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DESIGN FOR ADAPTABILITY IN MULTI-VARIANT PRODUCT FAMILIES

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ABSTRACT

Designing system structures for adaptability offers significant advantages for both customers and producers. But it is not simple, especially when the product is a highly complex product family, for example a heavy duty truck. This paper presents why the application of Design for Adaptability is problematic with existing approaches, if the product is complex. To close the outlined gap in methodology, a new methodical concept is proposed. This is based on Modular Function Deployment and strategic modularization, offering the opportunity for the necessary transparency, to make also very multi-variant products more adaptable. For making the complexity of high variant product families more tangible, this concept is applied on the components of a Generic Product Structure. The modularization is done by defining adaptability drivers and focusing not on interfaces, but on grouping components for distinct reasons. Therefore 'Strategic Modules' are defined offering a whole new perspective and transparency of component dependencies. This is shown on a real life product by MAN Truck & Bus AG. The result is a promising methodical concept that should be further developed by future research.

Keywords: design for adaptability, high variant product families, design for X, product architecture, product lifecycle management

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1 INTRODUCTION

1.1 Adaptability – a fountain of youth

The life of a product is not endless. Its life cycle ends after some time due to deterioration, which is caused e.g. by increasing customer needs or technological evolution (Willems et al., 2003). Nevertheless, it is possible to counter the deterioration and elongate the lifespan with small periodical upgrades (Engel and Browning, 2008). Those incremental updates make sure that the product can be held up to date fulfilling customer demands, even when circumstances like e.g. new technological solutions are coming up. The term describing the virtue of a product to be able to change due to changed circumstances is called "adaptability" (Engel and Browning, 2008). Prolongation of life is not the only advantage of adaptable products. Hashemian (2005) shows a bunch of benefits for both users and producers by adaptable products, such as lower cost, easy customization and higher market share.

1.2 The case of MAN

To achieve the outlined benefits for their products, the **MAN Truck & Bus AG (MAN)**, a German commercial vehicle company, took part in the European Commission project **AMISA** (Acronym: Architecting Manufacturing Industries and systems for Adaptability) as a case study. The heavy-duty trucks built by MAN are complex products with long model lifetimes from over ten years. Thus, they are often subject to changed circumstances during lifetime. An example for those circumstances are emerging emission restrictions by law affecting the whole portfolio like the obligatory EURO 6 emission standard. Also second life usage must be mentioned, because many trucks that have been used e.g. in Europe are sold afterwards to be used in other areas (e.g. Africa), where other environmental requirements must be fulfilled by products.

Adaptability is determined for a product by its design and structure (Willems et al., 2003). The relevant **Design for X (DfX)** subsidiary is called **Design for Adaptability (DfA)**. Because adaptability is a matter of product structure, adaptations always accompany with structural modifications (Kissel et al., 2012). An adaptable design is in general achievable by appropriate modularization of the structure, whereby most DfA approaches rely on modularization methods (Gu et al., 2004)

The very different application purpose of trucks makes the products of MAN not perceivable as a single product, but as a broad range product family. Therefore, adaptations for MAN trucks imply a severe intervention into the product family structure. This structure is very complex, because the trucks are configure-to-order products. The configurability according to customer needs encompasses different frame lengths, numbers, and positions of axles. This issue results in variance of configuration and functionality, but also the position of a component is variable. (Kreimeyer, 2012)

Finally, the product structure of such a multi-variant product family becomes too cross-linked to be educible or manageable sufficiently by currently known Design for Adaptability approaches, because they are naturally designed for single products. Also the software tool, developed in AMISA, which is based on modularization with Design Structure Matrix and Architecture Options Theory by Engel and Browning (2008), failed in application on the whole truck family, because of the too complex structure. Other problems, like the effort of preparing necessary quantitative input information decreased the applicability of the software for the MAN trucks, too. The arising question is now:

How is Design for Adaptability efficiently applicable on multi-variant product families?

To answer this question, first, the implementation of adaptability is treated in Chapter 2. Coping with multi-variant product families is attempted in Chapter 3. Because of the broad scope on these topics they are treated particularly in the context of the multi-variant product family from MAN. To combine multi-variant products and adaptability, Chapter 4 contains the selection of a suitable modularization method in this context and introduces the conceptual solution for DfA and the problems outlined above. The fifth chapter treats the application of the conceptual solution and shows the functionality and results of this approach exemplarily. This evinces as a promising approach to treat adaptability and occurring changes with transparency on a new level. In Chapter 6 those findings are discussed briefly. At the end, Chapter 7 gives the conclusion and points out the need for future examination of the presented method.

2 MASTERING CHANGED CIRCUMSTANCES

2.1 Design for Adaptability

Adaptability describes a subset of changeability and is therefore a capability of a system to cope with changes. Kissel et al. (2012) pointed out that the definition of adaptability is not used consistently throughout the research field, because it is often mixed up with “flexibility”. In consensus with authors like Gu et al. (2004), Kissel et al. (2012) or Engel and Browning (2008) the following definition describes what is meant by adaptability in this paper:

> *Adaptability is the capability of a system of being adapted for changing circumstances by external intervention.*

Although Engel and Browning (2008) mention some early exemplary approaches towards more adaptable systems in computer, software and production technology, the first DfA approaches in mechanical engineering were done as a subset of **Design for Changeability** during the early 2000s (Fricke et al., 2000; Schulz et al., 2000; Fricke and Schulz, 2005).

Gu et al. (2004) define two different types of adaptability, *design adaptability* with intervention by the manufacturer and *product adaptability* with customer intervention. In case of a product family design adaptability means that future functionalities or variants are already foreseen and somehow implementable by an adaptation of an existent product (Kissel et al., 2012). One of the first distinct Design for Adaptability methods was outlined by Hashemian (2005). He divides adaptability in *General and Specific Adaptability*. Specific means that the product is adaptable for a special reason of an expected change, like e.g. an expectable future facelift. Whereas General Adaptability is focusing on those parts of a product that are more likely subject to change, but with no specific reason expectable yet. He developed a method to develop products with increased General Adaptability.

Among others, Fricke and Schulz (2005) point out, that *modularization* is a useful instrument for encapsulation of changes to achieve higher adaptability and flexibility. Modularization is applied for developing products with exchangeable elements that are realized by the grouping of strongly interlinked components into modules. These are linked to each other itself by much weaker links (Ulrich, 1995). The approach towards General Adaptability by Hashemian (2005) uses function-based modularization as the core mechanism to segregate the parts of a product into modules by common functionality.

Engel and Browning treat the economic aspect for optimal adaptation in their Architecture Options Theory, where the number of modules represents the adaptability. On the one hand, more and smaller modules mean that more options for adaptation and so a higher adaptability is achieved. (Engel and Browning, 2008)

Beneath modularization, e.g. Fricke and Schulz (2005) or Hashemian (2005) mention further design guidelines, principles and guidelines towards adaptable design, which have to be considered for an holistic DfA approach. The other principles are to a certain extend also respected with modular products, so the principle of modularization remains the dominating strategy towards improved adaptability.

2.2 The difficulties of coping with changing environment

As it is clear now, that adaptability could be handled by modularization, the question is still:

> *How is a product designed by modularization for coping with occurring changes?*

Kissel et al. point out that distinct drivers of adaptability must be identified and applied on the product structure. For their identification a properly abstract architectural model is a necessary precondition. In this model the drivers are identifiable by examining the effects of adaptation. Therefore the mechanisms of changes and the effects on the structural elements must be respected. This should be combined with a business case perspective, to achieve an optimal cost-efficiency (Kissel et al., 2012).

Jarratt et al. (2010) name three major factors characterizing the impact on changes in a product that have to be examined at first:

- Complexity
- Product architecture
- Degree of innovation

Complexity in sense of changes is very much related to how the product is structured and the connectivity between the structural elements. So the truck’s product structure is very complex because of its cross-linkage. When components of so called “high coupled products” undergo a change they are likely evolving it to related components. Hence, the complexity makes it much more difficult to control the impact of changes (Fricke et al., 2000).

The product architecture influences the ability to change significantly. According to Fricke et al. (2000) architectures that are able to treat changes properly have "to incorporate the ability to be insensitive or adaptable towards changing environments".

Architecture, like a platform or product family, with common components over multiple products is very difficult to handle in case of changes, because the change of a common component is influencing over all products containing this component. (Jarratt et al., 2010) The truck, as it is conceivable as a family and platform as well, has to deal with common components, too. For example the rear light is used in very little design variance throughout the whole product portfolio.

Modular architectures have high adaptability, when interfaces are not changed. If this could not be guaranteed, the change becomes way more comprehensive. (Jarratt et al., 2010) For the truck the position variance leads to a significant change of interfaces especially regarding the package.

Complex products with complex architectures also have usually long lifespans, which makes it more difficult to predict future changes (Jarratt et al., 2010). So the truck example is very problematic in case of adaptability.

Opposing the degree of innovation is not so problematic in established products at all. Most products are basically known for a long time and have thereby reached a substantial level of maturity. The truck may evolve e.g. by more efficient propulsion technology or a more streamlined design, but all in all it will still be always a truck. Compared to less mature products, the probability of changes will be low.

At MAN the architecture development and variant management is nowadays implemented in very early stages of the product development process to prevent cost due to later changes (Kreimeyer et al., 2012). This refers to the much quoted ''Rule of 10'' (Clark and Fujimoto, 1991) that deals with the fact that treating changes earlier in the development process is less effortful. This so-called **"front loading"** is, besides modularity, also a strategy towards increased adaptability, because it helps predicting the effects of future changes and reduces their impact. Front loading could be done by **pre-equipping** those parts of future necessary components that are difficult to change. Supplemental strategies for successful change management are e.g. change prevention, effectiveness, efficiency, learning, and reviewing (Fricke et al., 2000).

Jarratt et al. (2010) provide a framework to characterize the components of a product in a way they behave with occurring changes. They divide them into:

1. **Absorber:** *(decrease complexity)* A component that suffers some changes itself and transfers no or only some changes to other components
2. **Carrier:** A component only transfer the change towards other components
3. **Multiplier:** A component that raises the complexity of a change by affecting other components more viciously

This means for adaptability that absorbers decrease the effects of a change and make a product more robust. In context of adaptability this robustness is useful because it provides insensitivity to changing environment, whereby the component behavior is not problematic in case of an adaptation. Multipliers and Carriers should be somehow isolated or paralyzed to gain more adaptability. For being adaptable they should be designed in a way that they are more absorbing external effects from other components or provide a certain reaction to control the change. This framework could be helpful to identify the change-critical components of the product.

To identify the postulated drivers for adaptability the reasons for changes must also be examined. For example Jarratt et al. (2010) provide a comprehensive list of possible reasons and scenarios. Bearing the scenarios for possible adaptations in mind, the components of a product can be characterized according to their demand for adaptability.

3 MANAGING MULTI-VARIANT PRODUCT FAMILIES

3.1 Generic Structuring Concept

A "**product family**" means that a wide range of different end products is composed out of a set of components. The truck, for example, has much more parts and functionality than e.g. a car as shown in Figure 1. Also the number of different purposes is much higher and so is the degree of customization. The set of components is therefore necessarily larger.

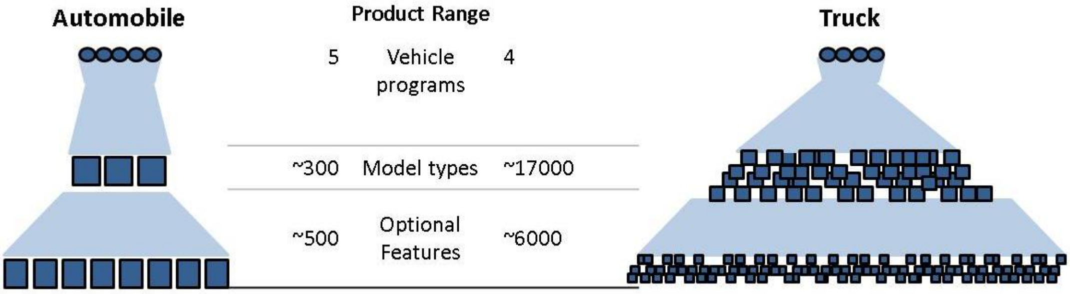


Figure 1. Product range comparison between an automobile and a truck. Data from (Fricke and Schulz, 2005) and (Stauske, 2012)

According to Erens the only transparently manageable structuring concept for a multi-variant product family is a generic architecture concept like a generic bill of material GBOM or a generic product structure GPS. This is an architectural concept consisting out of a widely invariant hierarchical tree of subfamilies that contain the variance. A single end product variant (=entity) is derived from this architecture by selection rules considering several combination constraints. (Erens, 1996)

The main aspect of this kind of product structure is therefore the configuration of a product entity and not the description of the interrelations between components, as in “normal” product structures. However, this is the major advantage of generic structures. Although they are invisibly inherent, physical interfaces do not matter on the generic abstraction level of the product family until a single product entity is derived. The absence of interfaces on this level reduces the complexity significantly. Hence, different position is no differentiation criteria in cases of variety anymore. Further variance could be encapsulated by packing all optional variants of one kind into a generic module (Du et al., 2001) or even whole subfamilies into compound modules (Erens, 1996).

3.2 “Green”, “Yellow” and “Blue” - The MAN Truck & Bus structure

Kreimeyer described a solution for a generic product structure at MAN Truck & Bus lately, which is described briefly below (Kreimeyer, 2012).

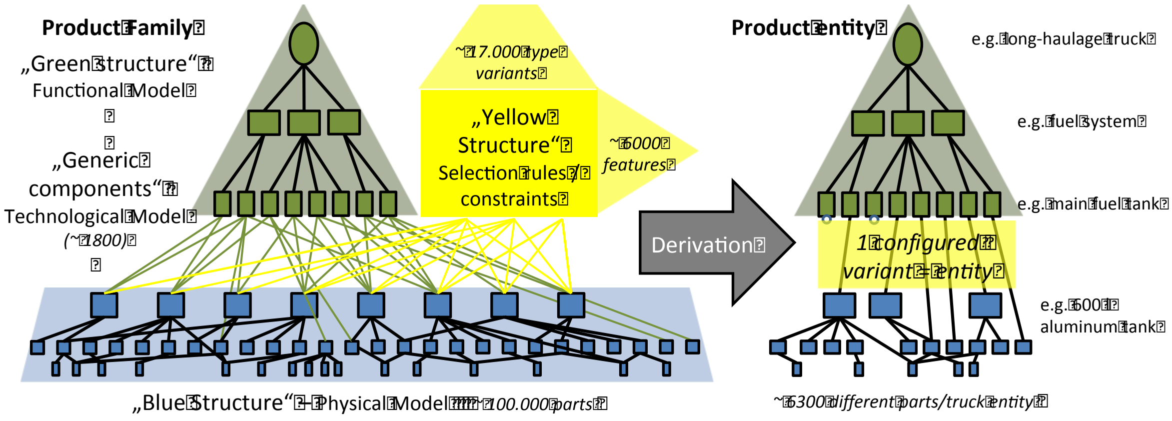


Figure 2. MAN Product family and role of the generic structure

Figure 2 shows the whole architectural model used by MAN to manage the product family “heavy duty truck”. To understand which part of information is contained in which part of the architecture, the three different kinds of structural models by Erens and Verhulst (1997) should be kept in mind.

The generic structure is called the “**Green Structure**”. The Green Structure is derived from a very simple functional model of the truck. On the lower levels of the Green Structure the range of functionality is higher than implementable into one single product entity, whereby no single entity provides the whole offered range of functions at once (Kreimeyer, 2012). The entity derivation process, as sketched in Figure 2, visualizes the fact that even if some generic components have no physical expression in a product entity, the Green Structure could be seen as common over the whole product range. Also the technological model is expressed partially by the Green Structure because the lowest generic level of generic components provides different technological variants, like e.g. an electrical or combustion engine for the same functionality. Therefore the optimal level for modularization and also DfA is the generic component level, due to the right level of decision impact and detail of information.

All selection and combination rules of options and choices for deriving single entities from the Green Structure are contained by the comprehensive “**Yellow Structure**”, which expresses the external variety provided for the customer. The physical model, the “**Blue Structure**”, consists of all components and assemblies that all product entities are built of and serves as a building block system.

All three structures together represent every part and every end product variant of the truck’s product range. As sufficiently transparent product architecture is displayed, only a suitable modularization method is missing to gain higher adaptability.

4 MODULARIZATION IN GENERIC PRODUCT STRUCTURES

4.1 Modularization and generic structures

Although intensive research was done on this topic, no modularization method was discoverable, which is explicitly applicable on generic structures. In a generic structure without information about interfaces, modularity could not be treated like proposed by Ulrich (1995) as grouping elements according to strength of interfaces. Although Erixon (1998) postulates modules with “specified interfaces” like Ulrich too, the major contribution in his definition of modularization is the phrase “driven by company-specific reasons“. The grouping according to company-specific reasons or other strategic aspects is the remaining core of modularization for generic structures without interfaces. We therefore introduce the term “***strategic modules***” that are oppositely to the classical, so called “***physical modules***”, defined more generally as “*a group of components for a strategic purpose*”.

4.2 The range of suitable modularization methods

The potential range of methodology to develop the strategic modules on generic component levels could be narrowed by the argument of Fricke et al. (2005) that excludes distinct variant management and platform development methods: Despite the fact that they may have similar sub-goals, their focus is more on variance and development of new platforms. Also all approaches towards modularity based on component couplings and interfaces must be excluded for now, because of the generic structure and configure-to-order product. This hits especially all methods based on the Design Structure Matrix.

The range of modularization methods is dividable into functional-technological and **product-strategic approaches**. Lehtonen et al. (2009) showed by examination of eight case studies (including the example of a SCANIA heavy truck) that function based approaches lead to significant wrong results in case of real-life product families and should only provide the basic boundary restrictions. Therefore the focus in further examination is set on product-strategic approaches.

Product strategic approaches are according to Lehtonen et al. (2009) **Modular Function Deployment** (short MFD) by Erixon (1998), the approach by Cantamessa and Rafele (2002) and some others, which are treating modularization from a too foundational perspective and are therefore not mentioned here. The Cantamessa and Rafele approach is sill very conceptual compared to MFD and does not outline a severe methodology and is therefore not further contemplated. Thus, the suitable and most promising approach is MFD. MFD is a mature methodology and its applicability was proven in many case studies. The core of MFD lies in treating strategic aspects of components or functions *before* it respects any interfaces. It treats modularization with the “**module drivers**” **-** qualitative criteria that characterize the “driving forces for modularization” (Erixon, 1998) or more generally are seen as “reasons for grouping parts or technical solutions into modules” (Blackenfelt, 2001). Blackenfelt (2001) even sees module drivers as “important carriers of strategic aspects”. The method was advanced by Stake (2000), to consider the interrelations and effects on platform products, as well as by Blackenfelt (2001), treating module drivers more generally and considering interfaces by using a product strategic DSM.

4.5 Module drivers for Adaptability

Because module drivers are not naturally applicable for DfA, the original ones need to be modified for the purpose of adaptability. We renamed this modified module drivers as **“adaptability drivers”.** Adaptability drivers have to cover the two aspects of DfA mentioned above. Therefore, revealing the drivers implies finding those drivers that either describe component behavior in case of adaptation or certain adaptation scenarios of components.

To find those drivers, we examined the original module drivers from Erixon (1996), Blackenfelt (2001) and Stake (2000) as well as aspects of adaptability outlined above (e.g. change propagation) for those factors, which incorporate reasons to group components into modules for improving adaptability. By consultation of several experts at MAN, we approved the validity and causality of those drivers for the MAN problem and revealed further MAN specific drivers. The narrowed focus of this empirical study on the MAN problem does not give evidence about a validity of these drivers for other and similar problems. Nevertheless, the essence of those drivers, which is listed in Table 1, gives a clue about possible driver candidates for related problems. The right column of Table 1 shows also some very conceptual ideas for design implications, which are derivable from the strategic modules, built by those drivers.

Table 1. Adaptability Drivers

Driver	Characteristic	Implication
Change propagation	Absorber	Group all “never changers” together
	Carrier/Multiplier	Pack in separated module and isolate
Change Scenario	Change expected (specific adapt.)	Pack origin component and those for future functionality together; group all updates
	Change unexpected (general adapt.)	Group acc. to other drivers or segregate
	Likelihood/Necessity	Make most likely and importantly changing comp. to a module or segregate them
Environmental dependence	Component is not suitable for all environment, e.g. temperature	Group with components with similar environmental requirements or segregate
Second Life application	2nd life purposes has different requirements	Pack origin component and those for future functionality together; group all updates
Platform Commonality	Component is carried over to most of the product range	Define invariant platform by grouping into module
Technology lifespan	Components that are subject to severe technology evolution	Pack in separated module or group with similar components as evolution module
Wear out	Components that get worn out over time during use e.g. brakes, fender	Group with components with similar wear out time or segregate
Prior usage	Components already used in former product generations unchanged	Group all “never changers” together

4.6 Intermediate conclusion

The above outlined research leads to the conclusion that adaptability in a multi-variant product family is manageable most promisingly by product strategic modularization of the components in a generic structuring concept. Therefore the generic components are grouped into *strategic modules* with respect to possibly multivalent called “**adaptability drivers**”. These drivers cover the component behavior in case of an adaptation and certain adaptation scenarios for components. The most useful process for utilizing the modularization refers to the method of Modular Function Deployment applied on the generic components.

5 EXEMPLARIC APPLICATION OF ADAPTABILITY DRIVERS

5.1 Application on a fictive example

To provide an illustrative example, a set of generic components is selected out of the Green Structure, which is displayed in Figure 3. Most of them have, as already mentioned, no interfaces (spatial or else) that connect them to each other. Nevertheless a functional relationship is conceivable. Each of possibly contains a set of physical variants, like e.g. an automatic or manually shifted gearbox. They can also be optional, like the transfer case, which is only needed for vehicles with mechanically propelled front axles. The variance in position could be imagined especially when we think about a tractor as shown in the figure or a dump truck for construction sites, which has usually a longer frame length and four axles. In the Green Structure, the variance, interfaces, position and optional characteristics do not matter, so the generic component level is perceivable as a list of components.

The components could be evaluated with the **Module Indication Matrix** by Erixon (1998) or simply mapped towards the highest relevant drivers like found in (Blees, 2011). Both approaches are shown in Figure 4. The matrix method is useful for more drivers, components and effects, while the Blees approach is applicable very quickly in small scale.

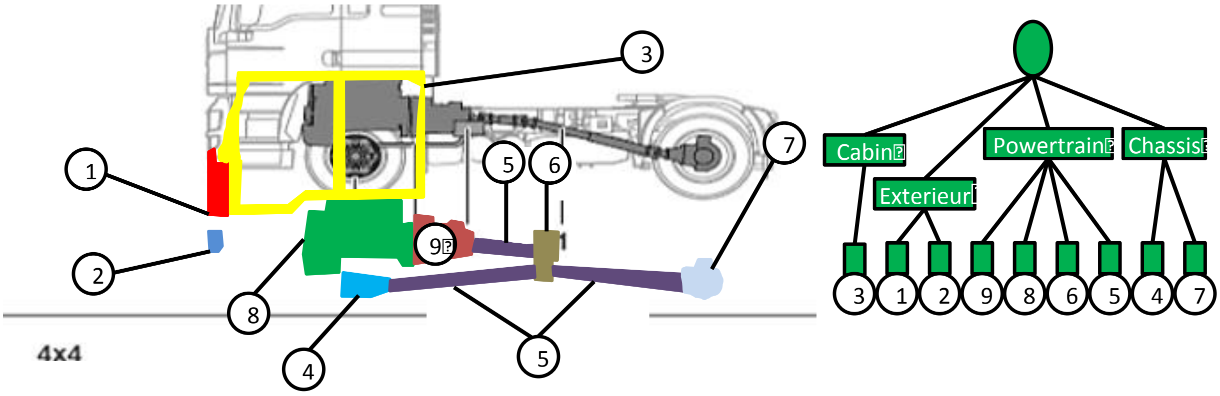
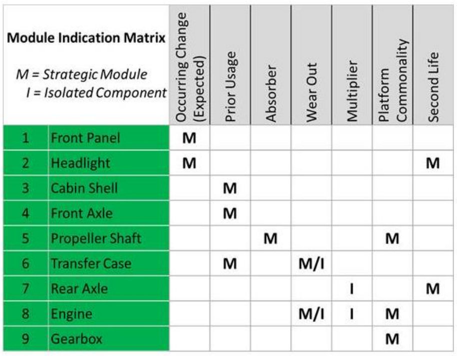


Figure 3. Example components from the truck's structure



Module Indication Matrix *M = Strategic Module* *I = Isolated Component*		Occurring Change (Expected)	Prior Usage	Absorber	Wear Out	Multiplier	Platform Commonality	Second Life
1	Front Panel	M						
2	Headlight	M						M
3	Cabin Shell		M					
4	Front Axle		M					
5	Propeller Shaft			M			M	
6	Transfer Case		M		M/I			
7	Rear Axle					I		M
8	Engine				M/I	I	M	
9	Gearbox						M	

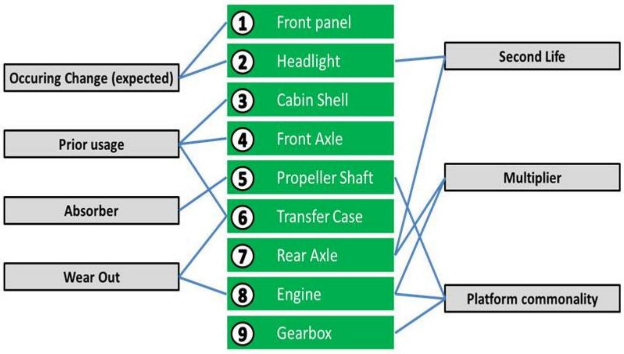


Figure 4. Module Indication Matrix (left) and direct mapping (right)

In the first applied examples it proofed to be useful to divide the effects of the adaptability drivers into those who force grouping into modules and those who tend to isolate components from each other. In both Figures 4 and 5, it is recognizable that conflicts between module borders occur between the perspectives of different adaptability drivers. This effect shows that also in this very simple example, the definition of modules is not unambiguous. These conflicts show interrelations between the generic components, although interfaces are not considered. Those interrelations are referring to the *strategic modules* as *"**strategic dependencies**"*, because their effect is similar to the strategic modules. All components that are either linked by *strategic dependencies* or part of a *strategic module* have common characteristics and should be treated together with the same management or design strategies. Figure 5 shows the result of the modularization, where *strategic dependencies* occur as connections between components or modules.

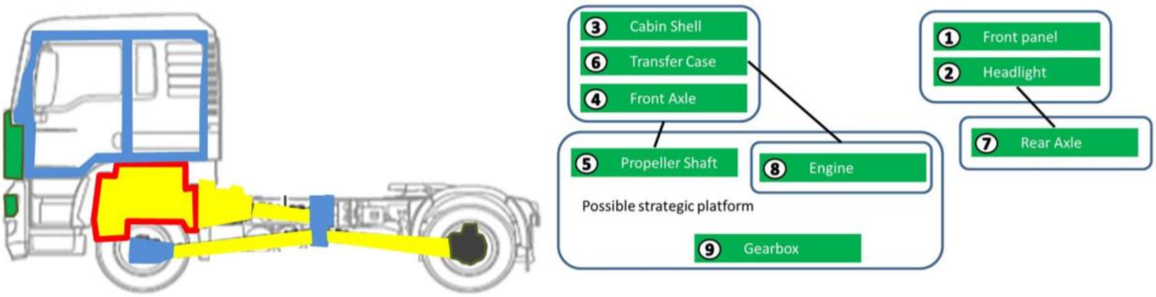


Figure 5. Truck example with strategic adaptability modules

Speaking further about the example in Figure 5, the module around the components 3, 4 and 6 is very robust and therefore adaptable as well. Components 1 and 2 are likely to be affected by the same planned design change like e.g. a facelift, while components 2 and 7 must be adapted for second life requirements and therefore e.g. pre-equipped for an easy update. Although the engine (component 8) is very critical in terms of adaptability, and has to be designed e.g. exchangeable or upgradeable. It builds, together with components 5 and 9 a possible platform. This has major impact on the whole product range. The platform should therefore be treated commonly in sense of adaptability.

5.2 Implications

The major benefit of applying adaptability drivers lies in revealing those components, which have a similar adaptability characteristic. This means that those components, which are affected by similar adaptability drivers in a similar way, are rationally treated by similar measures. Also the strength and number of drivers a component is affected by is perceivable as a KPI for the demand of adaptability. Is a component strongly affected by certain scenarios or a harmful behavior in case of an adaptation, it has to be designed very adaptable. This is realizable by existing and already known design guidelines for adaptable design. Thus, the adaptability drivers do not design the product more adaptable directly, but they reveal a structural model of the examined system. The model, consisting out of strategic modules and dependencies, provides rather taxonomy of those system elements that have to be designed more adaptable or are already sufficiently adaptable in their current design. Therefore the application of adaptability drivers is perceivable as an upstream operation in DfA methodology, which reduces the overall development effort for complex and multi-variant products by implementing adaptability more cause-specific and reasonable.

6 DISCUSSION

The provided example shows how the method works conceptually, but is not suitable as the validation of the approach. It works in this case, but a universal validity was not granted. This lack of maturity is therefore the most critical point. Hence the whole concept has to be further examined, validated and evaluated by research and case studies. However, the first applications on real-life problems at MAN showed promising results.

Even with application of the MIM, the finding of modules is not that easy or without conflicts. This issue has to be clarified also for large-scale examples. Therefore, the use of matrix computation and clustering tools must be kept in mind. A possible approach to calculate the *strategic modules* and *dependencies* especially for such complex examples could be Multiple Domain Mapping by Lindemann et al. (2008) and related software tools that proved well in similar problems.

The fact that the adaptability drivers are not generally valid because they are revealed only for the MAN context, requires further methodical examination, prioritization and customization of them to reveal the most suitable adaptability drivers for a certain case or general application.

In the current state, the methodology lacks also in terms of presenting the value gain and therefore proving effectiveness and efficiency. A business case assessment, as already postulated (e.g. by Kissel et al., 2012), has to give monetary or otherwise quantitative evaluation of the approach.

7 CONCLUSION AND OUTLOOK

In this paper a methodical concept is presented that is based on the established modularization method Modular Function Deployment. It manages the complexity of a high variant product family by using a generic structuring concept and modularization on the level of generic components. The grouping of components into *strategic modules* was done with an exemplary set of *adaptability drivers*. By the resulting modular structure the product can be designed with improved adaptability. This is promising also a new level of transparency of the complex product and therefore an easy assessment possibility for managerial strategies such as extended collaboration scenarios. The new perspective on generic components might turn out as a door opener for modularization in other purposes, e.g. for other DfX paradigms. The provided example does not proof the practical applicability, validity and value gain of the outlined concept sufficiently yet. Therefore it is necessary to examine the concept with extensive case studies and further research in this area.

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