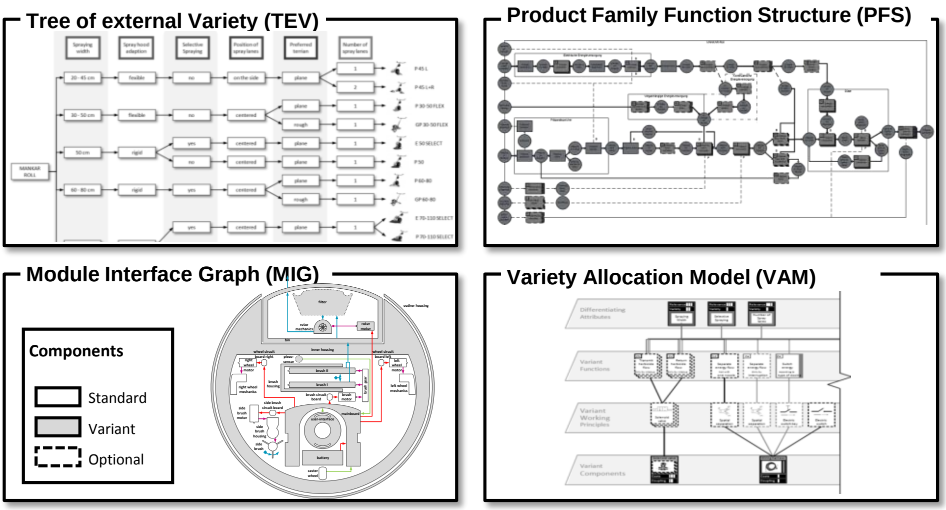

Figure 1. Tools for Design for Variety, according to Gebhardt et al 2012

External variety is represented by the Tree of External Variety (TEV); internal variety of components is shown in the Module Interface Graph (MIG) and the internal variety of functions is viewed in the Product Family Function Structure (PFS). In the Variety Allocation Model (VAM), elements of these tools are linked to each other. TEV, MIG, PFS and VAM are partial models. (Krause et al 2014)

Another way to reduce internal variety is by using a modular product structure. Modularization can be carried out based on Design for Variety. There are different methods for modularization; three are presented below.

Modularization based on the needs of all life phases can be developed with the method unit Life Phases Modularization of the Integrated PKT-Approach (Krause et al 2014). With the procedure of Stone, module formation is based on the flows within the functional structure. Three heuristics are determined: dominant flow, branching flow and conversion-transmission (Stone 1997). The basic premise of the Integration Analysis methodology, based on the Design Structure Matrices (Steward 1981), is that components exhibit the technical couplings information transfer, energy transfer, material transfer and spatial dependencies. The stronger that components are coupled the more they should be part of the same module (Pimmler and Eppinger, 1994).

2.2 Terms of Model-Based Systems Engineering

A model is an abstraction of reality which has three main characteristics. Representation means that models represent something; Reduction indicates that not all attributes are represented in the model, only the relevant ones; Pragmatism means that models are not clearly assigned to their originals. A meta model is itself a model that can be used to describe modeling. Here, the term data model is used, which is at an abstract level and is understood as a meta model. (Holt et al. 2012, Stachowiak 1973)

Consistency of time means that models can be used across different times; they are extendable. Consistency of vertical levels means that the model has to be vertically consistent. Consistency between different models of one product family is required (Bursac 2016, Scherer 2016). In their consistency management, Herzig et al. focus on the early identification of existing inconsistencies. Levels of inconsistency can be classified as internal or external inconsistency (Herzig et al 2011).

Systems engineering supports the developing process of systems, according to systems requirements. It consists of system architecture, system requirements and system behavior. With MBSE, system elements can be modeled and information can be linked, so that information can be saved and used in a networked model. The language SysML was developed for MBSE. The modeling software Cameo Systems Modeler uses SysML notation as well as diagrams and tables. (Weilkins 2008, Holt et al. 2012)

Previous work using model-based approaches in modular product development concentrated on either variant management (see Bahns et al 2015, Hanna and Krause 2017) or developing modular product families (Bursac 2016, Scherer 2016).

3 A Data Model for Consistent Development of Modular Product Families

The methodical approach is shown in this section. The challenges of data inconsistency, the procedure for developing a data model and the advantages of the data model are shown.

3.1 Challenges of Data Inconsistency in Product Development

A data model that supports consistency is needed. For example, Design for Variety in the Integrated PKT-Approach consists of several inconsistent partial models that are used mainly in Microsoft Powerpoint printouts. For example, the variant product properties that are created in the TEV are inserted at the top level of VAM. This does not happen automatically, which can lead to errors and high overhead during transmission. The same applies to the functions that are shown in the VAM at the middle level and come from the PFS. The components in the VAM are not consistently extracted from the MIG. In case of later changes, such as a change of component, all contained tools must be modified (in this case, VAM and MIG). Creating new versions is expensive and can lead to errors. There is no link between variant management and modular product family development. Beyond this, in the different tools the versioning is only partial available, but not consistent.

3.2 Procedure for Modelling a consistent Data Model

The following steps have been taken to shift from inconsistent partial models to a consistent data model for variant management. First, all used methods (for example, Design for Variety and Integration Analysis Methodology) and their tools (for example, the VAM and the DSM) are analyzed. Elements and how they link to each other are identified. Based on this, the data model was then built based on the components, because the components are found in many tools and form the center of the methods. The links were not defined exactly in the data model in order to remain as solution-neutral as possible in the modeling software implementation..

3.3 Data Model

A data model is needed to solve the consistency problems described in Section 3.1. The three levels of consistency mentioned above were taken into account: Consistency of time, vertical levels and between different models. The focus is not on the rapid identification of inconsistencies, as in Herzig et al., but on building a new consistency model, as one does not yet exist (Herzig et al 2011). The data model for both Design for Variety and modularization is shown in Figure 2.

The top of Figure 2 shows the elements and models needed for the method Design for Variety; the bottom shows the ones for modularization. Every element only exists once, in contrast to previous unlinked tools. Design for Variety and modularization can be considered as sub-models of the data model and include further models and elements. At their overlap area, components are presented once; they form the central elements here. In Design for Variety they are used in the MIG (III, colored green), where they are connected to the flows and in the VAM (IV, colored blue), where they are linked with the work principles. In the modularization the components are used in the DSM (V, colored red), where they are linked to the couplings and the modules. The tools used here are partial models because they are an abstraction of reality (for example, the MIG is an abstraction of the real product family).

All elements used are shown and linked to each other. Each element is built with four layers for the different versions. Elements can have different versions: before and after Design for Variety; and after modules are built and changes made. Each layer represents one of these versions. If an element exists in several versions, then the corresponding layers are colored gray.

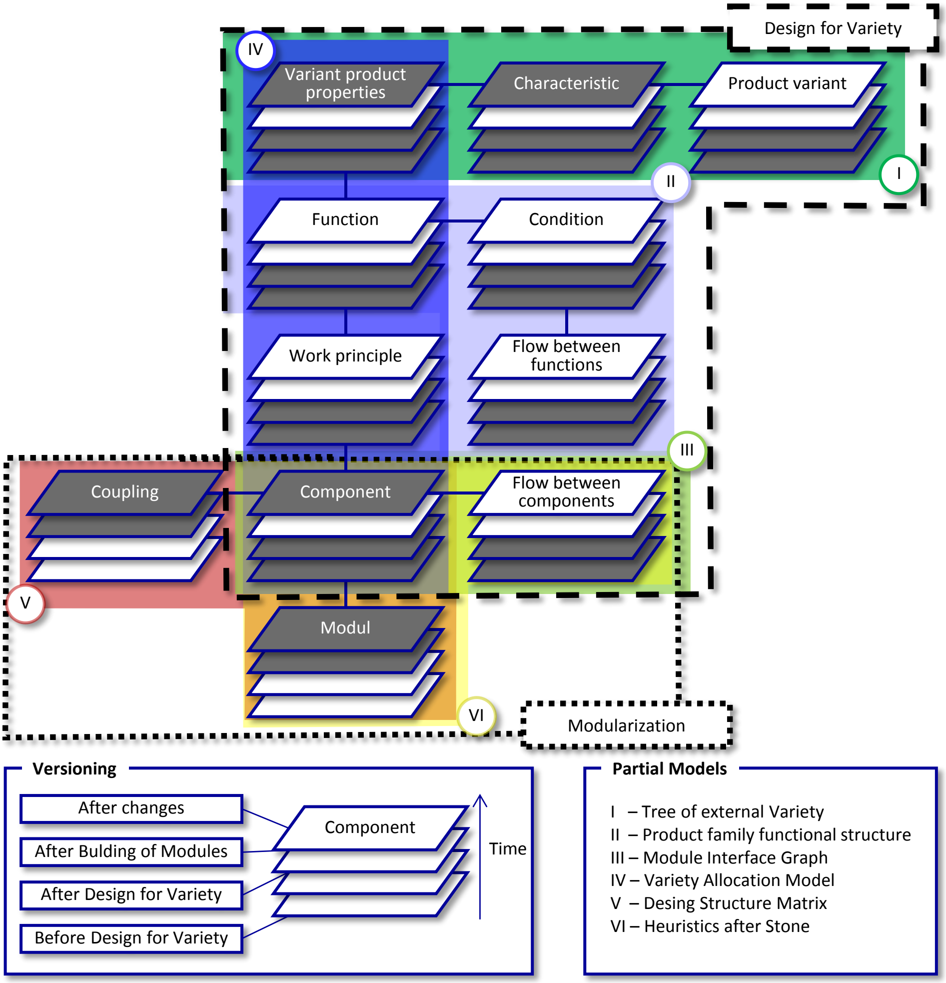

Figure 2. Consistent data model for Design for Variety and modularization

Components in Design for Variety may change. The type of variance can be changed constructively to achieve a variant-oriented product structure. For example, a component can be available in several variants at the beginning and standardized after Design for Variety. This is why the two lowest layers of the model element “component” are marked in gray in Figure 2. There may be one version before and another after using the method. After building modules, the components do not change with the modularization methods used. The third level is marked white. If there are subsequent changes, components can be changed again, which is why the top layer is highlighted in gray. In contrast to components, modules are not used during variant-oriented product design, which is why the two lowest layers are white. In addition, there is a version after modules are built, so the third layer is colored gray. After changes in the modular product structure, modules can be changed, so the fourth layer is also gray.

3.4. Advantages to the consistent data model

For the first time, a consistent data model for variant management and modularization has been created in which all the elements used are consistently linked. Elements that are used in both areas can be easily identified (for example, the components). This data model is an expandable meta model for the product development of modular product families. Based on the data model, consistent modeling of Design for Variety and modularization can now be achieved using MBSE. The data model was implemented in Cameo Systems Modeler.

The three levels of consistency are achieved as follows:

- Consistency between models: Because every element exists only once, changing an element in one partial model definitely leads to the same element changing in another partial model. Once an element (e.g. component) has been created correctly, it is correctly created in all partial models (e.g. MIG, VAM and DSM).
- Consistency of time: Using different layers, the different versions in which an element can appear are figured out. Which elements change over time becomes clear. Components change in Design for Variety and after changes.
- Consistency of vertical layers: Vertical consistency can be achieved using different hierarchical levels of the models. For example, the partial model DSM and the Heuristics of Stone are both part of modularization, which is part of the whole data model; they all use the same component.

4 Case Study based on the Data Model, using SysML

This section shows application of the data model using the Cameo Systems Modeler. A simple case study on the vacuum cleaner robot demonstrates application of the individual tools of Design for Variety and modularization comprehensibly. To generate a matching SysML model in Cameo Systems Modeler, first the tools are analyzed for contained elements and links between them. This produces the requirements for the SysML diagrams to be used.

For example, in the TEV allocations between the elements variant product properties, characteristics and product variants are used. This can be managed with block definition diagrams. An internal block diagram is used for the MIG because it can show different types of flows between the elements (in this case, components). In addition, the VAM was modeled. Besides the Design for Variety tools, modularization tools can also be modeled. In this case, the DSM, with its couplings between components, is realized with a dependency matrix in the Cameo Systems Modeler.

Individual partial models are implemented by different diagram types. They all use centrally stored elements that are linked to each other. Different versions of the individual elements are stored in separate packages in the model to allow versioning.

4.1 Modeling Design for Variety tools

The first step in Design for Variety is analyzing external variety using TEV. The MIG is used to analyze internal variety. Figure 3 shows implementation of the vacuum cleaner robot MIG in SysML. A detailed section is shown to clarify connections.

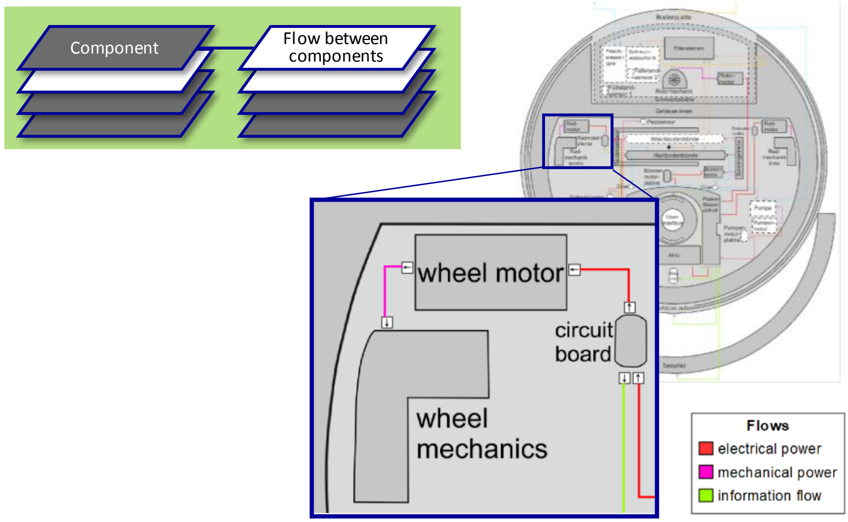

Figure 3. Module Interface Graph for the vacuum cleaner robot, modeled in SysML

The MIG for analyzing internal variety includes components that are linked to each other via flows. Pictures have been added to the individual elements and colored flows are linked to the components via ports. The components get their shape from the existing physical product and are shown in the color sheme, with gray colored components for variant components like “wheel mechanics” or “wheel motor”.

Together with a functional structure, these tools lead to the VAM (Figure 4), where the model elements variant product properties from the TEV are linked to the functions from the PFS. The functions, in turn, are linked to the work principles, which are linked to the components of the MIG.

The connections between the elements in the VAM are arranged vertically. The variant product property “Remote control” is linked to the function “Remote Control Detection”, and the function “Infrared Signal” is linked to the component “Infrared Receiver”. The variant product properties are characterized using a colored icon, which is also used for the connections between levels. For work principles, functions and components, the type of variance is pictured with a small icon in the upper right side. For example, the “Infrared Receiver” has a white symbol with dashed edge, which indicates that it is an optional component. The gray icon in the upper right corner of the component “Battery” indicates that it is a variant component.

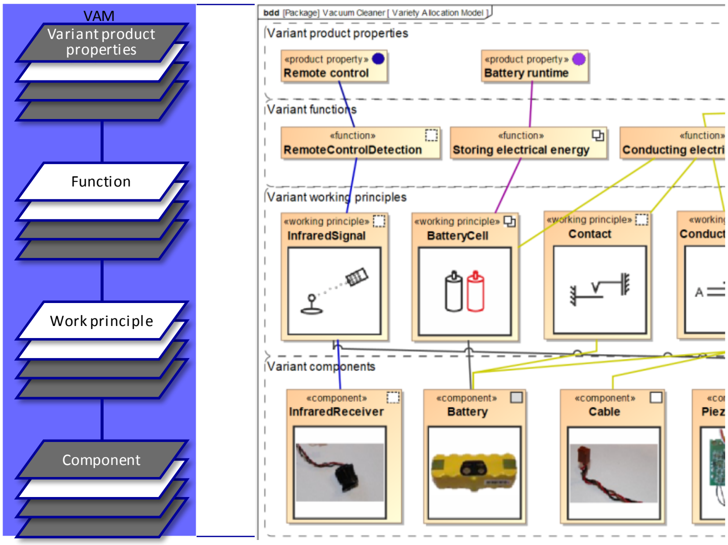

Figure 4. Variety Allocation Model implemented in SysML

4.2 Modeling Modularization with the Design Structure Matrix

Various methods can be used for modularization of a product structure. A DSM for modularization of the vacuum cleaner robot is shown here. The DSM includes components, couplings and modules. Figure 5 shows how these elements connect to each other.

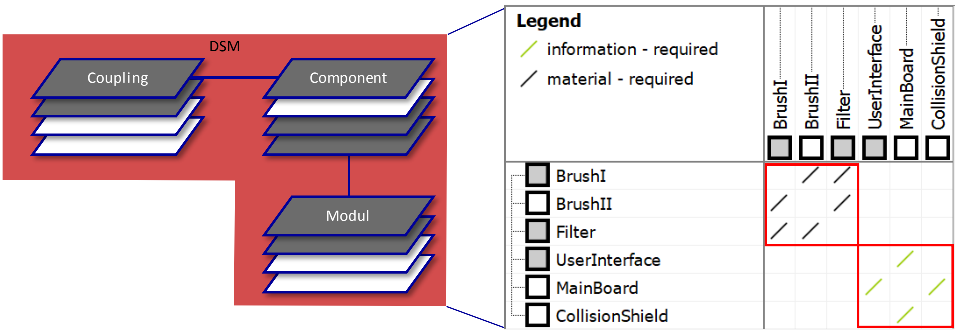

Figure 5. Detail of a Design Structure Matrix for a vacuum cleaner robot, modeled in SysML

Figure 5 is a detail from the DSM in Cameo Systems Modeler, showing the material and information coupling between components of the vacuum cleaner robot. The components “BrushI”, “BrushII” and “Filter” have a required coupling for material transport, and can be built to modules. The components “User Interface”, “Main Board” and “Collision Shield” are linked through required information flow.

In addition to the standard DSM, the type of variety is shown next to the components. For example, next to the component “BrushII” a white box is shown, which indicates that this is a standard component. A gray box next to component “BrushI” identifies this component as variant.

4.3. Evaluation of the application in SysML

By developing a data model the data can be managed. A data model makes it clear that components need only be present once, but can be used in different tools. A new level of continuity can be achieved. If a component is to be changed, the change is visible in every diagram where the component is used. However, visualization of individual tools is no better than conventional visualization, such as in PowerPoint. An advantage of using Cameo Systems Modeler is the possibility of adding additional information to individual model elements and defining connections between model elements that are consistent throughout the whole model. For example, information on variance of a component can now also be shown in a DSM. This makes the DSM more meaningful and supports module building. Information, which is generated in the DSM can be easily added to the model itself.

5 Conclusion

Design for Variety and modularization can be supported with a consistent data model. Methods used previously to reduce internal variety led to inconsistencies in the creation and modification of elements. Three levels of consistency are made possible with a data model. Model elements were linked consistently to Design for Variety and integration analysis methodology tools. Modeling of Design for Variety and modularization in one MBSE model, using the Cameo Systems Modeler, was presented. The SysML model was used in the case study on a vacuum cleaner robot and showed how the Design for Variety and modularization tools can be visualized and made consistent.

The data model can now be changed at a central location, which results in automatic change of the partial models used. Various versions can now be displayed in one model. In addition, DSM work is supported as not only individual products but also entire product families can be modularized, as the type of component variance becomes clear when combined with variant management.

The data model needs to be expanded with further research. By including life phases, the Life Phases Modularization can be added and more methods for developing modular product families used. Cost information can be added to the data model and through life phases, possibly via the Impact Model (Hackl and Krause 2017). Inclusion of the Impact Model in the data model is feasible, as it access the (modular) product structure. It also contains a lot of information, which could be handled with a continuous sub-model. The connection of boundary conditions is also relevant. Since the Impact Model contents are partly based on mathematical key figures, a link to Matlab is conceivable.

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