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The hunt for proper relation weights in product architecture clustering

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Abstract

A common view is that a module should be a functional building block, with well-defined and standardized interfaces between the modules, and that it should be chosen for company specific reasons. A modular product architecture is a strategic means to deliver external variety and internal commonality. Today, multiple modularisation methodologies exist to support the highly complex task to identify module candidates in the product architecting phase. One methodology is Modular Function Deployment with the Modular Indication Matrix (MIM) representation of company-specific module drivers. Other methodologies, such as Design Structure Matrix (DSM) clustering, may be used to identify modules from a technical complexity point of view. In this paper, the performance of the newly proposed Integrated Modularization Methodology (IMM), which is based on clustering of a strategically adapted DSM, is conceptually verified. The core of the IMM is to transfer company specific module drivers from the MIM into the component-DSM, before clustering this hybrid representation. A re-architecting industrial case, where a truck manufacturer with a unique business strategy had to redesign parts of its modular gearbox architecture to also become a First-Tier OEM-supplier to another large truck manufacturer, is used as test bench.
Reverse engineering of the investigated gearbox architecture indicates that the current modules are most likely not only based on technical complexity concerns. They are rather derived from different types of business strategic aspects, e.g. outsourcing. The study also indicates that the IMM is capable of identifying clusters without strategic conflicts, and with the most similar result to the analysed architecture, which is assumed to be based on expert judgements.

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

1 Introduction

Ulrich (1995) defined product architecture as “the scheme by which the function of a product is allocated to physical components”. Ulrich also defined it in a more formal way 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 type of mapping between functional elements and physical components, defines the architecture class. 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. Hölttä-Otto (2005) categorized these two types of architectures as being modular (uncoupled) and integral (coupled). Thus, a module is highly interconnected system element with few interrelations outside of the module (Ulrich, 1995), which implies that a module may very well have an integral architecture.
A modular product is configured from predesigned modules. The main purpose for the modular system is to enable external variety, i.e. a high number of product variants to the customers, and at the same time internal commonality by reducing the number of parts (Blackenfeldt, 2001). 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 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 modularising a product; *Heuristics*, *Design Structure Matrix* (DSM) and *Modular Function Deployment* (MFD). Heuristics is based on an analysis of the pattern of flow of matter, energy, and information between function blocks, see e.g. (Erixon, 1998). Browning (2001) classified DSM-methods as component- and people-based, as well as parameter- or task-based. With DSM, we further on refer to component-DSM. The main focus of DSM-based approaches is to minimize technical complexity by clustering the system components in a way that minimize the technical interactions between clusters of components, i.e. complex interactions are grouped within clusters.
MFD (Ericsson and Erixon, 1999) is a five-step method for translating customer requirements into a modular architecture, while considering the company specific strategic objectives, condensed into twelve predefined Module Drivers (MD:s). The MD:s are generic, but their importance is company specific, e.g. modules can reduce capital needs and bring economies in parts sourcing (Baldwin and Clark, 2000), (Ulrich and Tung 1991). In MFD, the MD:s are represented by a Module Indication Matrix (MIM). The MIM is an interdomain matrix that relates the physical function carriers, i.e. the components, and the twelve MD:s.

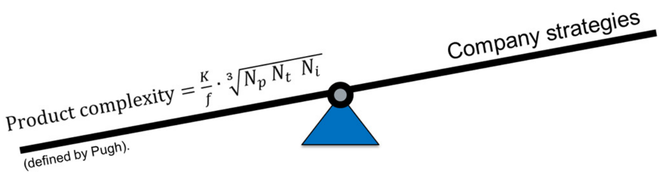

Figure 1. Integrated modularisation enable architecture trade-off studies.

DSM clustering addresses technical complexity but not strategic objectives (Blackenfeldt, 2001). In an attempt to balance technical complexity represented by a DSM and business strategies represented by a MIM, Stake (2000) presented several examples of manual clustering of a DSM and a MIM. Blackenfelt (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-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, as visualized in Figure 1, with a new method referred to as Integrated Modularization Methodology (IMM). The core of the IMM is to integrate company specific module drivers with a component-DSM, and then clustering the strategically adapted DSM.
The performance of the IMM approach compared to DSM-clustering has to be further analysed. Five specific research questions are addressed in this paper:

- How can we compare two clustering results?
- How can we represent of the spatial relations and the functional flows of matter, energy and signals with a component-DSM?
- How sensitive is DSM and IMM clustering to the relative weights of the spatial relations and the functional flows of matter, energy and signals?
- 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 hidden strategic reasons behind an existing architecture?

Hence, this paper presents a studied real case, where a truck manufacturer, further on referred to as Corporate A, with a unique business strategy, based on extensive in-sourcing, in a relatively short time period had to modify parts of its modular architecture to also become a First-Tier OEM-supplier to another large truck manufacturer, here referred to as Corporate B, with a completely different business and product architecting strategy. The new business relation between the two truck manufacturers affects the relative importance of some of the generic MD:s for a technically very complex product. The studied case, which is presented in chapter 2, is analysed with the previously proposed IMM, from both technical complexity and module driver perspectives in chapter 3, and discussed in chapter 4. The main conclusions and a path for future research are given in chapters 5 and 6.

2 Case study

This case study was conducted at Corporate A and KTH Royal Institute of Technology, in collaboration with Corporate B. The study presents how a specific product was re-architected, or transformed, the reasons for this transformation as well as the possible improvements, when it was integrated into another product family in the same multi-brand organisation.
The product architecture of the investigated system was initially developed in-house by Corporate A as a module in its modular system. However, when Corporate A became a part of a larger Business organization, Global Corporate, the Corporate A product architecture had to be modified in order to fulfil the new requirement to represent two different, and competitive, brands, i.e. to also be part of the modular system at Corporate B.
A multidisciplinary approach was needed in this investigation, and therefore an analysis of the mechanical and electrical systems, as well as the embedded control software was initially performed. It should be stated that only one gearbox variant is analysed in the presented study, i.e. the variant which is delivered to Corporate B. All other variants which are used by Corporate A have their original architecture intact.

2.1 Product architecture at Corporate A

Corporate A has a successful history in modularisation. The general business strategy of Corporate A is to maximise the number of product variants (external variety), while keeping the number of technical solutions low (internal commonality). The product architecture at Corporate A can therefore be seen as the result of the specific modularisation process and principles of Corporate A. In order to describe the large number of product variants at

Corporate A in an efficient way, the modular product is represented as a generic product structure. A generic product structure does not describe a single product variant, but rather the entire product portfolio, which is referred as the Modular Toolbox, see (Figure 2).

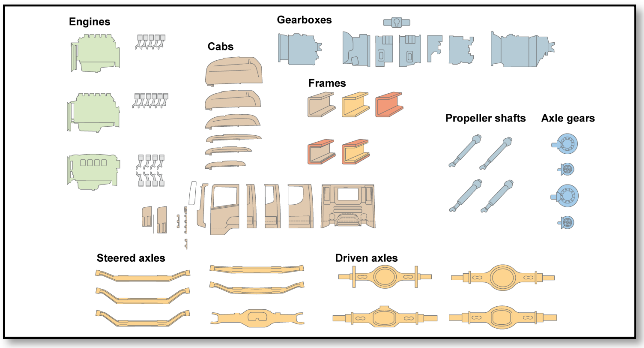

Figure 2. The modular toolbox, i.e. the modular system, at Corporate A.

At Corporate A, the modularisation process starts and ends with the customer. This means that Corporate A modularise its product to fit the needs of all potential customers. The core of Corporate A's modularisation principle is carefully balanced performance steps, i.e. module variants with standardised interfaces that can be combined to satisfy different customer needs, with a limited number of physical components. In order to efficiently develop and manufacture all product variants, Corporate A almost exclusively relies on in-sourcing, meaning that outsourcing generally is a weak module driver compared to many other performance related module drivers. Hence, the architecture does not have to be strictly developed according to predefined architecture rules, but rather to the solution which works best at the moment for the customer and Corporate A.

In order to efficiently enable trade-offs between high overall system performance and a high degree of configuration flexibility, the electrical system and the embedded software, are designed to be decentralized (distributed intelligence). This means that more of the intelligence is embedded in the different modules, with multiple Electronic Control Units (ECUs) distributed in the vehicle. At Corporate A, this type of architecture is also believed to increase the robustness of the complete electrical system, for example if one ECU malfunctions, it will not necessarily affect the entire system.

In general, all embedded software for all possible configurations is always included in the ECUs at Corporate A, independent of actual product configuration. However, the software needs to be adapted to the hardware configured in each specific product variant. The software is therefore parametrized to fit the different physical configurations, and is therefore modularised in "another way" than most hardware.

The dependency between software and hardware depends on what layer the software belongs to in the software structure. In a lower layer, there is usually a strong relation between hardware and software, e.g. software that control an actuator implies a strong interdependence between software and hardware and consequently there is a strong driver to integrate the software and hardware into a common module. However, the higher software layers, e.g. gear shifting or smart cruise control, are not tightly connected to any specific hardware, since these software components realise system functions on a higher level and only need real-time computing power, wherever it is available.

In comparison to Corporate A, Corporate B is more of a system integrator. Therefore, Corporate B has outsourced manufacturing and development of many components and subsystems to external suppliers. As a consequence, Corporate B is offering products with an architecture that relies on a supplier-robust architecture that also protects corporate specific strategic knowledge and plans, which is quite different from Corporate A. Furthermore, the electrical system, including the embedded software, is largely centralised at Corporate B.

2.2 Integrating a product architecture

To study how a specific Corporate A truck subsystem with heterogeneous technology has been transformed and evolved, during the collaboration with Corporate B, a specific Corporate A heavy duty gearbox, see Figure 3, was selected for analysis. This powertrain module is a synthesis of heterogeneous technologies. Furthermore, it is developed and manufactured in-house by Corporate A, that is, it is an in-sourced module. This gearbox was re-architected to fit the modular system architecture of Corporate B, and Corporate A now delivers it to Corporate B as a First-Tier OEM supplier. Hence, Corporate A is responsible for the product architecture and the complete gearbox design, based on the requirements stated by Corporate B. The gearbox is therefore thought to be a good representation of how, and with what reasons, Corporate A architects and re-architects its product.

Figure 3. Cutaway illustration of a Corporate A truck powertrain, with a heavy-duty gearbox.

To adapt the original gearbox architecture to Corporate B, several changes had to be made. These changes mainly related to the integration of the gearbox into a completely new system, with different requirements and interfaces. In this new environment, the gearbox was exposed to different types of heat, vibrations, air pressure, gear shift control strategy, external torque etc. Even if the gearbox is treated as a relatively independent module at Corporate A, it was designed and optimised to be a part of a powertrain in a Corporate A truck. To gain gear shifting system performance benefits some gearbox software components were located in the engine ECU.

Since Corporate B configures its products with gearboxes from multiple suppliers, it is treated by Corporate B as an outsource module. This business strategy makes it necessary to treat the gearbox as a highly independent module with some predefined functions. For that reason, it was not possible to simply use the original gearbox (with the original Corporate A software) in a Corporate B truck, without first performing some redesign, or adaptation.

2.3 Changed components

Before it is possible to visualise the required changes of the gearbox, its main components and their functional purposes must be identified. This was done by analysing the physical decomposition represented in the generic product structure at Corporate A. To limit the number of components to a reasonable level, all screws, gaskets and other small parts, were not considered when decomposing the technical solutions. The interactions of the 94 identified components were represented with a component structure diagram, see Figure 4. The interactions (also referred to as relations) are described with the principal technical function flow and spatial relations, where black indicates a spatial relation, green energy flow, blue material transfer and orange information flow. Since the goal was to focus on the relations, the layout of the components in the component structure diagram is not fully representing the actual physical layout of the gearbox. However, it still gives a conceptual understanding of the gearbox design structure.

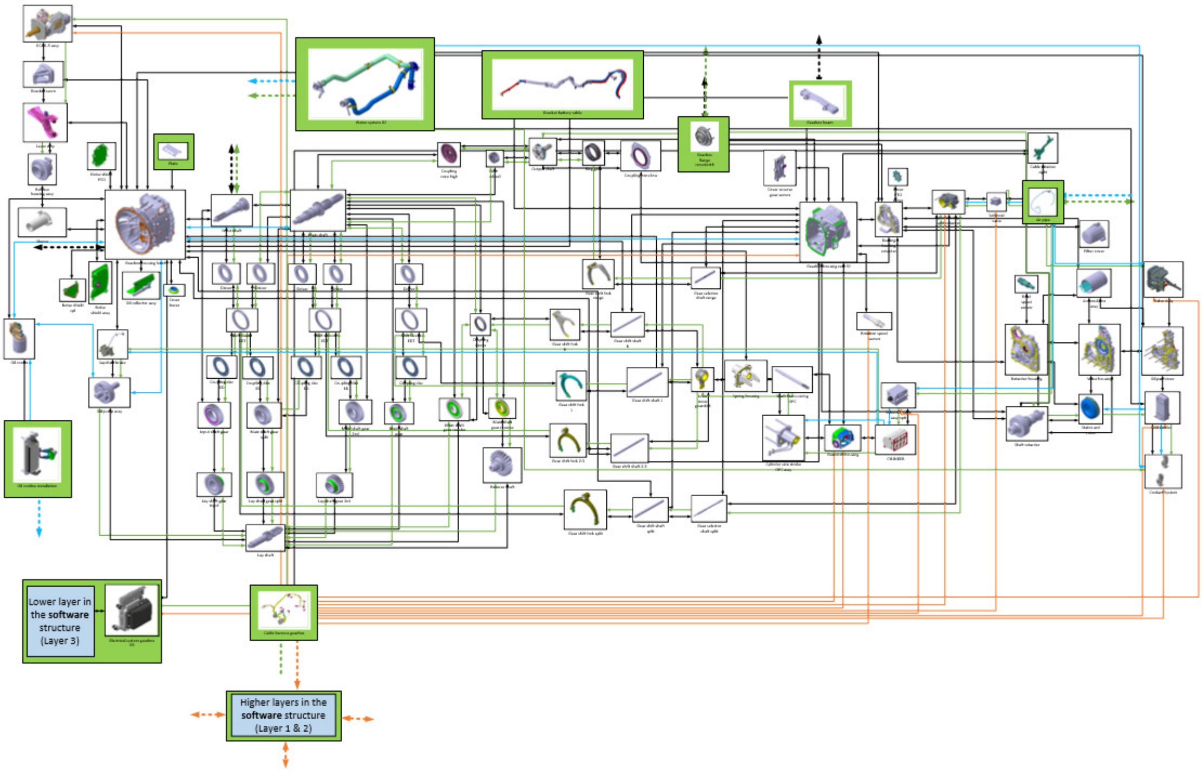

Figure 4. Changed components in the modular architecture redesigned for Corporate B.

The eleven components that, based on expert judgement, were changed are marked with green in Figure 4. In addition to these components, some unions and brackets also had to be redesigned. It should be stated that these changes were identified and performed by expert engineers at both Corporate A and at Corporate B, engineers with a large amount of product architecting experience and knowledge.

As seen in Figure 4, there are many relations and thereby component interfaces which had to be redesigned. Since an interface is a relation between features of a pair of mating components, a changed interface means that multiple components must be considered if one component is redesigned, which results in a relatively complex redesign task.

3 Analysis

The main purpose for the presented analysis was to study if a clustering analysis could be used to re-engineer the reasons why the original gearbox architecture at Corporate A was re-architected in the way it was, from technical complexity point of view, by elaborating on the relative weights of the spatial relations and the three different types of functional flows, and from an integrated technical complexity and the changed business strategy viewpoint.

3.1 Architecture analysis method

The transformed gearbox architecture was represented and analysed with both component-DSM clustering and IMM (Williamsson and Sellgren, 2016), which performs clustering of a strategically adapted DSM. All clustering was performed with the highly efficient algorithm IGTA++, which was proposed by Börjesson & Sellgren (2013). For DSM clustering, the technical system was represented as a component-DSM, with interactions represented as functional flows, i.e. flow of energy, mass, or information, and/or spatial relations. The four types of interactions 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. Information and mass flows are unidirectional, but spatial relations are dual, i.e., gives matrix symmetry. IMM clustering was performed on a strategically adapted component-DSM. The strategies that are addressed are the Module Drivers (MD) from the MFD modularization method, as presented in Table 1, with outsourcing treated *Black-box engineering*.

Table 1. The twelve MFD Module Drivers, from (Erixon, 1998).

Module Driver group	MD #	Module Driver description
Development and design	1	Carry over
	2	Technology push
	3	Product planning
Variance	4	Different specification
	5	Styling
Production	6	Common unit
	7	Process/organization
Quality	8	Separate testing
Purchase	9	Black-box engineering
After sales	10	Service/maintenance
	11	Upgrading
	12	Recycling

The starting point of an IMM-based analysis is a well-defined product architecture, as seen in Figure 5, where all technical relations (i.e. flow of energy, signal, and mass, as well as spatial geometric relations) are represented between the technical solutions (A, B, C and D).

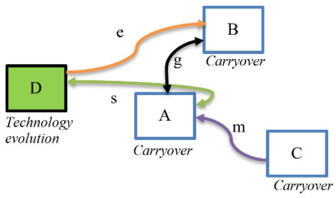

Fig. 5. A graph-based representation.

The relations between corporate strategies, as represented by the Module Drivers, and the principal solutions, i.e. the components in the component-DSM, are represented with the Module Indication Matrix (MIM) in the MFD method (Erixon, 1998). One of the main purposes of an MIM is to identify strategically conflicting module drivers, i.e. mismatches in strategies within a module candidate.

In IMM, the MIM (see upper part of Fig. 6) is represented as a strategy transfer DSM (see lower mid matrix in Figure 6), with all conflicting module drivers specified with a minus sign. By operating with the strategically transfer DSM on the component-DSM, with functional interactions in the off diagonal cells, we get the strategically adapted DSM. In this transformation, all relations interfering with a minus sign gets removed from the component-DSM, while empty cells remain unchanged. In the simple example shown in Figure 6, technical solution D has a conflicting module driver to the other technical solutions.

The components which had to be changed in order to facilitate an integration of the gearbox into a Corporate B powertrain, were treated as outsourced components in the IMM-analysis. The remaining components were treated as developed in-house, i.e. insourced. According to the MFD methodology, the components which are outsourced should not be clustered with the components which are developed in-house, in order not to cause strategic conflicts.

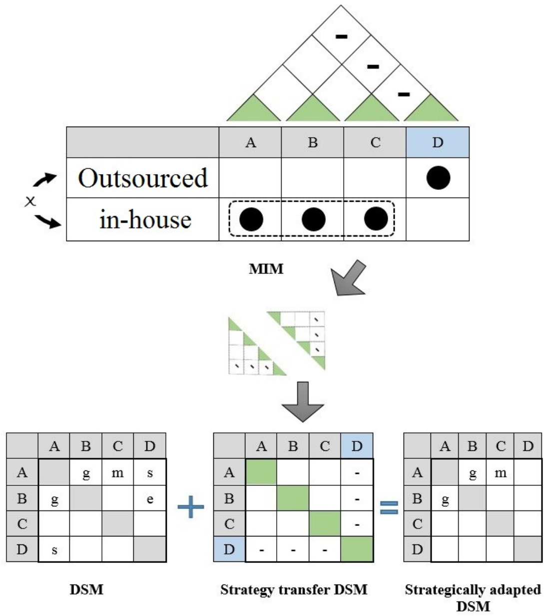

Figure 6. The integrated matrix-based systems architecting model IMM.

The method used to search for the reasons behind the architecture of the original Corporate A gearbox was to perform DSM-clustering, as well as IMM-clustering of a DSM that was strategically adapted to match the difference in the business strategy of Corporate B compared to Corporate A. Furthermore, the effects on the cluster proposals from the two methods from varying the relative weights for the different types of spatial relations and functional flows of matter, energy and signals were studied. The match between the cluster proposals from the two methods, and with different weights, were then compared to the transformed architecture as developed by the expert designers.

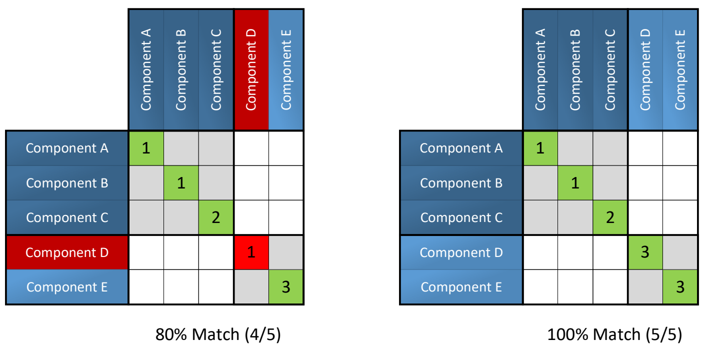

Figure 7. Example of two Cluster Match Matrices (CMM).

To enable comparison of a clustering result and a modular architecture, a new method was developed. The central part of the new method is referred to as a Cluster Match Matrix (CMM), which is a matrix containing a representation of the observed modular architecture, and of the clustering result. The areas marked with grey in the CMM in Figure 7 indicates the observed, or reference, modular architecture. In the example seen in Figure 7, components *A*, *B* and *C* are located in one module in the original modular architecture. In a similar way, components *D* and *E* are located in another separate module.
The numerical values in the diagonal of the CMM represent the cluster which the component is assigned to by the clustering algorithm. In the left part of Figure 7, 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 grey area (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 reference module. The cluster match is finally calculated based on how many components that are in the same module as in the reference system compared to the total amount of components.

In this way, multiple clusters may therefore 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 Figure 7. Hence, only components which are split from their assigned cluster (to fit the original 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 a reference modular architecture, in a quantifiable and repeatable way.

3.2 Analysis of the transformed architecture

In order to represent the transformed modular gearbox architecture in a compact format, the component structure diagram as shown in Figure 4 was used as a starting point, excluding the relations. In addition to the technical solutions, the company strategies were also represented in the component structure diagram.

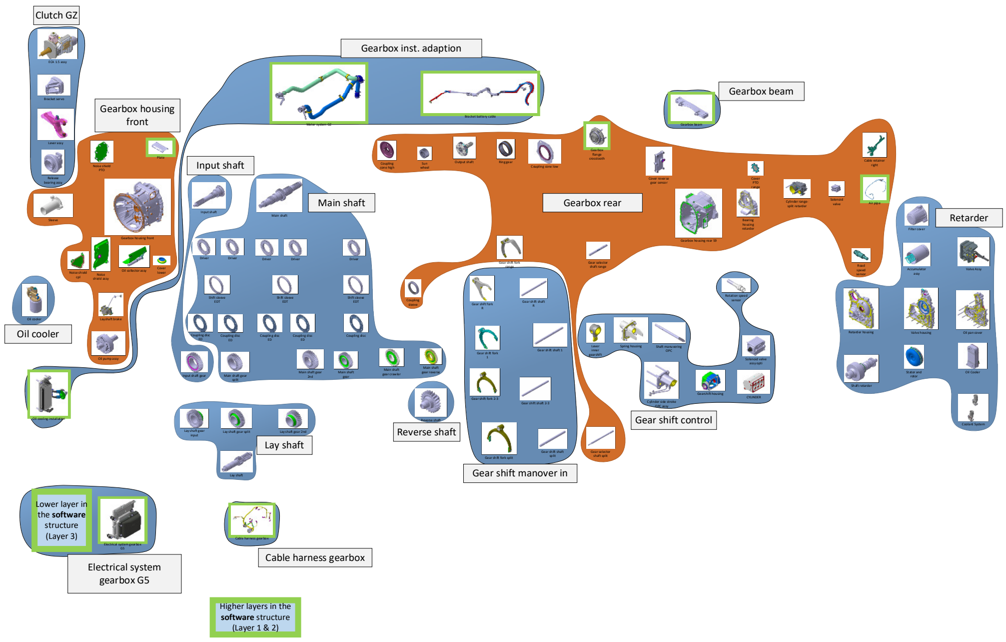

Figure 8. Schematic illustration of the transformed architecture redesigned for Corporate B.

The modules are visualised as blue and orange shapes (clusters) in Figures 8-10. An orange shape indicates that the module contains components with conflicting module drivers, i.e. in this case components which should be developed in-house and be outsourced at the same time. As seen in Figure 8, there are multiple strategically conflicting modules, which may result in a less efficient architecture from a strategic viewpoint. A blue shape indicates that there is no strategic conflict within the module.

3.3 Clustering analysis

The transformed architecture used at Corporate B was analysed according to how it could have been modularised, based on DSM-clustering or alternatively the IMM methodology. The analysis is performed with the purpose to identify the effects from assigning different weights

to the different types of interactions, and to see if IMM is capable to re-engineer the explicit and/or implicit strategic reasons for an observed modular architecture. The weights of the different types of spatial relations and flows of matter, energy and signals is also investigated in terms of how it affect the clustering result, including what combination of weights for the spatial relations and the three types of functional flows that would generate a result similar to the modular gearbox architecture redesigned for Corporate B.
In order to identify the weight combination that generates the most similar result, an iterative approach was used. Hence, multiple clustering analyses with different weight combinations were performed, followed by an evaluation according to the earlier presented CMM method. The result of these analyses is found in Table 2. It should be stated that the weights were selected based on assumptions by the authors and may therefore affect the result of the analysis. Convergence of each clustering result was found after 1500 iterations with the IGTA++ clustering algorithm in MATLAB.

Table 2. Investigated effects from functional relation weights on clustering results.

Analysis		Relation weights				Conflicting module drivers	# Components in wrong cluster	Match [%]
#	Type	Spatial	Information	Energy	Material			
1	DSM	1	1	1	1	Yes	24 of 94	74%
2	DSM	1	2	1	1	Yes	22 of 94	77%
3	DSM	3	1	2	2	Yes	21 of 94	78%
4	IMM	3	1	2	2	No	18 of 94	**81%**

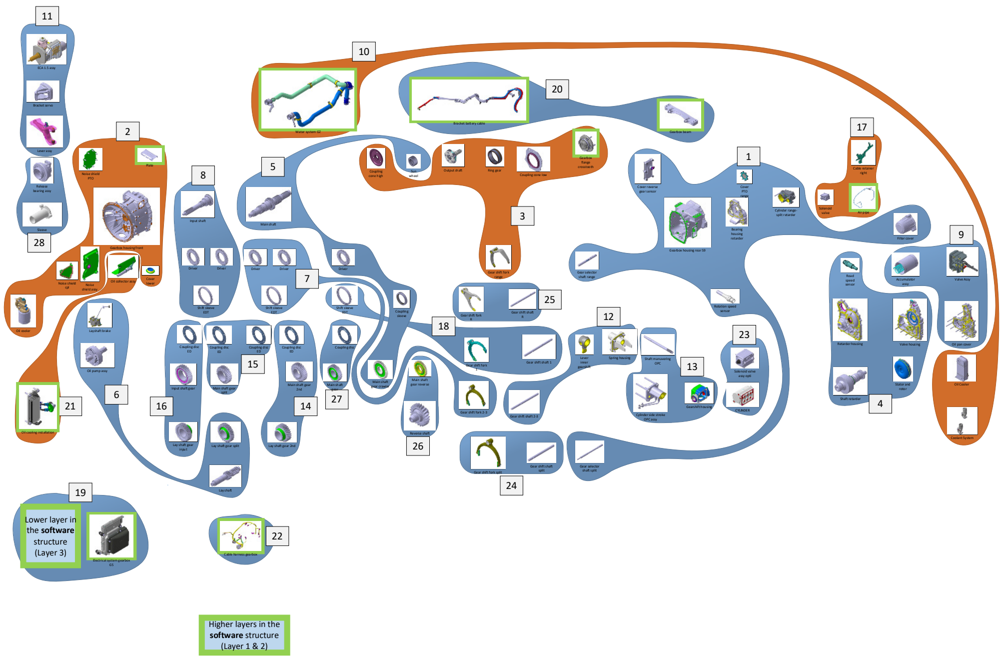

Figure 9. Schematic illustration of the architecture proposed by DSM clustering (analysis #3).

The result of DSM clustering with the closest match (analysis #3) is presented in Figure 9. This proposal is relatively different from the transformed architecture delivered to and presently used at Corporate B. This observed difference indicates that the existing modules were most likely not created with the aim to reduce product complexity. Figure 8 also shows several strategic conflicts within the clusters. This result is expected, since a standard DSM does not contain any strategic aspects. In order to consider the strategic aspects, the IMM methodology was applied, with the clustering result shown in Figure 10. As seen, the resulting clusters are somewhat different compared to the clusters proposed by DSM, but now no strategic conflicts are present. This result is also the most similar to the transformed architecture delivered to Corporate B, since it has the closest match.

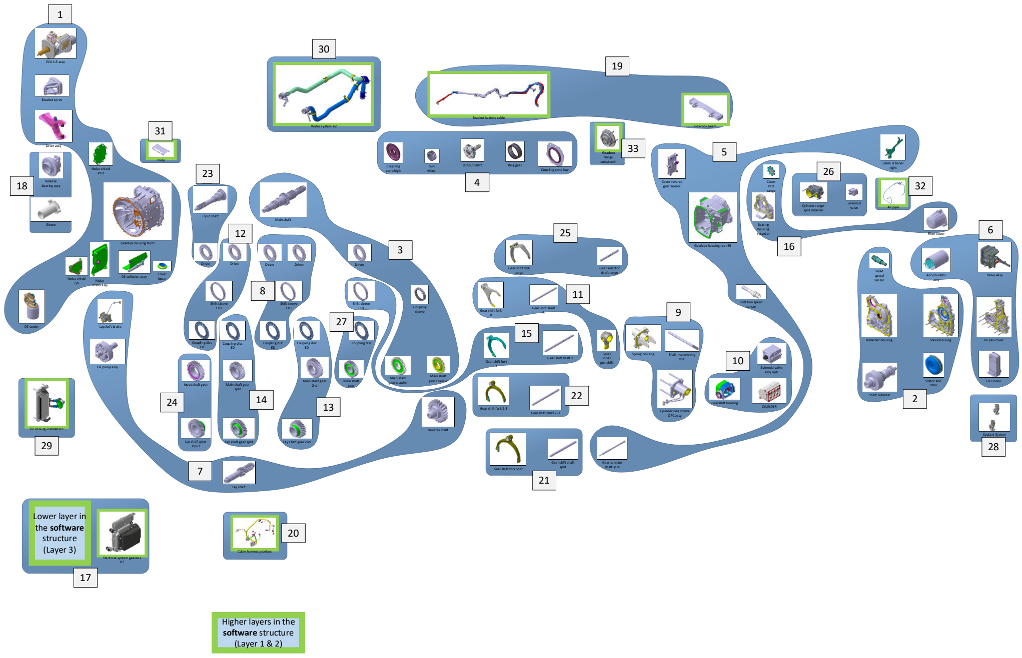

Figure 10. Schematic illustration of the architecture proposed by IMM clustering (analysis #4).

4 Discussion

Multiple relation weight combinations were investigated during the clustering analysis, in order to identify which combination that generates the most similar result compared to the architecture used at Corporate B, i.e. the one with the highest cluster match score. The weights of the relations were selected based on assumptions and experience by the authors. As seen in Table 2, the clustering result was affected when the relation weights were changed. Hence, a separate investigation is needed in order to fully identify the robustness of the result by investigating all other possible weight combinations, as well as an hierarchy of weights depending on performance requirements and safety concerns.

In the first clustering analysis, all relation weights were assigned to be of equal importance. This analysis therefore served as a reference to the following analyses. By increasing the relation weight of the information flows, and at the same time keeping the importance of all other relations intact, the result of the clustering analysis started to become more similar to the transformed modular architecture delivered to Corporate B, though it was still far from a full match. On the other hand, when the weight of the information flows was assigned with a low importance compared to other types of relations, the proposed clusters were even more similar to the Corporate B architecture, indicating that the gearbox was probably modularised according to its mechanical design before any electronics or control software was added.

However, all results proposed by the DSM clustering analyses, independent of weight combination, were still relatively far from a full match. One way to increase the cluster match result in the DSM analysis may be to assign different relation weights to the same type of relation, since some relations may be more important than others. Nevertheless, none of the results proposed by the DSM analysis was able to treat strategic aspects, which was illustrated and confirmed in this study. Hence, only clustering according to complexity did not result in a solution close to the modular architecture, redesigned by expert designers to be delivered to

Corporate B, mainly since strategic aspects were not considered. It is therefore possible to state that the original architecture was most likely not developed only according to complexity concerns, but also to company strategic benefits. If more strategic aspects would be considered during the IMM analysis, it would most likely be possible to reach a full match, i.e. a score of 100% in the CMM.
This illustrates the importance of considering strategic aspects during the clustering stage, where the IMM has shown promising results. Since there is currently no accepted method on how sudden changes in business strategies could or should be reflected as changes of an existing modular product architecture, a new methodology is clearly needed.

5 Conclusions

- To enable comparison of clustering results of the same system, a Cluster Match Matrix was developed.
- Clustering a component-DSM with relations that represent spatial relations and flows of energy, matter and signals may propose clusters based on technical complexity, but not on strategic business concerns.
- The result of the DSM clustering depends on the relative weights of the different types of functional interactions that are represented by the DSM.
- The result of the IMM clustering analysis gained the highest cluster match score according to the proposed Cluster Match Matrix method, thus it proposed the most similar module candidates in comparison to the architecture re-designed and delivered to Corporate B. The presented case study indicates that the IMM methodology is capable of identifying and proposing reasonable module candidates according to both product complexity as well as company specific strategies.
- The IMM methodology can be used for analysing and finding the explicit and/or implicit reasons behind the architecture of an existing product.

6 Future work

Since the overall aim is to develop a robust and efficient modularisation methodology that also is agile, several future product development cases have to be analysed in order to verify, generalize, and improve the clustering result. It is also highly important to thoroughly investigate how the weights of the relations in the component-DSM affect the clustering result, and the reasons behind the weights, i.e. reliability, safety or other concerns.

Acknowledgement

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