NordDesign 2012
August 22 – 24, 2012
Aalborg, Denmark

Design for Adaptability – Identifying Potential for Improvement on an Architecture Basis

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Abstract
Adaptability provides additional value to stakeholders over the whole life-cycle. But the systematic design of product life-cycle properties into complex systems constitutes an ambiguous task. Design for Adaptability (DfA) is an evolving topic in both science and industry. However, the transformation of a system to a desired "amount" of adaptability is impeded by lack of transparency of dependencies among system elements and their vague influence on the properties. Therefore, we present methodology, which allows improving systematically the adaptability of a system. The first step clarifies of the adaptability business case. Then, the system model is generated and analyzed. Dependent on the business case measures for improvement can be derived. At the example of an automotive braking system for an electric vehicle, we demonstrated the application of the methodology.

Keywords: Product Architecture Design, Design for Adaptability, Structural Complexity

Introduction
The **design of system life cycle properties** (LCP) – which means the conditioning of the systems for an anticipated behavior during future changes or changing needs – must be considered in early phases of the product development. A system architect determines the properties of a system – purposely or unknowingly – starting from the transformation of stakeholders' requirements via definition of technical specifications through to the delineation of the system architecture. If certain system properties should conform to a company's product strategy, they could be shaped best in the phase of Architectural Design. In a new product development the design freedom is rather taller than in a redesign project of an existing system. But also in an evolutionary product development process, it is advisable to run these projects under the lead of system architects due to their overarching and integrating role in the product development process [1]. Nevertheless, it remains an ambiguous task either to compose or to change form and functions of a system in a way that it performs the functional requirements and – in addition to it – features desired life-cycle properties. In this paper, we focus on the evolutionary development of existing systems, as it is the majority of engineering projects in industry.
Some scholars call system life cycle properties the **"Ilities"** [2–5]. "The *ilities* are desired properties of systems, such as flexibility or maintainability (usually but not always ending in "ility"), that often manifest themselves after a system has been put to its initial use"[3]. "Ilities" are system properties that are "neither well-defined nor easily evaluated in isolation" [5]. They can characterize form-related aspects of the system such as modularity, which can be evaluated with structural metrics. Whereas operational "Ilities" (e.g. portability) are

function related. Adaptability referres to both [4].

In this paper, we focus on **Design for Adaptability** (DfA) – a subset of changeability. Fricke and Schulz [6] name four aspects of changeability: Adaptability, Flexibility, Robustness and Agility, where the later describes how rapidly a system can change. Haberfellner and de Weck [7] used the term agility synonymously with adaptability. The definitions in literature of the words flexibility and adaptability make for some fuzziness and confusion. Gu et al [8] state that adaptions are conducted by a person outside of the product, like the user or the designer. In contrast to adaptable systems, flexible ones have the ability to change internally to fit changes from the environment. By contrast, the definition of Ross et al. [4] and Fricke and Schulz [6] is the exact opposite. In fact, both terms have not been invented by engineering scientists, but they are part of habitual language use. The Merriam Webster [9] dictionary defines the words adapt, adaptable and flexible as follows: to adapt stands for "to make fit (as for a new use) often by modification" and adaptable stands for "capable of becoming adapted". In contrast, the word flexible is explained as "capable of being flexed", "yielding to influence" or "characterized by a ready capability to adapt to new, different, or changing requirements". According to this definitions adaptable can be considered as "capable of extrinsic modification" whereas flexible can be considered as "capable of intrinsic modification". However, this paper follows the understanding of flexibility and adaptability congruent with the Merriam Webster [9] dictionary and Engel and Browning [10]. As a third term to be delaminated from the term adaptive is robust. Robust systems can withstand external noise factors without changing themselves [11].
Like in adaptability, the basic concept of an "ility" is normally to combine a verb or an adjective with the appendix "-ability". Here, the *ability of adapting something* expresses to perform this task in a reasonable time with a rational amount of effort. Therefore, we determine the amount of adaptability of a system as the triangulation of time, effort, and costs to perform an adaption. The faster, easier, and the cheaper the adaption is, the higher the adaptability of a system. Hence, we **define adaptability** as the ability of a system to perform external adaption cost-efficiently and effectively.
There are **different aspects characterizing adaptability** [8], [12], [13] (see also Fig.1). If there is a clear intention of what should be adapted – which is usually the case – we speak of *specific adaptability*. If adaptability should be a *general* property of a system, the parameters of adaption are not yet defined. A further distinction is in who the adaption performs. *Design Adaptability* (also called producer adaptability) refers to adaptations within the design of a product. Like this, the similar design with some modifications will be used for various products. *Product adaptability* (also called user adaptability) refers to the ability of a product to be adapted by the user in the form of a physical change. Hashemian [12] describes user adaptations as either the customizing or upgrading of a product or the combination of several functions within a versatile product.

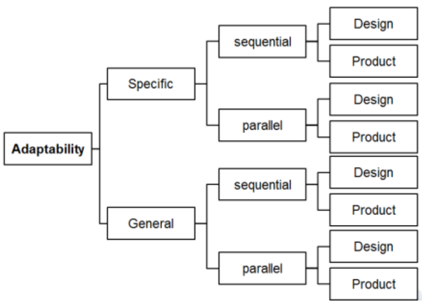

Figure 1. Characterization of Adaptability [12]

Additionally, Hashemian [12] distinguishes *parallel* and *sequential adaptations*: a parallel adaptation extends the scope of applications of a design or a product. A reconfiguration is usually reversible and should be as simple as possible for the user (compare a blender [8]). Sequential adaptations are not necessarily reversible but are conducted in order to equip the design or the product with the most modern available technology.

Design for Adaptability is a topic intensively **discussed in literature** since several years [7], [8], [10], [12], [14–18]. Adaptable products are considered to better fulfill stakeholders' needs and have longer life time due to their upgradeability[10], [19]. A product that features adaptability can – in theory – easier be updated in a way that it delivers utmost value to the stakeholder. Therewith, also the lifetime of the product can be enlarged. Adaptable design helps the manufacturer to modify or reuse existing designs more efficiently to provide a variety of products on the markets [8].

Some authors describe **approaches to DfA**. We found several approaches to quantify adaptability [7], [8], to improve systems on an architectural basis towards more adaptability [10] and to systematize different types of business cases for adaptability [12], [14]. **However**, in order to design a life-cycle property like adaptability into existing systems, the three aspects of (1) clarifying the business case of an adaptation, (2) analyzing the system towards its adaptability, and (3) deriving measures to improve the adaptability must be consolidated in a sound methodology. Therefore, we propose the central question of this paper:

> *How to proceed to specify systematically the adaptability in terms of the business case and the system in focus, analyze the system, assess the adaptability and derive measures for improvement?*

The **goal of the paper** is to propose a proceeding to improve the adaptability of *existing systems* in terms of the individually underlying business cases. This proceeding should be exemplarily illustrated at hand of a mechatronic system – the braking system of an electrical kart. In the context of the EU-funded research project AMISA – "Architecting Manufacturing Industries and Systems for Adaptability" – we observed this need for a systematic procedure for DfA among our project partners operating in various branches, i.e. automotive, aerospace, manufacturing equipment, packaging, optical engineering, and communication technology. The results of this research will then be further transferred to the industrial cases of the AMISA project in a future step that is not part of this paper. The aspects of optimizing Option Costs and Upgrade Costs with regards to the Option Value is further investigated in [20], but also not in scope of this paper.

We will explain the steps of our methodology at the hand of the **braking system of an electrical kart** (ekart) that was developed at our institute for an electrical kart formula. The example should support the understanding of the proceeding even if the methodology itself should qualify to support different business cases of DfA. Fig. 2a and 2b show the ekart and the subsystem in focus.

Fig. 2a Electric kart

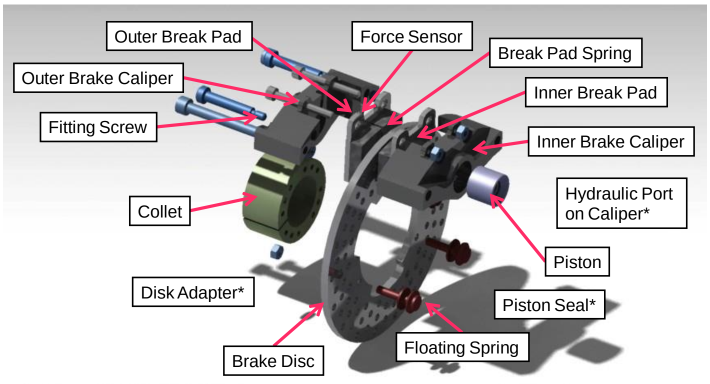

Fig.2b Components (partly) of the braking system

The first **step of our methodology** is the understanding of the business case and the formulation of the problem statement. In the following section we introduce the analysis step to spot potential for improvement. The deduction of measures to improve the adaptability of a system is highly dependent on the individual business case. The steps of the methodology are illustrated at the example ekart. The results of the braking system are discussed in the ensuing section. After that, we give a conclusion and outlook.

Methodology

Aim of our methodology is to provide guidance how to navigate through all necessary steps to design a system (more) adaptable. We adopted and consolidated several ideas from literature in our approach [7], [8], [10], [12], [14–18]. We assume that an *existing* system S_0 should be transformed in a system with a new desired amount of adaptability S_{ad}. The **basic idea of our approach** is illustrated in Fig. 3. The system has to be examined on a more abstract architectural level purposefully and systematically. Therefore, we need to analyze the dependencies and influences on adaptability of system entities in terms of the underlying business case.

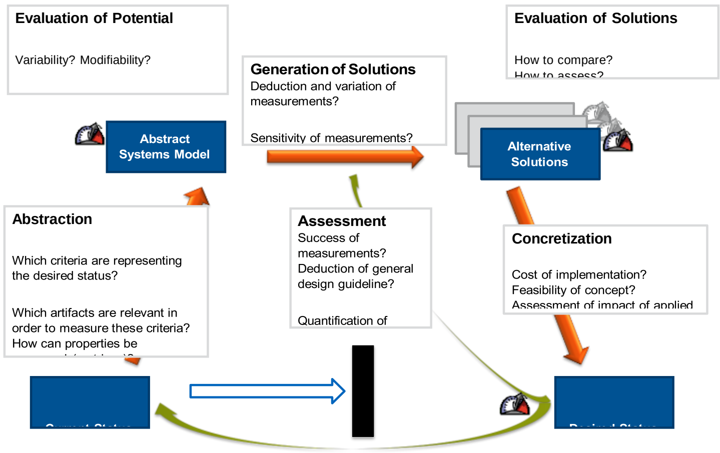

Figure 3 Concept of Designing Life-Cycle Properties on an abstract architecture level

The **blurry task of improving non-functional requirements** towards system life cycle properties – like adaptability or other “ilities” – can only succeed when the applied business case is clarified, the right entities and relations of a system are chosen for analysis and – in the end – the main drivers for adaptability are identified. Having modeled the system appropriately on an abstract architectural level, criteria and metrics have to be determined to assess the adaptability of the system. On this abstract level, structural characteristics in the system model can be identified and analyzed to clarify which aspects facilitate adaptions and which exacerbate these. From there, we can start to develop systematically solutions for a new system set-up, which exhibits a higher degree of adaptability. This set of alternative solution has to be evaluated in terms of the value of this adaption for the stakeholder (option value), the costs for adaptability (option cost) and costs of possible adaptations (upgrade cost). After the evaluation, the best solution can be implemented in the system and a final validation of the measure be done. Here, we want to present three steps of how to clarify the business case, to analyze the system, and to derive measures to improve the adaptability of the system.

Clarification of the business case

It is essential to clarify the business purpose of designing adaptability into a system in a **problem statement**. In the previous section, we discussed different types of adaptability: design or product; general or specific; parallel or sequential. In the problem statement, it should be apparent from the formulation:

- *Who* should profit from the adaption to what extend and who should perform the adaption: the user, the manufacturer, or even another stakeholder?
- *What* should be adapted or is the purpose to design for general adaptability?
- Should the adaption be *reversible* or should it be *irreversible*?
- *When and how often* should the adaptions take place? *How likely or how frequent* is the case of an adaption?

The need for an adaptable design could arise from various reasons. The clarification of the problem statement should be discussed intensively with the stakeholder of the adaptation use case. To give an example of the ekart for a resulting problem statement:

> "*The ekart should participate in different competitions with differing rules for the braking power. Therefore, the technicians in the team should be able to adapt the rear brakes to different set-ups with different amount of brake power reversibly with little effort. This is a specific, parallel product adaptability. The frequency of adaptations is two times a year. The effort should be minimized by easy replacement at pre-defined interfaces. Where in the product should these interfaces appear and how do they have to be designed properly?"*

In the best case, a problem statement contains information about the agent, the mechanism, the effect of an adaption and possible system elements that are affected. Ross et al. [4] explains these three aspects of a change as the following:

- The *change agent* is the instigator for the change, e.g. human beings, software or Mother Nature (*here*: the technicians of the team).
- The *change mechanism* is the way, or path, how the new state is reached (*here*: replace).
- The *change effect* is the difference between the original and the new state (*here*: the difference between two settings of the rear brakes).

In terms of our study, we complement this list with the ***adaption artifacts***. These are the components of the original system, which are directly affected by an adaption and other (external) artifacts, which are introduced in the process of adaption. In our case, we cannot define the adaptions artifacts yet. Before that, we need to model the braking system to identify which elements are affected by the adaptation.

In order to classify **change mechanisms** of all possible adaptions, we propose to define elementary mechanisms of adaptions. Koller & Kastrup [21] describe elementary functions for energy, material and signals turnover. Adaptions of a system can be affiliated to these elementary functions. When a system gets adapted, its artifacts (tech. components or software) can be *attached, detached, transformed, scaled, merged,* or *separated*. We define these elementary adaption mechanisms as the following:

- *Attach* means to join together the original system with a new component or sub-module.
- *Detach* means to remove completely a component or sub-module from the original system.
- *Transform* means to give a component or sub-module a new property.
- *Scale* means to change the value of a property of a component or sub-module within a pre-defined range of values.
- *Merge* means to conflate two or more existing components into a new sub-module of the system.
- *Separate* means to cut off one or more existing components from a sub-module of the system.

Of course, to reflect real-life adaptions these elementary adaption mechanisms have to be combined to mechanism sets. In our example, if one brake set-up should be *replaced* by another one, the elementary adaption mechanisms detach and attach can be combined. Or else, if the modularization of a system should be *restructured*, the mechanisms merge and separate can be applied.

Analysis of the system structure

In contrast to other papers, which quantify adaptability of whole system (e.g. [16], [17]) we believe that each individual business case calls for **distinct modeling** of the system in focus. The leading question when modeling the system must be: What are relevant system entities and relations that have to be modeled in order to derive answers to the problems stated in the beginning? Also the boundary of the system in focus can be adjusted accordingly.

For the ekart braking system, we propose as a set of entities and relations given in the following meta-model (see Figure 4a). Dependencies between the components were recorded, whether they are spatial, information, energy and material interfaces. Also the mapping between components and functions was depicted. These dependencies can represented in a Multiple-Domain-Matrix (MDM) [22] or in the corresponding graph as shown in Fig. 4b. Depended on the problem, the system modeling can be complemented by further aspects of the system (e.g. additional entities, attributes, system dynamics, cause-and-effect-networks etc.).

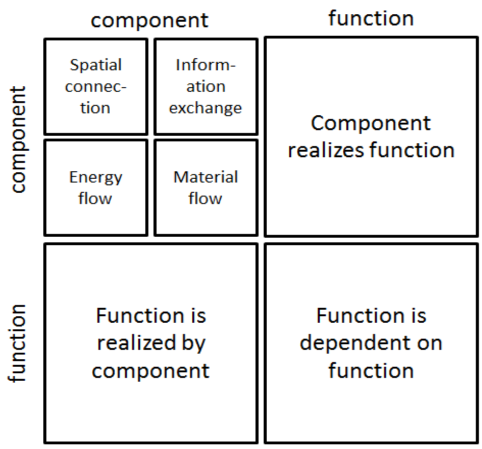

Figure 4a Meta-Model for the basic system model

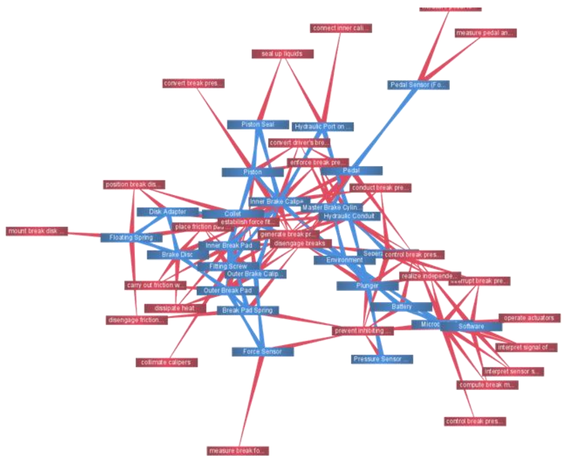

Figure 4b correspondig graph of Components (blue) and Functions (red)

These **structures of the systems** can be evaluated component- and system-wise. As the evaluation builds upon individual system models, we see again the need to customize the choice of meaningful metrics to derive adequate solutions. Therefore, we do not propose an enclosed set of metrics to be calculated, but present a choice of possible metrics from literature, which can be raised.

Some authors provide concepts to **quantify adaptability** as a system factor (e.g. [17]). This factor – suggested as one dimensionless figure with a value range from 0 (non-adaptable) to 1 (ideally adaptable) – should enable the designer, e.g., to decide between two or more systems which is the most adaptable one. Even though, the simplicity of such a factor is quite charming and especially the way to calculate this figure was very inspiring to us, the significance of this figure is rather low and can give guidance in only few problems. We believe that the use of a set of criteria can support the decision process in this multi-dimensional problem more sustainable.

Thus, we want to refer to the **criteria of adaptability** and propose a set of metrics which could – but do not have to – be applied in this phase of the process. In literature, there exist a list of approaches how to quantify these criteria (e.g. [16], [17], [23], [24]). To make adaptability measurable in context of the business case, we generate criteria categories that express the contribution of adaption mechanisms to the effort of an adaption. Quantifiable criteria are the *impact* of an adaption, the *compatibility*, and the *complexity* of the adaption artifacts.

When the system is adapted, the delta between the original S_0 and the adapted system S_{ad} is called the change effect. Adaption mechanisms can have an **impact** on the functionality, the behavior, and the structure of the rest of the system. Therefore, we formulate the first assumption: *The more impact an adaption mechanism has on the system, the more effort it cost to perform this change.*

Possible metrics should express to what extend the rest of the system is affected by the adaption mechanism. They should quantify the impact and propagation of an adaption on the overall system. As exemplary metrics, Clarkson et al. [25] provide methods to calculate and analyze change propagation in system networks. Also Kissel et al. [26] suggest a figure for structural robustness of the system, when a change occurs.

The **compatibility** of the adaption artifacts describes the interconnectivity, interaction, and the interdependency of the artifacts altered after the adaption. It has to be checked, if the system behavior after the adaption is still desirable or if further engineering effort has to be done to restore the functionality of the system. Hence, our second assumption is: *The less compatible the adaption artifacts interconnect, interact, and interdepend, the higher is the additional effort to restore the functionality of the system.*

The idea of examination the compatibility of the adaption artifacts is to check if the system still works properly after an adaption. For this criterion both could be considered a qualitative analysis and a quantitative evaluation. **Qualitatively**, a cross-check of the affected adaption artifacts and the system could to be performed. Therefore, it has to be evaluated if the functionality of the overall system is still given or has even improved after the adaption. Furthermore – dependent on the adaption mechanism – it has to be examined if the adaption artifacts can interconnect and interact properly when a new component is attached or if an interdependency of two or more adaption artifacts is given when, e.g., a component should be detached. According to the results of this qualitative analysis, the effort for recovering the system functionality can be estimated. A good indicator is to analyze to component-function mapping (Fig. 4b). When two or more components realize a function, it can be expected, if one of these components should be detached or replaced, that there is considerable engineering effort required to restore the functionality. Further insights can be achieved when indirect dependencies are calculated according to Lindemann et al. [22].

To **quantify the interconnections, interactions, and interdependencies** in the system and the adaption artifacts Shao et al. [9] define calculation methods to asses (1) independency of functional parameters, (2) independency of functional modules, (3) interface adaptability, and (4) the performance of adaptable requirements. They further combine all these aspect into an adaptability figure for the overall system. Fletcher et al. [16] do something similar by quantifying a physical interface parameter, a physical interaction parameter, a functional interface parameter, and a functional interaction parameter with weighting factors. Also, these factors are further summarized in a metric that quantifies the adaptability of a system. Sosa et al. [23] suggest a metric to quantify the modularity of sub-systems and components.

The **complexity** of the adaption artifacts can be expressed through the relations to adjacent artifacts and the embeddedness in the structure. The dependencies can be various – be it physical (e.g. spatial interface between to components) or logical (e.g. via common functions). Highly linked artifacts in a system structure require substantial more effort to adapt, because related adjacent artifacts have to be considered when changes occur. Consequently, we formulate the third assumption: *The more inter-linked an adaption artifact is, the higher is the effort to cross-check affection ofv adjacent artifacts in the dependency network.*

Looking into graph theory, we find a set of **structural metrics** that can be interpreted in terms of adaptability. An easy to measure metric is the degree of a node (which can be for example the outer brake caliper of the braking system). The *degree* is the number of [weighted] edges (relations/dependencies). The higher the degree, the more dependencies – ergo – the higher is the effort of adaption. Admittedly, it is a rather simplified metric, but could help as an initial orientation.

If we want to express in numbers how easy it is to assembly or disassembly a component, the *path centrality* is a factor, which can be interpreted in this way [24]. The more central a nod is positioned in a network, the more effort it takes to disassemble this nod.

The *cluster coefficient* of a nod [27] expresses its changeability in a network. The higher the cluster coefficient is, the more constraint can be expected, when the node has to be changed

[24]. In addition, the *number of cycles* could be used as an indicator how difficult the planning of an adaption can be [24].

Let us assume that in the **case of the ekart** the team wants to replace reversibly with little effort two set-ups of braking systems with different braking power. One set-up with smaller brake power has one breaking piston. The more powerful one should have two pistons. When we look at the function of "establish force fit between chassis and wheel" and all components realizing this function (Fig. 5), the question is: Which component can be adapted with little effort? This will be further discussed in the discussion section.

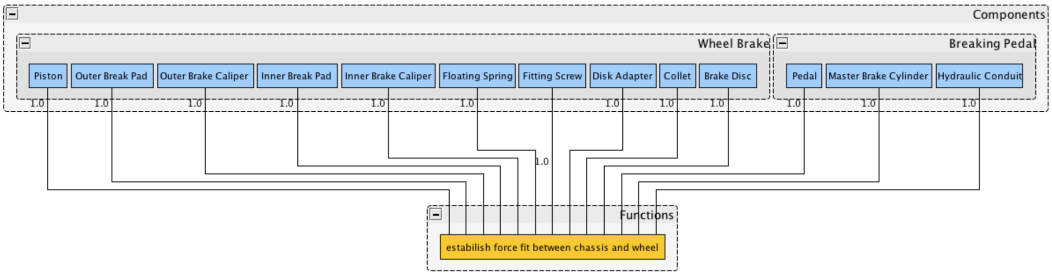

Figure 5 Concept of Designing Life-Cycle Properties on an abstract architecture level

Potential for Improvement and Deduction of Measures

Based on the results of the analysis improvements can be derived respectively. By an in-depth analysis of each factor of the applied metrics, it becomes clear which parameter to reduce or to improve. E.g. it has to be verified, if critical dependencies of an adaption artifact can be mitigated or deleted. Furthermore, in a sensitivity analysis, one can develop a better understanding of which factors are the main driver for adaptability. Additionally, it enables the designer to estimate, if a factor exhibits a linear increase when it gets changed and what influences it has on the others.

These main drivers have to be evaluated thoroughly in terms of the underlying business case. With this understanding, measures can be defined. A systematic variation of measures can be applied to further produce some alternative solutions on an abstract architectural level. These solutions can then be assessed, compared, and selected in terms of the chosen criteria. When a solution is selected, the feasibility has to be checked, whether the abstract concept can be transferred to a real-life implementation in the system (compare Fig. 3).

It seems advisable to qualify if the measures applied to the real-life system are of visible avail. Therefore, we propose to perform a delta evaluation of both the real original system and the new physically adapted system. Leading questions may be, to which extend did the property of the system change? How can the change be quantified?

Discussion

When we look at the example of the braking system, we see a highly *encoupled design* which means many components share different functions. Therefore, it is quite difficult to perform adaptions in a system like this. We decided to calculate exemplarily degree, path centrality, cluster coefficient, and number of cycles of all components affected by the change (see Table 1) in order to analyze which component has the most potential for being adapted with little effort. An easy way to add another piston is to provide space in one of the brake calipers. The high degree of the inner brake caliper indicates many dependencies to other system elements that have to be considered when an adaption should be done. Also the path centrality is considerable higher than that of the outer brake caliper as well as the number of cycles. It can be seen also in the design that the disassembly of the inner might cause more effort than of the outer brake caliper. But from a change of the outer brake caliper more constraints of its neighbors can be expected (indicated by the cluster coefficient). Nevertheless, in the case of adapting the outer break caliper the number of adaption artifacts seems to be manageable (Fig.

6). For further analysis, it would be interesting to analyze the option and upgrade costs of both components to support the decision making process.

	Degree	Path Centrality	Clustering Coefficient	
Brake Disc	8	36	0,167	287
Collet	4	38	0,000	263
Disk Adapter	6	24	0,333	264
Fitting Screw	8	0	0,500	233
Floating Spring	4	0	1,000	132
Inner Brake Caliper	14	212	0,190	322
Inner Break Pad	10	48	0,200	275
Outer Brake Caliper	7	28	0,500	211
Outer Break Pad	10	16	0,200	280
Piston	6	0	0,667	114

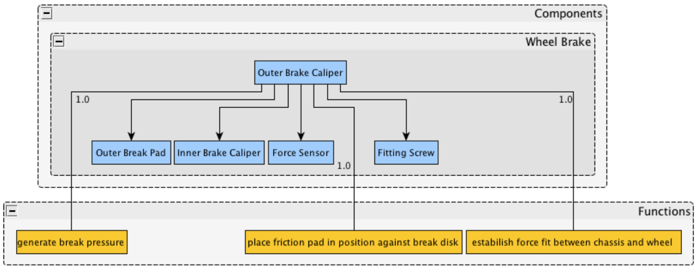

Table 1 Degree, Path Centrality, Cluster Coefficient and number of cycles

Figure 6 Neighborhood analysis of the outer brake caliper

Of course, this exemplary analysis is limited to a moderate complex system. It should visualize the proceeding and give an impression of how results can be derived. This approach is limited in its strength to the right application. Competing DfX-approaches can be reflected in a constraints modeling. Or, this approach can be further developed in the direction of Pareto-frontier optimization.

A critical aspect – that was not focal in this paper but is considered in further work of the AMISA consortium – is the aspect of costs. Hence, it should be reflected what the value of an adaption for the stakeholder is, what can be invested today (option costs) to provide the option but not the obligation to perform an adaption in the future under certain costs (upgrade costs)[10], [20].

Conclusion and Outlook

We presented a customizable methodology to assess adaptability of systems and derive potential for improvement systematically. The proceeding was illustrated at the example of a braking system. The proposed methodology will be further validated in six individual case studies at the industry partners of the AMISA project.

Acknowledgments

Partial funding for this research work was received from the European Commission: project AMISA (Call identifier: FP7-NMP-2010-SMALL-4, Grant agreement: 262907). More information about the AMISA project is available at Website: http://www.amisa.eu/.

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