HOLISTIC APPROACH FOR DESIGN AND RE-DESIGN OF PRODUCTION UNITS

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Abstract

This paper presents a novel approach to enable change within the life cycle of a production unit and enhance the usability of a re-design and change process by consistent interaction between the design and evaluation method. The method, based on Axiomatic Design, is used to find a design solution for a changeable production unit in a structured way. In a later phase of the life cycle the corresponding evaluation method gives a result which results in the need for parts of the previously designed production unit to be adjusted in order to improve the changeability of the entire system. The paper demonstrates a significant improvement in usability by combining design and evaluation process. In addition, the holistic approach is validated and explained by an use case of the automotive industry.

Keywords: Complexity, Design methods, Evaluation, Robust design, Product lifecycle

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1 INTRODUCTION

Due to shifting conditions, such as shortened product life cycles, increasing numbers of variants and high market volatility, the automotive industry must be flexible to manage new challenges. Therefore, the handling of re-design and changeability of complex systems is becoming significantly more important. Multiplicities of methods are known which relate to re-design and change. Eckert et al. (2004) for example introduces two approaches companies use in order to deal with change. In general, it can be stated that methods concerning change and re-design are infrequently used in practice. One possible way to increase the acceptance of methodical approaches in industry is to improve the usability of these methods. Thus, it is challenging to increase usability and still to keep up the quality of results in design process. To limit the scope of this publication the focus is on designing a changeable production unit with the Axiomatic Design Theory and on how to enable change in a life cycle of the production system. Currently, the life cycle of a production unit within the automotive industry is linked to the lifecycle of the produced product. Today, when producing a new product, a new production unit has to be implemented or an extensive re-design has to be made. As mentioned before conventional life cycles are disrupted by (un-)predicted occurrences and the implementation of change requirements within a short time-frame and are therefore hard to realize and cost-intensive.
Within this framework, the paper proposes a novel approach, called "adapt!", to enable change within the life cycle of a production unit and enhance the usability of a re-design and change process by consistent interaction between the design and the evaluation method for changeability (Figure 1). The method, based on Axiomatic Design, is used to find a design solution for a changeable production unit in a structured way. In a later phase of the life cycle the corresponding evaluation method answers the question which parts of the previously designed production unit should be adjusted in order to improve the changeability of the entire system.

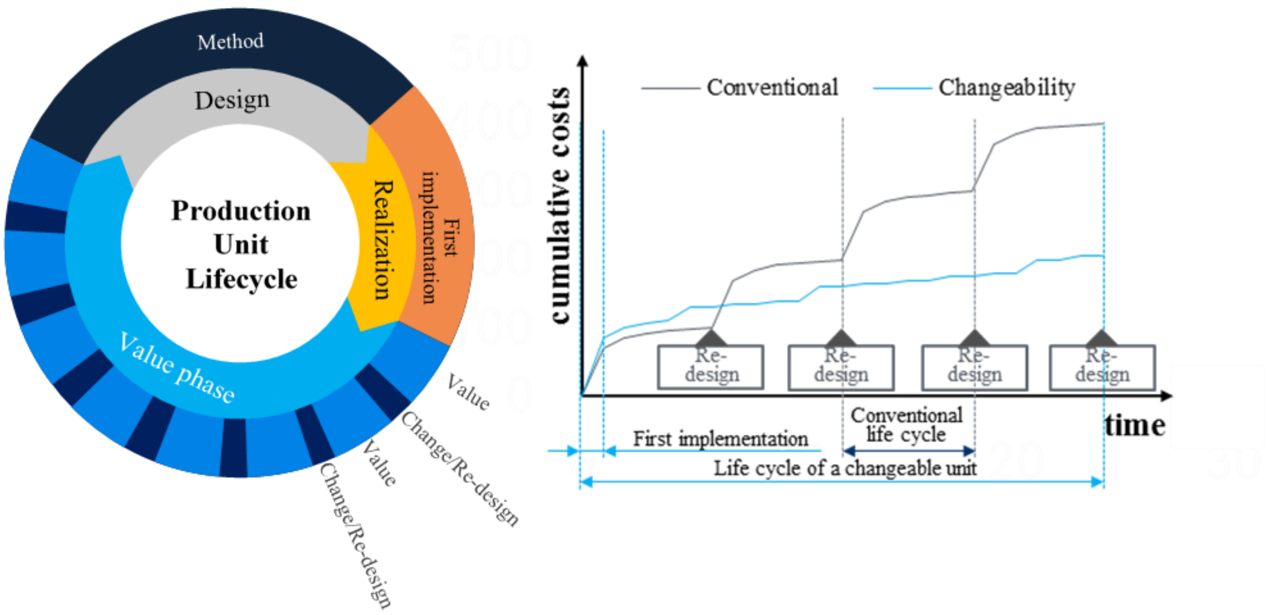

Figure 1. The Presented Approach and its Benefits

A lean design and evaluation process for an initial development and re-design will be pursued. During the design process a design task is decomposed into as many independent functional requirements as possible and the dependencies are determined. These results contribute to the evaluation process when the need of changeability has reached an action limit. So by using the new approach the added value of the production unit can be increased compared to the conventional life cycle.
Hence, three key questions regarding the proposed approach can be formulated:

1. What can a holistic approach for changeability and re-design look like?
2. Is it possible to improve the acceptance of change methods in industry by using a holistic approach?
3. Is it possible to maximize objectivity within an evaluation process?

2 STATE OF THE ART AND RELATED WORK

Firstly, for a common understanding, the term changeability regarding production units is explained. Following, the basics of Axiomatic Design Theory and related works dealing with the industrial application of this theory are summarized. Finally, basics about system theory and how to cope with changes are presented.

2.1 Changeability of Production Units

Changeability in context of production describes the possibility of a production system or lower level of a production unit to react to foreseen and unforeseen changes in the environment. According to Wiendahl (2002, 2007) and ElMaraghi (2009) changeability can be seen as an umbrella term for various classes of changeability on different hierarchical levels of a production ranging from station level up to production network level. On the low level of a production unit or production system this is e.g. reconfigurability or flexibility. In Weber et al. (2016a, b) it is emphasized that modularity and mobility are two key enablers for realizing a reconfigurable system in assembly.

2.2 Axiomatic Design

There are several function oriented design methods e.g. Characteristics-Properties Modelling and Property-Driven Development (CPM/PDD) by Weber (2005) or Axiomatic Design (AD) Theory by Suh (1990, 2001). The main idea behind most of these design theories is to preserve the independence of the functions of the desired design in order to assure a robust design. In AD a robust design is achieved by the use of mainly two axioms. First, the Independence Axiom ensures the independence of the so called functional requirements (FR). The second axiom, the Information Axiom, helps to select from two designs which are according to the first axiom equally independent. This approach ensures the best design solution is found.
The design process itself in AD is of hierarchical nature. There are customer attributes which are mapped to the functional domain. The functional domain can be described by "what we want to achieve" with the design task. From this domain the requirements are mapped to the physical domain where the physical solution is generated. This domain can be described by "how we want to achieve it". The mapping between the domains starts on the highest and also very abstract level and proceeds downwards into more detail on the lower levels. The design task is decomposed by switching back and forth between the different domains. With this procedure a hierarchical design tree can be generated. In order to detect the dependencies between different functional requirements the design tree is transformed into a design matrix. Here the dependencies are marked and regarding the design can be optimised.

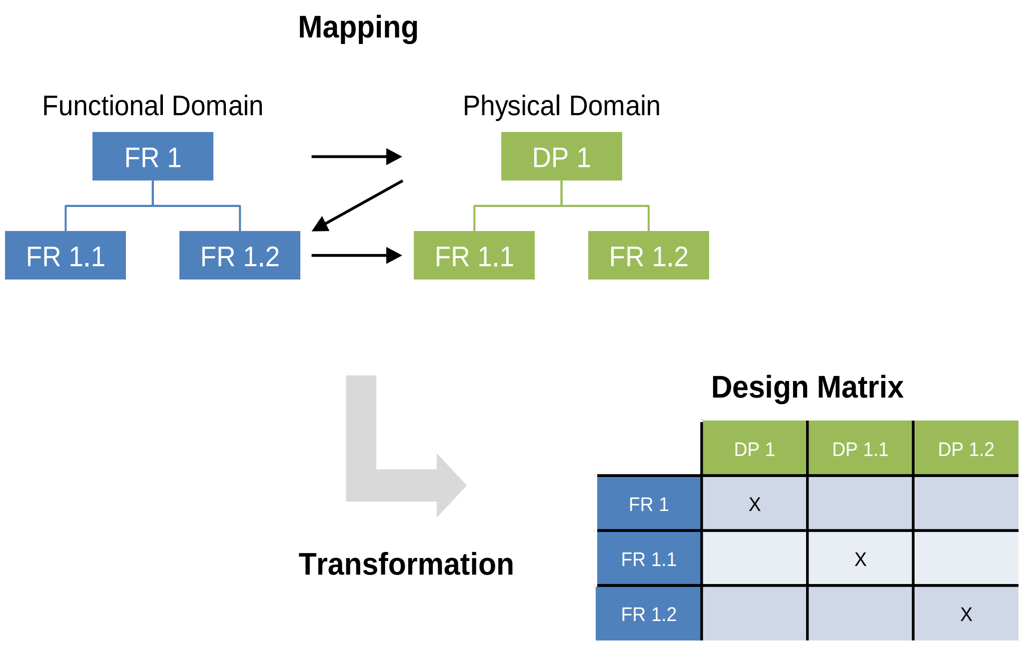

Figure 2. Mapping and Transformation in Axiomatic Design

2.3 Industrial Application of Axiomatic Design

Axiomatic Design is applied across a wide range of different industries. It is used for product design in the classical sense e.g. of software. AD is also applied in the area of manufacturing system design. With an increasing number of scientists dealing with AD in this area, AD has become more and more important in recent years (Rauch et al., 2016). Another insight into the work of Rauch et al. is the fact, that most research involving AD in manufacturing system design involves the use of the independence axiom while the application of the information axiom is left aside.

With the aim to increase the usability of AD in an industrial environment, the initial work is done. In (Weber et al., 2015a) an approach is discussed purposely ignoring the Information Axiom. This is motivated by improving the quality of manufacturing design with an affordable effort. In (Weber et al., 2015b) a proposal for usefully introducing AD in a large company like an OEM is made. It is emphasized how the theory can be used in order to reduce complexity of a design by discussing functional requirements with different stakeholders within the same company. Thus, by reducing complexity, the design of a changeable production unit is benefited.

2.4 System

Derived from the system theory, various definitions are known such as Vester and Hesler (1980), Ulrich & Probst (2001) Pahl and Beitz (1996) and Wasson (2006). Lindemann et al. (2009) compares them to each other and generates the closest thing to an all-encompassing definition:

"A system is created by compatible and interrelated parts that form a system structure, possess individual properties, and contribute to fulfil the system's purpose. Systems are delimitated by a system border and connected to their surroundings by complexity in the context of product design inputs and outputs. Changes to parts of a system can be characterized by dynamic effects and result in specific system behaviour. (Lindemann et al., 2009)".

Technical systems tend to have an implicit complexity. If there is an optimized product structure, a reduction of complexity can be detected or rather the complexity managed can be improved (Ericsson and Erixon, 1999; Baldwin and Clark, 2000). A functional-oriented product development as described in chapter 2.2 helps to generate an optimized product structure. Pahl and Beitz (1996) describe this procedure as a method of factorization, where the System is divided into sub-functions. Other scientific publications name parts of a system subsystems. These are often defined by their function, but can also be defined by factors like assembly modules or responsibilities. To have a better understanding of a System and if necessary to modify it, it is important that the constraints of sub systems are known and methodically controllable (Lindemann et al., 2009). Methods which have their main focus on the detection and quantification of constraints of a system are often based on a design matrix (Eppinger, 1994). In other methods, correlations are primarily displayed visually however the logic is usually also based on a matrix (Maurer et al., 2010; Cheng and Chu, 2012).

2.5 How to deal with change?

To implement changes within a system, different approaches are possible. Eckert et al. (2004) distinguishes two possibilities, how required changes are managed in the industry: The „Forwards partial re-design" and the „backwards patching / debugging re-design". The approach of forwards partial redesign has its main focus on evaluation. Possible solutions are compared, followed by a technical plan to solve the design problem. This approach is very structured and similar to known design processes. In the approach of backwards patching / debugging re-design a detailed solution finding process is skipped and a solution is directly generated. Afterwards, an evaluation of the solution takes place with a following iteration loop if the solution is not satisfying. Thereby the duration of the backward redesign process cannot be estimated exactly, because it depends on the amount of iteration loops (Eckert et al., 2004).

In recent years the science community has recognized that there are several evaluation methods available, however they are not being implemented often in industry. One reason for the lack of acceptance of the methods is the limited usability. Shackel et al. (1991) drew the conclusion that "Usability became of equal importance to functionality", to increase the acceptance of the user.

3 METHOD ADAPT!

As mentioned previously, a structured procedure for the development and evaluation of changeable systems is needed. Simultaneously, high user friendliness and a reduction of the design period have to be achieved. The approach is to improve the acceptance by consequent data use, so that the evaluation method will be implemented. The results of the design methods are systematically used in the evaluation method to evaluate a system regarding its changeability towards a transformation in a post phase of life. For that purpose the evaluation method should give an idea of what and how much of a system has to be changed, in order to be a viable solution to the new challenges.

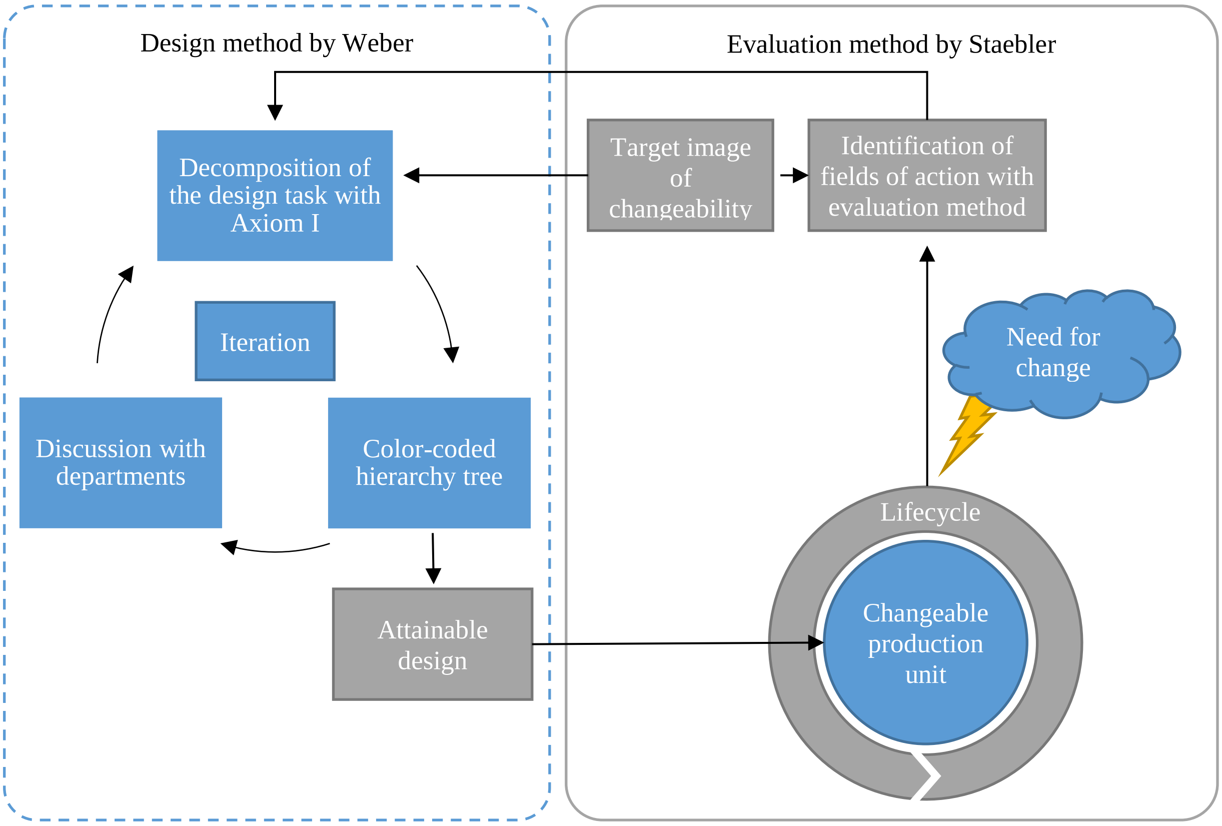

Figure 3. ADAPT! - Approach for Design and Re-Design of a Changeable Production Unit

3.1 Design Method Adapt!Design

In order to create and to keep a production unit changeable a dedicated approach is useful. The design task gets decomposed according to the Independence Axiom of AD Theory (Figure 3). As a consequence of Weber et al. (2015a) the Information Axiom can be neglected to facilitate the application of AD. Furthermore the application of the Independence Axiom is limited to the highest hierarchical levels of the decomposition to keep the effort manageable. Weber et al. (2016b) strict modularity is a key enabler for a changeable design should be considered. The result of the decomposition step is a hierarchical tree. Based on the assumption, that the method is applied within a large company, the FR are coloured according to their origin. This helps to identify which stakeholder group or department within the company generates most dependencies in the design. Following this, the dependencies are discussed with the responsible departments with the aim of weakening the FR and therefore reducing complexity. With this outcome the process starts all over again. If according to AD Theory a good design is found, the iterative design process ends and the production unit is implemented. During the life cycle of the production unit a need for change may occur. By using the evaluation method which is explained in the following section, the fields of action for the re-design of the production unit can be recognized. Due to the modular design of the changeable production unit only the identified modules have to be re-designed using the described design procedure. After this the new designed modules can be integrated or added to the existing production unit without beginning from scratch.

3.2 Evaluation Method Adapt!Eva

The evaluation method Adapt!Eva has the goal of providing an answer to the question of whether a system is already qualified for upcoming tasks or, if not, which system has to be changed or re-designed. Thus, the changeability of the entire system should be influenced positively. The three cornerstones of the methodology are the **determination of subsystems and their dependencies**, the **effort** to enable a system to have high changeability, and the impact to the overall system when changing a subsystem, the so-called **effectiveness**. In this paper the focus is on determining subsystems and their dependencies. The other two cornerstones of the evaluation method will not be discussed in more detail in this publication. For more information refer to existing publications (Stäbler et al., 2016a, b).

In order to increase usability as well as to decrease development time, a coherent interaction between the development and evaluation method is significant. Therefore, results of function-oriented development are reused for a solid validation in order to determine the required subsystems and their dependencies among each other. The axiomatic design hierarchy tree is used as a basis for subdividing the entire system into function-based subsystems (Figure 4).

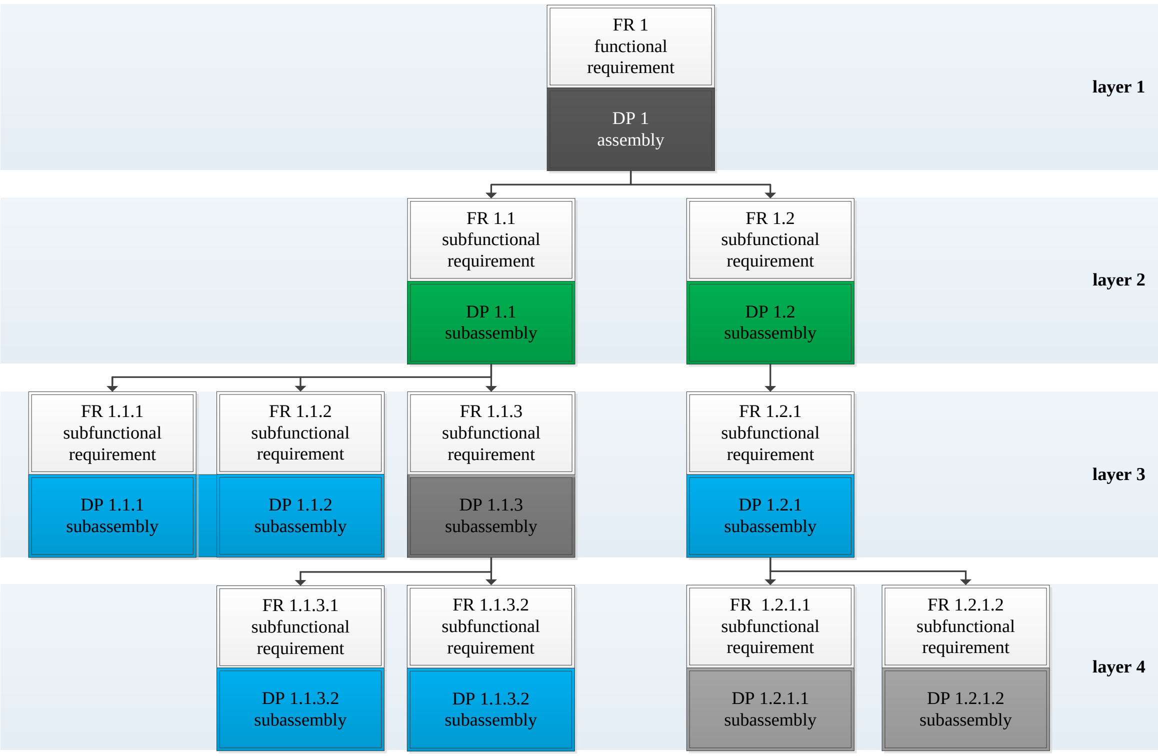

Figure 4. Building Subsystems by Hierarchy Tree

The granularity of the subsystems can be adapted for the complexity of the system and the evaluation requirements. In the case of complex systems, it is recommended to use subsystems with a higher degree of abstraction. This way for further evaluation steps uninterested sub-branches can be excluded and the number of subsystems which are included in the evaluation process can be limited. With this course of action evaluation complexity remains controllable. If the results are not sufficient to proceed in the re-design, a further evaluation round can be made one hierarchy level lower according to the top-down principle. Those subsystems may consist of individual Design parameters or can include several. By applying the research results it is found that the strict determination of subsystems within a hierarchy level is not necessary and expedient. If the user favours to granulate several subsystems during determination process, then this is not a problem. This can be advantageous if clearly defined design parameters can be bundled, which can then be assigned to different persons or areas of responsibility within an organizational structure. It may be also suggestive if a further detailing of the evaluation is not provided.

After defining the subsystems per hierarchy tree, the already existing design matrix is used to determine dependencies of the subsystems among each other. For this purpose, the already defined subsystems are visualized in the design matrix (Figure 5).

functional requirement / design parameter (layer)	DP 1	DP 1.1	DP 1.2	DP 1.1.1	DP 1.1.2	DP 1.1.3	DP 1.2.1	DP 1.1.2.1	DP 1.1.2.2	DP 1.2.1.1	DP 1.2.1.2
FR 1	X										
FR 1.1		X									
FR 1.2			X								
FR 1.1.1				X					X		
FR 1.1.2				X	X						
FR 1.1.3						x					
FR 1.2.1		X					X				
FR 1.1.2.1								X			X
FR 1.1.2.2								X	X		
FR 1.2.1.1										X	
FR 1.2.1.2											X

Figure 5. Quantification of Dependencies

Dependencies within a subsystem are not considered. Dependencies within a hierarchy layer (marked with yellow) are less critical than dependencies on a lower level (marked with red). Dependencies of minor design parameters are also considered. Within the evaluation method, it is not intended to distinguish between positive and negative dependencies. Instead, subsystems which have as few dependencies to other subsystems as possible are identified. Therefore, yellow dependencies are measured with one and red dependencies with two points.

4 USE CASE: BOLTING OF A REAR BUMPER BEAM

The bolting of a rear bumper beam (Figure 6) with the car body is a safety-relevant so called A-joint. The specified final torque of approximately 60 Nm is manually applied to four different bolts in overhead work with EC-screwdrivers. The final torque is absorbed by the workmen executing this process. Furthermore the correct execution of the bolting has to be documented for each produced car.

Figure 6. Mounted Rear Bumper Beam

Because of the process being ergonomically unfavourably, the design task is to find a semi- or fully-automated solution. Using to the presented design procedure several solutions are generated. Because of the Independence Axiom a semi-automated solution is determined as the most favourable generated solution. A detailed explanation of this would go beyond the scope of this paper. The focus lies on the use of the data in the re-design process, which is generated during the design process. This is described in the following section.

Based on the results of the design process the evaluation method can be executed. Figure 7 displays the defined subsystems which are generated by using the hierarchy tree. Thereby five subsystems are determined. The first subsystem includes all design parameters which refer to human tasks. Subsystems 2 and 3 are determined one hierarchy layer lower. This is carried out because a clear separation of the robot and the needed tool is possible and useful. The Robot and the adapter is a buying-in component and the tool is an in-house development. Subsystems 4 and 5 are determined on layer 3. In this case a further granulation of them is not prioritized. Through the application of this approach it is shown that it provides a very structured and transparent way of defining subsystems. Furthermore, the usability is assessed as very good due to the already existing hierarchy tree before starting the evaluation process.

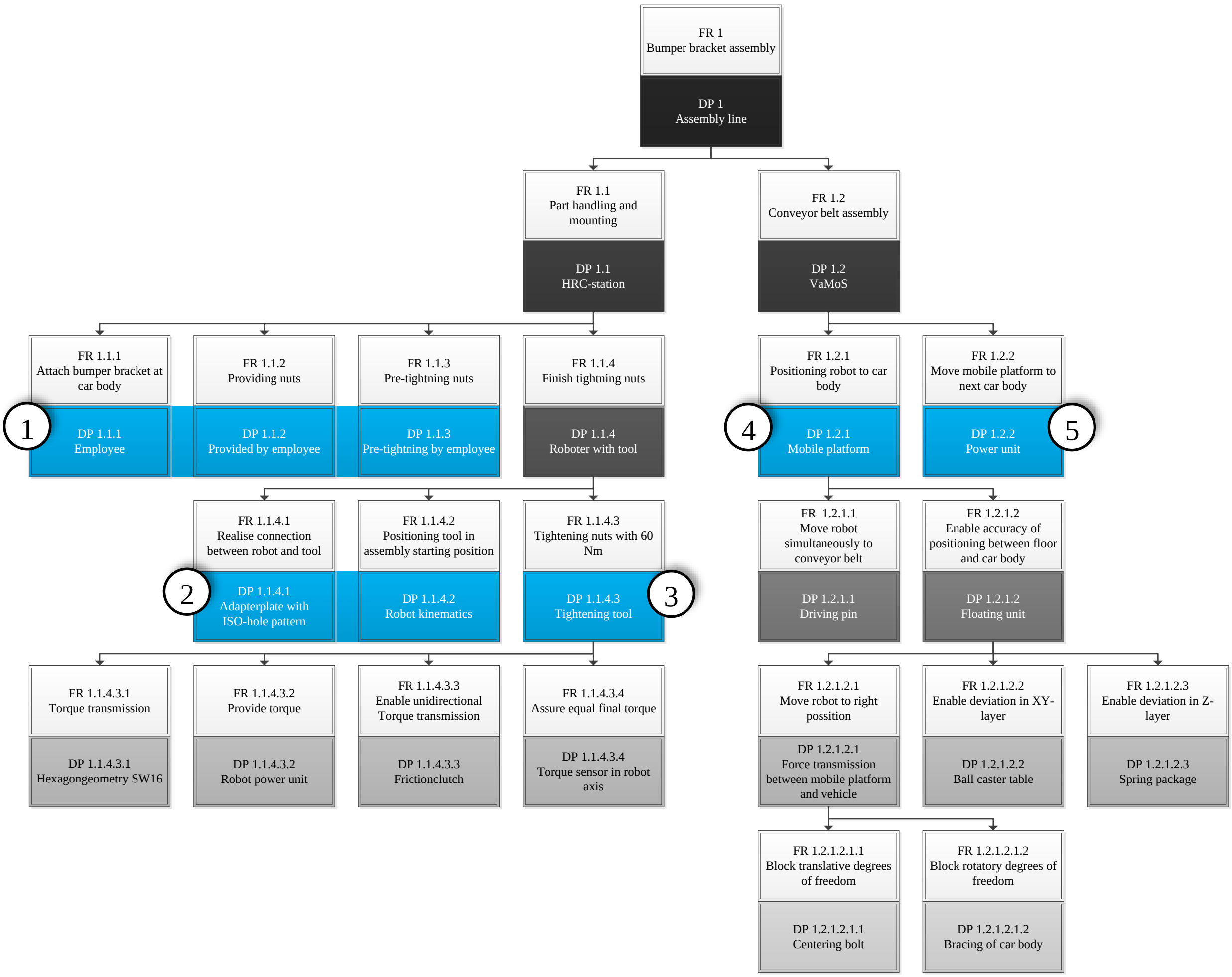

Figure 7. Use Case: Building Subsystems

After determining the subsystems the result is displayed in the already existing design structure matrix of AD Theory (Figure 8). Since the DSM is too large for its row and column headers to be legible, subsystems and their minor sub-design parameters are marked with the same colour and shading. As stated previously, dependencies within a subsystem are neglected. For example the dependency between DP 1.1.1 and FR 1.1.3 is within subsystem 1 and therefore is not further considered. The other dependencies are displayed vertically under the respective subsystem and are summed up to generate the dependency index of the subsystem. The results of the determination of the dependency index show that the whole system is a very independent system. Subsystem 2 has the highest dependency index with 2. All the other subsystems are independent. This is due to the fact that this production unit is designed under the premise of being independent and modular. This evaluation is also a pre-indicator that the goal of designing an independent and modular production unit is achieved. Furthermore the first cornerstone of the evaluation method "determination of subsystems and their dependencies" is complete and the results are used for the entire evaluation method.

		Designparameter	Assembly line	HRC-station	VaMoS	Employee	Provided by employee	Pre-tightning by employee	Roboter with tool	Mobile platform	Power unit	Adapterplate with ISO-hole pattern	Robot kinematics	Tightening tool	Driving pin	Floating unit	Hexagongeometry SW16	Robot power unit	Frictionclutch	Torque sensor in robot axis	Force transmission between mobile platform and vehicle	Ball caster table	Spring package	Centering bolt	Bracing of car body
Function requirements		Ebene	DP 1	DP 1.1	DP 1.2	DP 1.1.1	DP 1.1.2	DP 1.1.3	DP 1.1.4	DP 1.2.1	DP 1.2.2	DP 1.1.4.1	DP 1.1.4.2	DP 1.1.4.3	DP 1.2.1.1	DP 1.2.1.2	DP 1.1.4.3.1	DP 1.1.4.3.2	DP 1.1.4.3.3	DP 1.1.4.3.4	DP 1.2.1.2.1	DP 1.2.1.2.2	DP 1.2.1.2.3	DP 1.2.1.2.1.1	DP 1.2.1.2.1.2
Bumper bracket assembly		FR 1	X																						
Part handling and mounting		FR 1.1		X																					
Conveyor belt assembly		FR 1.2			X																				
Attach bumper bracket at car body	FR 1.1	FR 1.1.1				X																			
Providing nuts	FR 1.1	FR 1.1.2					X																		
Pre-tightning nuts	FR 1.1	FR 1.1.3				X		X																	
Finish tightning nuts	FR 1.1	FR 1.1.4							X																
Positioning robot to car body	FR 1.2	FR 1.2.1								X															
Move mobile platform to next car body	FR 1.2	FR 1.2.2									X														
Realise connection between robot and tool	FR 1.1.4	FR 1.1.4.1										X													
Positioning tool in assembly starting position	FR 1.1.4	FR 1.1.4.2											X												
Tightening nuts with 60 Nm	FR 1.1.4	FR 1.1.4.3												X											
Move robot simultaneously to conveyor belt	FR 1.2.1	FR 1.2.1.1													X										
Enable accuracy of positioning between floor and car body	FR 1.2.1	FR 1.2.1.2														X									
Torque transmission	FR 1.1.4.3	FR 1.1.4.3.1															X								
Provide torque	FR 1.1.4.3	FR 1.1.4.3.2										X						X							
Enable unidirectional Torque transmission	FR 1.1.4.3	FR 1.1.4.3.3																	X						
Assure equal final torque	FR 1.1.4.3	FR 1.1.4.3.4																X		X					
Move robot to right possition	FR 1.2.1.2	FR 1.2.1.2.1																			X				
Enable deviation in XY-layer	FR 1.2.1.2	FR 1.2.1.2.2																				X			
Enable deviation in Z-layer	FR 1.2.1.2	FR 1.2.1.2.3																					X		
Block translative degrees of freedom	FR 1.2.1.2.1	FR 1.2.1.2.1.1																						X	
Block rotatory degrees of freedom	FR 1.2.1.2.1	FR 1.2.1.2.1.2																							X

Figure 8. Use Case: Determining Dependencies of Subsystems.

5 DISCUSSION

A critical assessment of the proposed procedure can be done by questioning the results of the design procedure. By neglecting the Information Axiom it is not guaranteed the absolute best solution is achieved. Apart from this, it must be mentioned that the Information Axiom only helps to decide between equal independent design solutions, where the probability of occurrence is very low. So the mentioned procedure helps to implement a method in industry with limited costs and efforts.

According to key question 3, another critical view can be taken to the objectivity of the evaluation method. Especially during the definition of subsystems the whole process depends on an expert executing the explained steps. This can be answered by the fact that to a certain extent the whole design and re-design process is subjective. This is based on the circumstance that every design process is influenced by the personal style and experience of a designer. This is a point of criticism which affects all design methods in general and not this proposed procedure in particular. Using the information of the design process ensures the use of reliable data as an input for the evaluation process. Consequently, a very subjective procedure is improved and made more transparent by defining the consistent use of knowledge from the design process.

6 CONCLUSION AND OUTLOOK

Today's automotive industry faces many challenges caused by turbulent market conditions. In order to react to these challenges the companies have to adapt their design and re-design processes especially for production systems. In these fields of action, major work has already been done yet most design and re-design methods still require large efforts to be applied in industry. Furthermore, no approach is known that focuses on the design- and re-design-process at the same time. The presented paper addresses how a holistic approach for changeability and re-design look like which ensures that the knowledge of the design process is also used during the re-design process. The approach is designed to be easy to learn and apply in industry. The core idea of Adapt! is that the design process is found through the Information Axiom of Axiomatic Design Theory. The solution of this step is discussed with different stakeholders within the company. When a proper design is achieved the production unit gets implemented into the production system. During the life cycle of the production unit some need for change may occur. At this time the hierarchical design tree is used as input data for the evaluation method. Within the evaluation method the required fields of action are identified for the re-design in order to cope with the needed change. During the whole life cycle of the production unit there is a consistent use of data and knowledge which is generated during the design process to improve the objectivity of the evaluation process. Future work involves the refinement of the presented approach. Additionally, more experience has to be gained through the application of the approach in an industrial environment to quantify the acceptance over an extended period.

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