

A hunt for the hidden reasons behind a product architecture

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Abstract: A modular product architecture is a strategic means to deliver external variety and internal commonality. In this paper, a heavy duty modular gearbox architecture is represented and analyzed. In focus is re-engineering of hidden technical complexity and business strategy concerns behind an existing product architecture. The architecture of the investigated gearbox is represented and analyzed with a *Product Architecture DSM* and the *Integrated Modularization Method (IMM)*. Furthermore, a *Cluster Match Matrix (CMM)* is proposed as a means to compare multiple clustering results. The case study indicates that the IMM methodology and CMM can be used for analyzing and finding the explicit and/or implicit reason for a targeted existing product architecture.

Keywords: Product Architecting, Integrated Modularization, DSM, MFD, IMM.

1 Introduction

Ulrich (1995) defined product architecture as “the scheme by which the function of a product is allocated to physical components”, or more formally as: (1) the arrangement of *functional elements*, (2) the mapping from *functional elements* to *physical components* (also referred as technical solutions) and (3) the specification of the *interfaces* among interacting system components.

The architecture of a product may be categorized based on the type of mapping between functional elements and physical components. If there is a one-to-one mapping between functional elements and physical components, the design is said to be uncoupled, while it is said to be coupled if the mapping is complex. In 2005, Hölttä-Otto defined these two types of architectures as being modular (uncoupled) and integral (coupled). Thus, a module is a configuration of highly interconnected system elements with few interrelations with components outside of the module (Ulrich, 1995). This implies that the architecture of a module may very well be integral. A common definition is that a *module* is a functional building block, with well-defined and standardized interfaces between modules, and that it should be chosen for company specific reasons, i.e. support a company specific business strategy (Erixon 1998). A *module variant* is a physical incarnation of a module with a specific performance level or appearance. A module may therefore have multiple module variants, which may be configured in multiple ways in order to satisfy different customer requirements. Thus, a *modular system* can be defined as the collection of module variants by which all the required end products can be built (Börjesson, 2014).

Hölttä-Otto (2005) presented the following three main approaches for modularizing a product; *Heuristics*, *Modular Function Deployment (MFD)* and *Design Structure Matrix (DSM)*. Heuristics is based on an analysis of the pattern of flow of matter, energy, and

information between function blocks, see e.g. (Erixon, 1998). MFD (Erixon, 1998) (Ericsson and Erixon, 1999) is a five-step method for translating customer requirements into a modular architecture, while considering the strategic company specific objectives, represented by twelve predefined generic *Module Drivers* (MD:s) that should reflect the strategic objectives of the company, e.g. modules can reduce capital needs and bring economies in parts sourcing (Baldwin and Clark, 2000), (Ulrich and Tung 1991). In the MFD methodology, the MD:s are represented by a *Module Indication Matrix* (MIM), which is an interdomain matrix that relates the physical function carriers, i.e. the components, and the twelve MD:s. The main focus of DSM-based modularization approaches is to minimize technical complexity by clustering the component-DSM in a way that minimize the technical interactions between clusters of components, i.e. complex interactions are grouped within clusters. A cluster is a module candidate.

There are two main categories of relations or interactions that are important to consider when representing the product architecture, i.e. hierarchical (vertical) and lateral (horizontal). Hierarchical relations are used when modeling a breakdown of a product into subsystems, modules and components etc., e.g. a *product breakdown structure* (PBS), also referred to as a *product structure*. Lateral relations describe how the elements in the product architecture interact, at a given level of decomposition. Hence, different types of relations can be represented in the DSM. Pimmler & Eppinger (1994) proposed four generic interaction types to represent the lateral relations between the technical solutions or functions in a Product Architecture DSM. These are *spatial relations* and *flow of matter, information and energy*. Some relations may be more important than others. *Relation weights*, also known as *interaction strengths*, are therefore used to represent their relative importance. With DSM, we further on refer to a *Product Architecture DSM*, which we define as a component-DSM with all interactions represented as functional flows (information, energy, matter) and spatial relations. This type of architectural representation is sometimes referred to as *system architecture DSM*, *product DSM* and *component-based DSM* (Eppinger & Browning, 2012). DSM representations are mainly used to visualize the complex lateral interactions between the product components, however, it may also be used to model hierarchical interactions, see the color-coded clusters in Figure 1.

The DSM clustering algorithm presented in Börjesson and Sellgren (2013) enables highly efficient clustering of DSM:s with arbitrary numerical values for the dependencies. DSM clustering addresses technical complexity but not strategic objectives (Blackenfeldt, 2001). Stake (2000) presented several examples of manual clustering of a DSM and a MIM, in an attempt to balance technical complexity (represented by a DSM) and business strategies (represented by a MIM). Blackenfeldt (2001) presented a method on how the MD:s could be condensed into the four generic groups *Carry over*, *Commonality*, *Make or by*, and *Life cycle*, and represented the relations between those four groups as a *Component-Based DSM*, but performed no further DSM-based analysis. Williamsson and Sellgren (2016) addressed the challenge to perform trade-offs between technical complexity and company specific business strategies, and proposed a methodology referred to as *Integrated Modularization Methodology* (IMM). The core of IMM is to integrate company specific module drivers with a *Product Architecture DSM*, and then cluster the strategically adapted DSM.

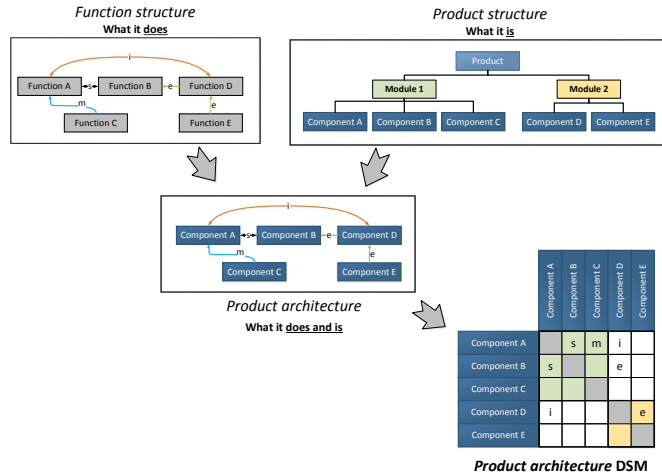


Figure 1. The type of DSM used in this paper.

A significant challenge in systems engineering is to represent and analyze the effects of architectural changes and expansions. De Weck (2007) introduced Component-Based Δ DSM and *Change-DSM* to represent and manage existing or future changes in complex products. A Δ DSM represents the difference between an original and a changed product. The *Change-DSM* contains the *change propagation paths*, i.e. how a change propagates from one component to another. A *Change-DSM* may therefore be used to identify components that are likely to multiply or absorb changes. No method has been proposed that can efficiently be used to analyze the difference between two DSM cluster results.

Five specific research questions are addressed in this paper:

- How can we compare multiple clustering results?
- How sensitive is DSM clustering to the relative weights of the spatial relations and the functional flows of matter, energy and signals?
- Can the DSM be used to re-engineer hidden relation weights of an architecture?
- Is IMM capable of identifying reasonable module candidates that are reasonable trade-offs between technical complexity and business strategies?
- Can IMM be used to re-engineer strategic reasons behind an architecture?

The questions are elaborated on with an industrial case. The studied case, which is presented in chapter 2, is analyzed in chapter 3 with DSM and IMM clustering, i.e. from technical complexity and module driver perspectives, and discussed in chapter 4. The main conclusions and a path for future research are given in chapter 5.

2 Case study

The presented architectural investigation was conducted at the heavy truck manufacturer Scania, which is part of Volkswagen Truck & Bus GmbH, and at KTH Royal Institute of Technology in Stockholm, Sweden. The studied gearbox was developed in-house by Scania to be a module in its modular system. Analyses of the mechanical and electrical

subsystems and the embedded control software were initially performed. It should be noted that only one gearbox variant, see Figure 2, was analyzed in the presented study. This was a deliberate delimitation, since a large number of variants can be configured from the modular system.



Figure 2. An illustration of a Scania truck powertrain (left), with a heavy-duty gearbox (right)

The product architecture

Scania is frequently used as a role model for modularization. The core of Scania’s modularization principle is balanced module variants configured from a limited number of physical components and with standardized module interfaces that can be combined to satisfy different customer needs. In order to efficiently describe all potential product variants, Scania represents the modular product as a generic product structure. A generic product structure does not describe a single product variant, but rather the entire product portfolio, which internally is referred to as the *Modular Toolbox*.

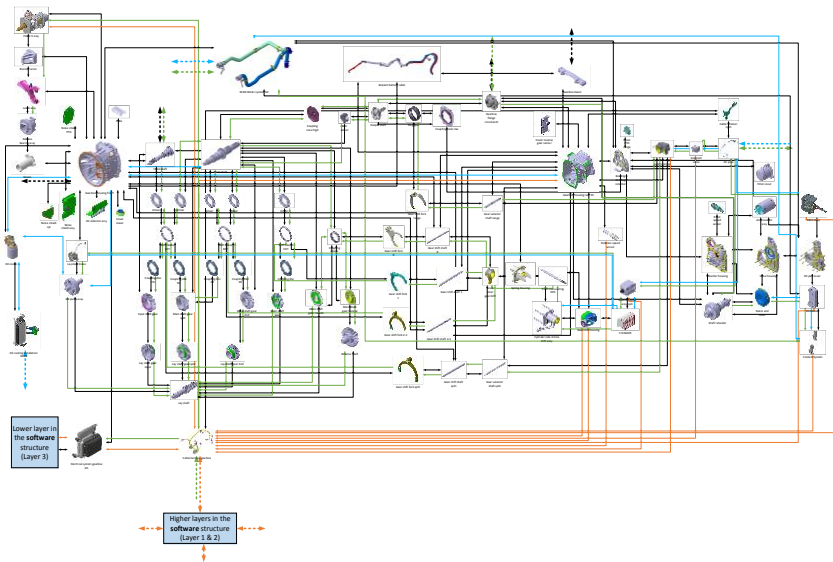


Figure 3. A component architecture diagram of the investigated gearbox architecture.

To represent the current architecture, the components and their functional purposes must first be identified. This was done by studying the physical decomposition from the generic product structure, as well as parts from the logical structure representing the

electrical and software architectures. To limit the number of components, all screws, gaskets and other small parts, were not considered in the decomposition. The interactions of the targeted 94 components were represented with a *component architecture diagram* (CAD). This representation, as shown in Figure 3, visualizes the components and their functional dependencies, i.e. the principal technical function flows and spatial relations, where black indicates a *spatial relation*, green *energy flow*, blue *material transfer* and orange *information flow*.

3 Analysis method and results

The modeled product architecture was used as a test bench for studying if and how the DSM and IMM approaches may support us to find the implicit reasons (reduced technical complexity and/or business strategies) for the architecture of a highly complex engineered system, such as the targeted gearbox.

The architectural analysis method

The product architecture was represented both as a product architecture DSM and as a strategically adapted DSM to be used with the *Integrated Modularization Method* (IMM) (Williamsson and Sellgren, 2016). DSM and IMM clustering was performed with the highly efficient algorithm *IGTA++* presented in (Börjesson & Sellgren, 2013). The four types of interactions in the DSM were initially assumed to have an equal importance or weight, but the number of interaction types were added in the off-diagonal matrix cells, e.g. energy flow and a spatial relation gives an interaction value of 2. IMM clustering was performed on a strategically adapted DSM. The strategies addressed were the Module Drivers (MD:s) from the MFD modularization method.

The starting point of an IMM-based analysis is the product architecture. The relations between corporate strategies, as represented by the MD:s, and the principal solutions, i.e. the components in the DSM, are represented with the Module Indication Matrix (MIM) in the MFD method. One of the main purposes of a MIM is to identify strategically conflicting MD:s, i.e. mismatches in strategies within a module candidate. In IMM, the MIM (see upper part of Figure 4) is represented as a strategy transfer DSM (see lower mid matrix in Figure 4), with all conflicting module drivers represented with a minus sign. By operating with the strategically transfer DSM on the Product Architecture DSM, with functional interactions in the off diagonal cells, we get a strategically adapted DSM. In this transformation, all relations interfering with a minus sign gets removed from the Product Architecture DSM, while empty cells remain unchanged. In the simple example shown in Figure 4, component *D* has a conflicting module driver to the other components. According to the MFD methodology, components with conflicting module drivers should not be clustered together, in order to avoid strategic conflicts. Hence, component *D* should be separated from the other components in this case.

The module drivers, i.e. also those in conflict, for the studied gearbox were unknown. A new method was therefore needed to identify components with potentially conflicting module drivers. The core of the new method is to identify components that frequently

end-up in a “wrong” cluster, compared to the existing modular architecture. This is done by comparing multiple clustering results from DSM:s with different weights for the different types of functional relations. The working hypothesis is that components which frequently end up in “wrong” clusters do that because of some (hidden) strategic aspects rather than technical. The same type of cluster comparison is also used to reveal implicitly/explicitly chosen relation weights, i.e. the technical complexity aspects behind the decisions for the existing modular architecture.

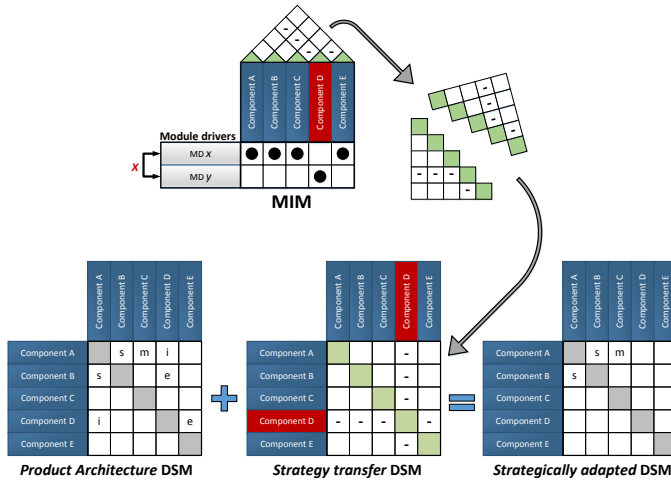


Figure 4. The integrated DSM-based product architecting model IMM.

The central representation used by the new cluster comparison method is referred to as the *Cluster Match Matrix (CMM)*, which is a matrix containing a representation of a modular architecture, and the clustering results based on the different relational weight combinations. In the example seen in Figure 5, components A, B and C are located in one module in the original (base) modular architecture. In a similar way, components D and E are located in another separate module. Notice that the module drivers are unknown for all components in this example, i.e. we do not know that component D has a conflicting module driver with the other components.

The numerical values in the CMM represent the cluster number which the component is assigned to by the clustering algorithm. In the left column in Figure 5 (equal relation weights, or dependencies of the same strength), components A, B and D are all assigned to *cluster 1*. In a similar way, component C is assigned to *cluster 2* and E to *cluster 3*. However, since component D is not in the same original module as components A and B, it is marked with red, indicating that the clustered component is in the “wrong” module compared to the studied gearbox. The cluster match is finally calculated based on how many components compared to the total amount of components that are in the same module as in the actual system. With this comparison method, multiple clusters may be located in the same original module and still fulfil the criteria of a full match. For example, the original module containing component A, B and C is an integration of *cluster 1* and *2* in the left column in Figure 5. Hence, only components which are split from their assigned cluster, to fit the existing modular architecture, are treated as being in

the wrong module. With the CMM, it is possible to compare how close a clustering result is to an existing or base modular architecture in a quantitative and repeatable way. The relation weight combination with the highest cluster match score is the one closest to the base architecture, i.e. the hidden relation weights are thus partly revealed.

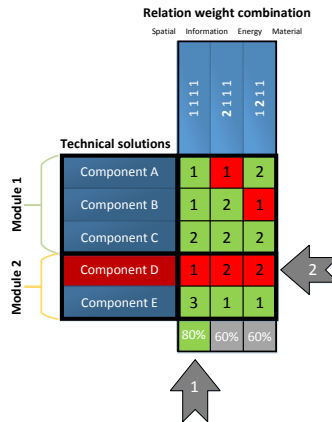


Figure 5. Example of a Cluster Match Matrices (CMM).

Components with conflicting module drivers may also be identified in the CMM. In the example seen in Figure 5, component D frequently end up in the “wrong” clusters and is therefore identified as being potentially being in conflict with the other components in the cluster, and consequently has been grouped not to reduce technical complexity, but because of some strategic reason. The same approach may also be used for situations with multiple conflicting module drivers. Furthermore, to enable CMM-base comparisons of IMM clustering with multiple conflicting module drivers, it is important to distinguish between conflicting module drivers within the same original module (based on the exiting/base architecture) and conflicting drivers external to the original module, i.e. relations should not be removed between conflicting module driver within the same original module.

Architectural analysis of the gearbox architecture

First, the studied modular gearbox architecture was represented as a component architecture diagram excluding the relations, as shown in Figure 3. The original gearbox modules are visualized by a *Component Cluster Diagram* (CCD) in Figures 6. To identify the weight combination that generates the most similar result with the existing (expert designed) gearbox modules, an iterative approach was used. Hence, multiple clustering analyses with different combinations of relation weights were performed, followed by a CMM-based evaluation. The values used for the relation weights were 1 (functional dependency) or 2 (strong dependency). The results of these analyses are presented in Table 1. Convergence of each clustering result was found after 1500 iterations with the IGTA++ clustering algorithm in MATLAB. After performing the CMM analysis, 20 of the total 94 components were frequently (at least in 10 of 15 DSM analyses) identified to be in the “wrong” cluster. These components, marked with red in Figure 6, were

identified as chosen from strategic aspects, hence, having conflicting module drivers with all other components, except components from the same original module.

As seen in Table 1, analysis #6 scored highest in the DSM based clustering. This indicates that that spatial relations and flow of information has a higher importance compared to flow of energy and material. However, this result is still far from a full match, which indicates that the existing modules were most likely not only created with an aim to reduce technical complexity.

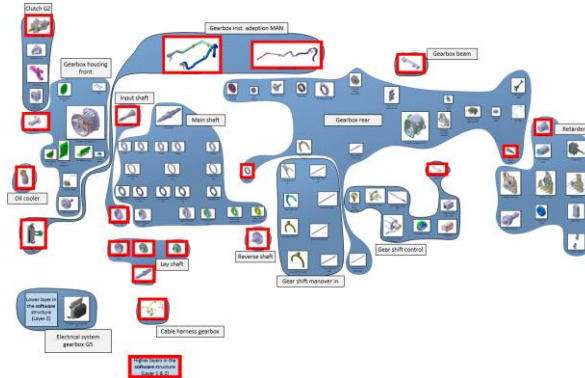


Figure 6. The studied modular gearbox architecture, including the CMM analysis result.

To include the strategic aspects, the IMM methodology was used with the relation weight combination from the base reference (best and worst CMM scores), i.e. analyses #1, #6 and #11. As shown in Table 1, all IMM results are more similar with the existing architecture since, since they got the highest score.

Table 1. Effects from different relation weights on the clustering results.

#	Analysis Type	Relation weights				# Components in wrong cluster	Match [%]
		Spatial	Information	Energy	Material		
1	DSM	1	1	1	1	24	74%
2	DSM	2	1	1	1	26	72%
3	DSM	1	2	1	1	22	77%
4	DSM	1	1	2	1	29	69%
5	DSM	1	1	1	2	23	76%
6	DSM	2	2	1	1	18	81%
7	DSM	2	1	2	1	27	71%
8	DSM	2	1	1	2	24	74%
9	DSM	1	2	2	1	24	74%
10	DSM	1	2	1	2	29	69%
11	DSM	1	1	2	2	31	67%
12	DSM	2	2	2	1	24	74%
13	DSM	2	1	2	2	23	76%
14	DSM	2	2	1	2	23	76%
15	DSM	1	2	2	2	21	78%
16	IMM	2	2	1	1	11	88%
17	IMM	1	1	2	2	10	89%
18	IMM	1	1	1	1	9	90%

4 Discussion

The core of the IMM method is a strategic DSM, which integrates a Product Architecture DSM with a Module Indication Matrix (MIM). The Product Architecture DSM represents technical complexity. Consequently, it is not capable of handling strategic aspects. This limitation of DSM clustering has been illustrated and confirmed in this study. Since clustering of a DSM did not result in a solution close to the investigated modular architecture at Scania, it may be postulated that the original architecture was most likely developed to provide company strategic benefits, besides from an aim to reduce technical complexity.

As seen in Table 1, the relation weights are highly important in all DSM-based analyses, since the result is largely affected by changing weight combinations, i.e. the level of dependency has a significant effect on the technical complexity. The results from the IMM analyses, on the other hand, clearly indicate that the relational weights become less important (compared to DSM clustering) when multiple strategic aspects are introduced, i.e. the solution space becomes reduced due to all constraints. In an extreme case, only the relations but not their weights will be of importance if strategies were to be considered. If more strategic aspects would be treated in the IMM analyses, e.g. if all components ending up in the wrong cluster one single time (in one analysis) would be treated as having conflicting module drivers, it would most likely be possible to reach a full match, i.e. a score of 100% in the CMM. There is also a possibility that some of the original modules were selected based on other (subjective) aspects, i.e. there may not be any technical or strategic reason behind a choice.

As earlier stated, there may be multiple conflicting module drivers, which makes it important to distinguish between conflicting module drivers within the same original module (based on the existing modular architecture) and conflicting drivers exterior to the original module, i.e. relations are not removed between conflicting module drivers within the same original module. If not considered, components with conflicting module drivers may be clustered together, even if they are not in the same original module. This will significantly lower the cluster match score.

The presented case study illustrates the importance of considering strategic aspects simultaneously with the technical complexity aspects in the architecting stage, where IMM has shown promising results. Since there is currently no accepted method on how business strategies could or should be included in DSM clustering, a new and robust methodology is clearly needed.

5 Conclusions and future work

- A *Cluster Match Matrix* (CMM) is proposed for comparing clustering results.
- Clustering a *Product Architecture DSM* is able of proposing module candidates that reduce technical complexity, but do not address strategic concerns.
- The results of the all IMM clustering analyses gained the highest cluster match scores with the existing architecture, thus IMM proposed module candidates that are most similar with the architecture as designed by domain experts.

- The presented case study indicates that the IMM methodology is capable of identifying and proposing reasonable module candidates, from both product complexity and company specific strategies points of view.
- The IMM methodology can be used for analyzing and finding the explicit and/or implicit, technical as well as strategic, reasons behind the architecture of an existing product.

The long term aim of the presented research is to develop a robust, agile and efficient modularization methodology. It is highly important to systematically investigate how the weights of the relations/dependencies in the DSM affect the clustering results, and the reasons for chosen proper weights, i.e. reliability, safety, cost and other concerns. To be able to verify, generalize, and improve the clustering results, a larger range of products and development cases have to be analyzed.

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