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PRODUCT ARCHITECTURE DESIGN AS A KEY TASK WITHIN CONCEPTUAL DESIGN

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1. Introduction

The conceptual design stage is characterised by two main issues: Firstly, the task has to be clarified by analysing and interpreting intention, goal, needs, user behaviour, markets, etc. Secondly, based on the defined requirements, concepts have to be elaborated giving as much detail as possible to evaluate their suitability regarding both realisation and success of the product [Andreasen et al. 2015].

Thus, in the process of conceptualisation, the designer starts with an abstract, solution-independent description of the product and concretises the product idea subsequently by creating product models like function structures, working principles, function carriers, etc. [Roth 2000]. The concepts worked out define the main properties of the product (functionality, utility, costs, etc.).

The more complex the development task given, the more necessary it is to structure and decompose the design problem. Working with smaller tasks enables the designer to proceed in the conceptualisation, for example, by finding partial solutions for sub-functions. Later, the product is composed of the partial solutions. In this process, the product architecture is defined, which describes the allocation of product functions to physical components including their interactions [Ulrich 1995]. For instance, a modular product architecture is formed when specific functions are implemented in separated modules, e.g. to enable variety by replacing modules. In contrast, functions could be integrated, meaning that one physical component realises multiple function, resulting in a more compact design or lower production costs. The decisions made for product architecture have a great impact on companies success such as customer satisfaction, efficiency or strategy [Yassine and Wissmann 2007], [Richter et al. 2015].

To support product architecture design, various methods exist. Set up with a specific purpose ("Design for X"), these methods often focus on the design of particular architectures, for instance, modularity for changeability or integration for compactness. However, at the beginning of the development task, the effects of the product architecture design are not clear and decisions on methods to use is difficult. As a result, important effects are not considered and non-optimal concepts are created. Thus, the main question to be addressed in this paper is: How can the designer's understanding of the effects of product architecture be increased in order to elaborate a suitable concept for design task at hand?

To answer this question, in chapter 2 the challenge of product architecture design and the range of its effects are described using the example of a ball pen. In chapter 3, existing methods supporting product architecture design are analysed regarding their main goals. Based on the findings, in chapter 4, a framework for product architecture design is proposed to emphasise the connection between effects of product architecture design and product models representing these effects. In chapter 5, application scenarios for the framework are presented. Chapter 6 summarises the achieved results and gives an outlook on further work.

2. Product architecture design in product development

Since the term product architecture (PA) is not used consistently in literature, an example is introduced in the following section to create a common understanding and to emphasise its importance in product development.

2.1 Definition

The product architecture is a model to integrate two viewpoints of the product: the functional and the physical [Ulrich 1995]. The functional view is described by function structures, which arise due to the decomposition of the overall product function into sub functions and their interactions, for instance regarding energy, material and information flows. The physical view describes the product structure, which includes all physical parts of the product as components, assemblies as well as their interfaces.

An example for a product architecture for a ball ben is given in Figure 1. On the left side, some functions of a ball pen are represented such as "enable ink application", "hold in hand" or "attach to paper, shirt pocket, etc.". These functions are realised by physical parts on the right side such as "pen refill" does for "enable ink application" or "top-housing" does for various functions ("polyhierarchical linking" [Roth 2000]).

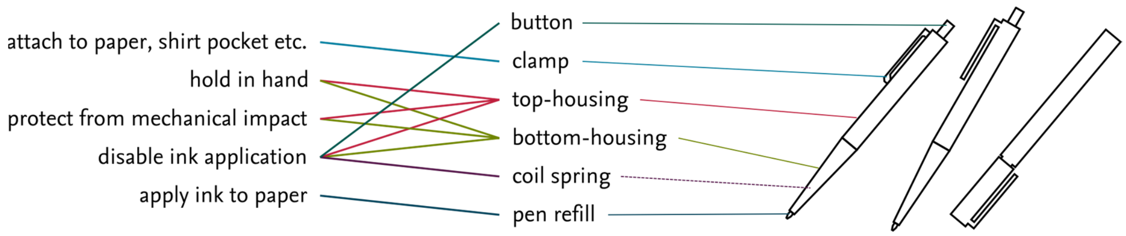

Figure 1. Example of the product architecture of a ball pen

Obviously, this functional structure is just one possibility of many, since functions could be aggregated in another way or split up for more detail [Erens and Verhulst 1997]. Hence, functions with various connections to components could be decomposed further.

2.2 Basic principles for product architecture design

When designing the product architecture, two general possibilities arise: functional integration and modularisation, which are often referred to as “conflicting requirements” [Erens and Verhulst 1997]. Integration means that one component fulfils more than one function (see "top-housing" of the ball pen). Superior goals of functional integration is a reduction of the number of parts or an extent of the number of functions while sticking to the number of parts [Ziebart 2012]. Moreover, in some cases costs could be saved, mounting be simplified or weight be reduced.

Modularisation, as the second basic principle, aims at clustering the functions into modules while minimising the coupling among the modules and maximising the cohesion within the modules [Fricke and Schulz 2005]. Reasons for modularisation are various and could be described by module driver focusing on the whole product life cycle [Blees 2011]. With regard to the example of the ball pen, the "pen refill" is realised as an independent module in order to enable easy replacement.

Since the example in Figure 1 is just one possibility for the ball pen's architecture, many variations are possible – and could be found on the ball pen market. For instance, the clamp could be manufactured as a part of the top housing (see Figure 1, pen in the middle). This does not change the principles to realise the functions, but it does change the product architecture. Furthermore, variations could be made on more abstract levels: If the function "disable ink application" is fulfilled by a tap (with integrated clamp, see Figure 1, pen on the right), the principles are changed. Thereby, the number of parts and the geometrical complexity of the parts could be reduced significantly.

2.3 Effects of product architecture on the success of the company

As the example of the ball pen illustrates, the product architecture has a wide range of impacts on the product development – or, in more general, a company's success. Often, the success of a company is described by cost, time, and quality. In the last years, this point of view has changed and factors like service, flexibility and product diversity have become more important [Kaluza 2005]. Based on these general factors and an analysis of aims of existing methods to support PA design, an effect model to describe different areas of effects of PA design has been derived from established literature like [Ulrich 1995], [Andreasen et al. 1996], [Ericsson and Erixon 1999], [Yassine and Wissmann 2007], [Renner 2007] and [Ziebart 2012] see Figure 1.

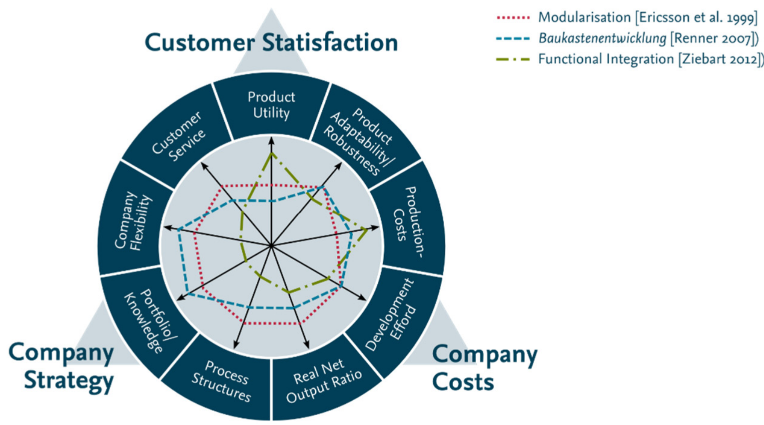

Figure 2. Effects of PA design and classification of methods (radar chart), cf. [Richter 2015]

The factors in the top of the depicted triangle – service, product utility and adaptability/robustness – contribute to the main goal customer satisfaction. Thus, product architecture influences, for instance, the utility of the product through higher compactness or increased changeability through modules. Adaptability and robustness become more important, facing the challenge of varying requirements and product properties during use. This could be addressed with modular structures for higher adaptability or more integration contributing to robustness. The service could be improved, for instance, by enabling the replacement of worn or damaged parts.

The other two main goals, company strategy and company costs, focus on organisational aspects of product development. Thus, from the view of the company strategy, a product architecture geared to long-term design could raise the flexibility, as products are not only developed for specific customers, but also under consideration of possible upcoming demands of future markets. In the same context, the product and knowledge portfolio is strongly determined by product architectures, for instance, due to the configurability of products by the help of modular product systems (German: Baukasten). By modularisation, process structures could also be addressed, for instance, if assembly steps are considered defining component interfaces.

Company costs are directly affected by costs of product production and development. Product architecture could contribute to this, for instance, if high integrated mechatronic solutions required an expensive interdisciplinary design, although the solutions could be manufactured from lower-cost standard parts. In addition, the composition of the product affects decisions on the real net output ratio, as the possibility of outsourcing depends on the subsystems dependencies.

3. Methods for product architecture design

While in the previous chapter the design freedom regarding the definition of the product architecture and different areas of impact was discussed, this chapter focuses on the support of the designer. Based on two hypotheses about the lack of existing methodical support, an overview of methods is given, leading to needs for the development of a new method to support PA design.

3.1 Aims and focus of methods

The preceding step to create concepts for individual problems is to get a deeper understanding of the task at hand [Andreasen et al. 2015]. Thus, considering the product architecture as a key lever to find

optimal concepts, its role in development has to be clarified. Often, modularity or integration are defined as starting points for the conceptualisation although its underlying reasons are not identified.
However, a closer analysis of methods points out that the aims of methods of modularisation (e.g. [Ericsson and Erixon 1999]), building block concepts/"Baukasten" (e.g. [Renner 2007]) and functional integration (e.g. [Ziebart 2012]) are similar, yet have different focuses (see Figure 2, radar chart). While aims of the modularisation example are very wide-ranged, "Baukasten" development focuses more on the company strategy and functional integration mainly addresses customer satisfaction and company costs. This leads to the first hypothesis for future work:

Since the effects of product architecture design are wide-ranging, an integrated understanding of these effects is necessary in order to support product development.

The second hypothesis is based on the fact that PA design is related to the whole concretisation process in conceptualisation implying the allocating of functions to physical parts of the product. To describe this process, five levels of PA design are defined based on established approach of product development, see Table 1.

Table 1. Definition of levels of product architecture design

Level	Information provided by product models	Example
Functions	Teleology of the objects, i.e. what it is for. [Gero and Kannengiesser 2004]	Apply ink to paper
Principles	Principles from which an effect to fulfil a function could be derived [Pahl and Beitz 2007]	Roll ball pen principle
Function Carriers	Technical elements to fulfil a function [Pahl and Beitz 2007]	Ball, ball housing, ink reservoir
Components	Individual physical parts from which the system could be assembled [Hubka and Eder 1988]	Metal ball, pen tip, tip socket, reservoir, end piece
Modules	Decomposition of a product into building blocks with specified interfaces, driven by company-specific strategies [Ericsson and Erixon 1999]	Pen refill

These levels of PA design bring a deeper view into PA design. Since every product could be described and structured on each of these levels, the product architecture is defined by the structure of the elements on each level and the allocation between the levels (for instance, components to modules). In this way, the question of modularisation or integration has to be examined and answered between each of the levels. Taking this into account, the following hypothesis serves as a basis to examine on which levels methods for PA design focus:

Product architecture design is a key challenge of conceptualisation and has to be considered explicitly in each stage of concretisation from functional modelling to the composition of the physical product.

In section 4.3, the levels defined will be described in more detail as key element of the proposed framework to identify appropriate methods supporting allocations of product models between the levels.

3.2 Method classification

The literature dealing with product architecture design is wide-ranging. In this paper, a short overview of methods and their analysis regarding the stated hypotheses is presented. The aim of this study is to motivate the main idea for the development of the framework presented in the following chapter. In chapter 6 it will be discussed whether and how a further literature study has to be conducted.
Table 2 gives an overview of the methods including their main goals and a classification of their coverage of considered effects and levels of PA design. It can be seen that the methods consider different

effects of the presented effect model (Figure 2) and different product models from the defined levels of PA design (Table 2).

Table 2. Evaluation of methods for product architecture design

Method	Main Goal		Aims			Level				
		Task Clarif.	Cust. satisf.	Comp. Strat.	Comp. Costs	Functions	Work. princ.	Funct. carr.	Components	Modules
Principle variation [Köckerling et.al. 2003]	max. principle exploitation (by integration)	◑	◑	○	●	●	●	◑	○	○
One-piece machine. [Ehrlenspiel 1995]	reduce number of parts (by integration)	◑	◑	○	●	○	○	◑	●	●
Integration of work. princ. [Roth 2000]	reduce number of parts (by integration)	○	◑	○	●	○	○	●	●	○
Modular funct. deploym. [Ericsson et.al. 1999]	life cycle optimisation (by modaulrisation)	●	◑	●	◑	○	○	○	◑	●
Design structure matrix [Eppinger et al. 1994]	reduce complexity (by modularisation)	○	○	●	◑	◑	○	○	◑	●
C&CM Dependency Matrix [Albers et al. 2007]	reduce complexity (by modularisation)	○	○	●	◑	◑	○	●	○	●
Variety oriented design [Kipp 2012]	reduce product family variety (*Baukasten*)	◑	○	◑	●	●	●	○	●	○
Funct. orient. *Baukasten* dev. [Renner 2007]	reduce company complexity (*Baukasten*)	●	○	●	◑	◑	○	○	◑	●
Baukasten dev. [Pahl et al. 2007]	reduce product variety (*Baukasten*)	◑	○	●	◑	●	◑	○	○	●

● focus of consideration ◑ considered to some extend ○ not/little considered

Although the demarcation is not clear, the methods could be clustered into three groups perusing similar targets:

The first group contains methods aiming at integration. The focus of these methods is on cost reduction by reducing parts through a re-definition of the physical design or by re-using principles of function realisation. However, the methods focus on different levels and could optimise function structures, working principles, function carriers, components and modules.

The second group of methods is based on the principle of modularisation, with a focus on company strategic goals by creating modules or cost reduction by minimising variety of functions, working principles and components. The considered levels reach from functions to reduce functional variety up to modules to decompose products. The approaches always take, besides the prouct, the process of development, production etc. into account.

The last group of methods focuses on developing a concept of building blocks (Baukasten) to create different variants. These approaches focus on the variety of functions to be structured for a suitable allocation to building blocks, i.e. modules. However, in contrast to methods of the second group, the focus lies on the product view, not on the processes.

The analysis of existing methods confirm the hypotheses stated above. On the one hand, it is shown that the aims of existing methods vary widely; the full range of effects shown in Figure 2 is rarely covered by a single method. Furthermore, most of the approaches focus on integration or modularisation, but do not include both. Thereby, single methods make only use of some of the five defined levels of PA design. In this way, the solution space is limited from the beginning, and potentials for finding the best solution are not exploited sufficiently during conceptual design.

4. An integrated approach for product architecture design

Based on the identified needs, in this chapter an approach to support product architecture design is presented. In the first section, aim and area of the application of a new framework are emphasised, before its structure and application scenarios are described.

4.1 Aim and area of use

As stated before, the conceptualisation of products includes many decisions about the product, and therefore, is of great influence for the success of the development task. In order to find the optimal product architecture, the designer has to understand the effects and aims on different levels of PA design.

From these considerations, requirements for the development of a new methodical approach are derived. Thus, it has to be able to:

- explain to the product managers and designers that product architecture design is a part of every product development and should be considered explicitly during conceptualisation
- increase the understanding of the effects of product architecture decisions and avoid premature focusing on single effects only
- provide a general product architecture model to be used continuously in the process of product concretisation to integrate several product models
- facilitate access to existing methods for product architecture design to be used in the right steps in order to address specific aims of the product development

Basically, the approach should be generally applicable for product development tasks from different domains (mechanics, mechatronics, electrical etc.) and types (original, re-design, variant) as it is entitled to consider the whole range of effects of the product architecture. Since the framework is described very generically in this paper, it could be applied to different kinds of development projects. However, in a first step, the main focus for the approach is to deliver methods for small and medium sized enterprises that often do not know about the variety of methods for product architecture design and are not able to choose a suitable approach for their individual development tasks at hand. Thereby, it has been applied to products or subsystems of low complexity.

4.2 Framework

As defined in the second hypothesis, the main decisions of product architecture design could be described as arrangements of elements on the five levels defined (see section 3.2.). On each of these levels, product models are developed containing solution elements as functions, working principles, etc. as well as their structure and interactions. These product models provide the basis for methods of product architecture design. The main approach of the framework for integrated product architecture design is to use these levels to understand the connections of the effects of PA design and the most suitable development procedures defined through the selection of methods.

Figure 3 shows the main elements of the framework: Effects of PA design are defined through the aims of the development project, e.g. to reduce weight of a product. The frameworks provides five levels of product architecture design, on which different product models could be allocated. Connections between effects and levels are provided by product models containing suitable information about the effects. Thus, it could be decided on the most suitable development procedure, respectively, the most suitable path through the levels using specific product models and methods.

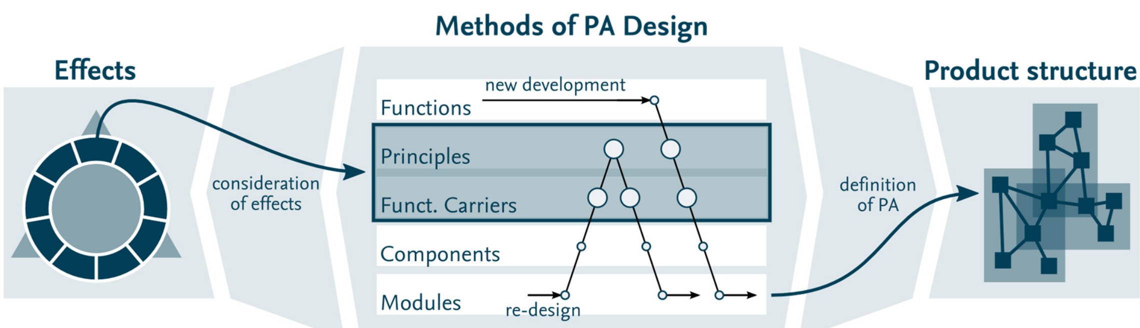

Figure 3. Levels of PA design as key element of the framework for integrated PA design

The figure shows two exemplary paths: The first path could be chosen for a new product development. It starts from defining functions and passes through all levels until the definition of modules. The framework highlights the importance of considering product models on the level of principles and function carriers, as the allocation of these elements has a great impact on specific effects of PA design. A second path, representing a re-design project with similar goals, starts with an analysis of an existing product on the physical levels of modules and passes upwards until the re-definition of the allocation between solution principles and function carriers. Afterwards, the synthesis is completed with the definition of components and modules.

4.3 Product models representing information about effects of PA design

It was shown that the selection of appropriate methods is key for a successful PA design. The levels of PA design facilitate the navigation through the development process. On each level, various product models are created, depending on the considered aspects of the product being important for the current design activity. In the following, examples of product models on the different levels are shown.

On the first level, product functions have to be derived from the product requirements. Product models are, for instance, a function list or a function structure based on flows of energy, information and materials. Some models aim directly at the derivation of solutions (cf. Function-Means-Tree [Andreasen 1980] and [Hubka and Eder 1988]). An example for a model aiming at a definition of the product architecture is the function classification after [Pahl and Beitz 2007] regarding its repetition in other product variants (Grundfunktionen), its variety (Sonderfunktionen) etc.

The goal of product models on the second level is to define principles including physical effects. For this, design catalogues could be used to identify solutions (cf. [Roth 2000]). On this level, the consideration of adjacent levels supports the optimisation of the product architecture. For instance, when working principles could fulfil several functions (cf. [Köckerling and Gausemeiner 2003]) or be realised by common function carriers.

Based on the working principles, function carriers are identified on the third level. Function carriers, in this context, are physical elements that are defined by their required behaviour that is prescribed by the working principles to be realised. Geometrical characteristics like materials, dimensions, production techniques etc. are not defined. The consideration of this level is important to define physical elements of the solution and evaluate modularisation and integration principles on an abstract level without focussing on geometrical details (cf. [Roth 2000], [Albers et al. 2007]).

Coming from function carriers, components have to be defined on the fourth level. As a component has to be a producible part, technological issues have to be considered. Through the examination of components separation (cf. [Ehrlenspiel 2009]), optimal components compositions could be defined. Currently, this step is becoming increasingly important against the background of new technologies like additive manufacturing, which provide new potentials of PA design (cf. [Laverne et al. 2015]).

Product models on the last level describe the modularisation as it is often considered as a clustering of components (cf. [Pimmler et al. 1994], [Ericsson and Erixon 2000]). Thereby, product models could represent various views on the product, for instance, phases of the life cycle (cf. [Blees 2011]).

These examples of product models describing information on the different levels of PA design highlight the difficulty in selecting suitable approaches for PA design. The framework, describing the product models and methods in the levels, should support designers to get an increased understanding of the connection between effects and design activities.

5. Examples of application scenario

The introduced framework had been developed accompanied by several industry projects dealing with re-designs or new developments of products in the fields of consumer goods, automotive engineering and industrial mechanical engineering. In each case, designers had difficulties to decide on methods to apply due to the variety of effects to be considered, although methods of PA design had been known. Examples of three of these projects are described in the following in order to demonstrate possibilities to apply the framework. In the first section, the aims of development of these projects are presented, before in the second section the proposed solutions are shown.

5.1 Development aims

The presented subsystems of the development projects are shown in the top of Figure 4, separated into three columns. From each project, subsystems have been chosen to demonstrate potentials of approaches of integration, variety reduction and modularisation.

The first example is a housing for a piezoelectric stack actuator used in an adaptive robot joint. The purpose of the piezoelectric stack is to enable the adjustment of friction in the joint during use in order

to optimise the system behaviour for specific use cases [Inkermann et al. 2013]. As it is shown, the housing consists of several parts, which are necessary to enable a rigid clamping of the actuators. The pre-stress is applied by an adjusting screw. The aim of the re-design is a reduction of parts in order to reduce cost, weight and assembly afford.
The second example is a linear guide for a drill head on the tower of a mobile drilling rig, for instance, for drilling of wells for groundwater. The rig manufacturer suffered from a high diversity of variants, as three examples are shown in the picture. Thus, some variants are based on roller glides on surface-treated rails. Others move on sliding blocks over rails. Each solution exists in different size variants. The focus of a development of a new series is a reduction of variants.
The third example is the central element of a joystick for steering forklifts. The joystick manufacturer assembles different subsystems like the shown frame of aluminium die-cast and a PCB. Both elements are developed and manufactured by specialised suppliers. Difficulties in the product development process arise through the definition of the geometric interface between the components as the PCB is connected directly to the frame by screws. The aim of development of a new architecture is to modularise the system to facilitate the development process.

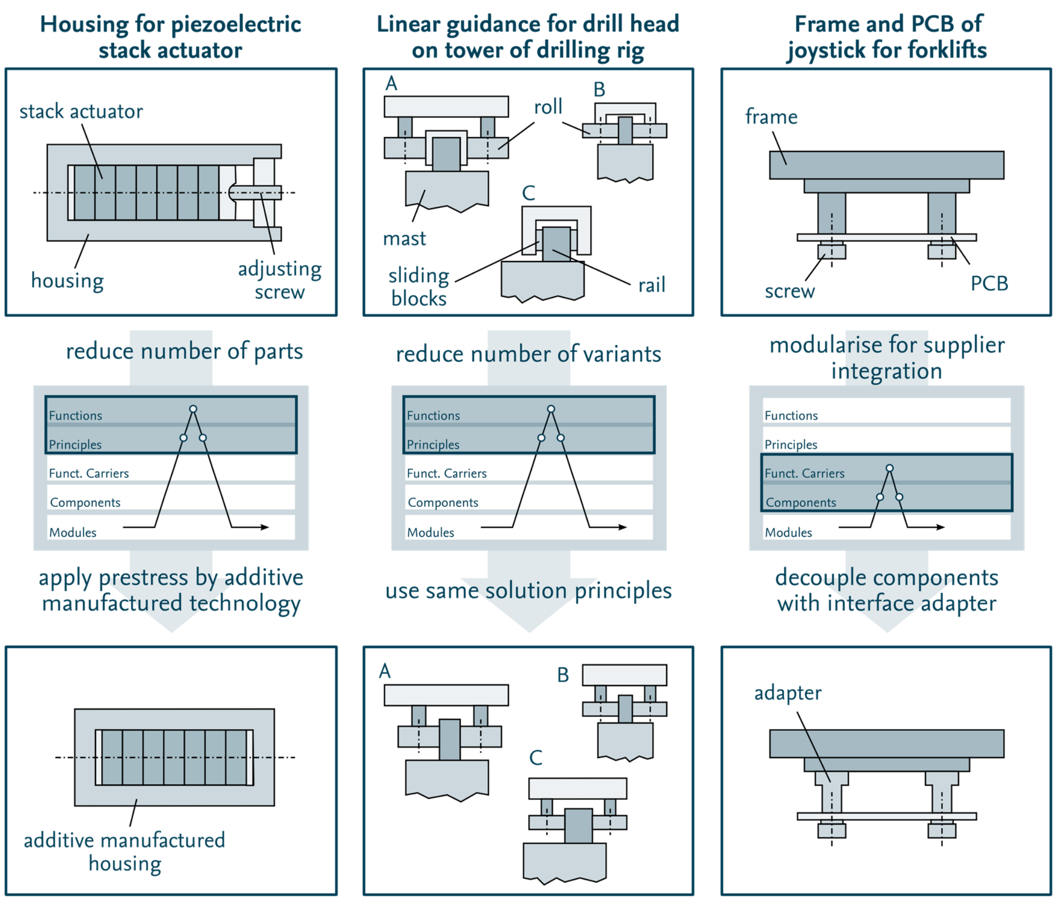

Figure 4. Application of framework to three product examples

5.2 Application of framework

Since the development aims of the three introduced projects differ widely, the development procedures also do, which is shown in the middle row of Figure 4 by paths through the introduced levels of PA design. The bottom of the figure shows a proposed new design of the subsystems.
A reduction of the number of parts of the housing for the stack actuator leads to approaches for integration. An integration could be achieved by multiple utilisation of properties of system elements to fulfil various functions [Ziebart 2012]. Thus, a variation of the product description on the level of

principles could support the product architecture design. Starting from the description of an existing solution with modules and components, the solution is abstracted to the levels of principles and functions. On these levels, with the help of the method proposed by [Köckerling and Gausemeiner 2003]), multiple effects of technologies could be identified. As result, the pre-stress for clamping the actuators could be applied by the effect of thermal shrinkage in the manufacturing process. Using this principle, the housing could be printed from one piece (cf. [Mayer et al. 2015]).

In the second example, the aim of the re-design of the guidance for the drill head is to reduce the variety in the company's product portfolio. Variety could be caused by diversification on different levels of product architecture design, for instance, on the level of principles. Analysing existing products (cf. Variety Allocation Model after [Kipp 2012]), it could be identified that variety occurs by different solution principles (rolling vs. sliding) for the same function. Thus, the first step to reduce variety is to decide on one of these principles. From this, size variants could be derived (variety on the level of components) that could be manufactured with the same manufacturing processes.

The modularity of the supplier manufactured parts of the joystick (frame and PCB) could be measured by interactions on two levels: the physical components level and the functional level ([Ericsson and Erixon 1999]). In the example, functional coupling results from the bearing function of the frame for the PCB. However, difficulties arise through the geometrically defined interface in between, which could cause time and cost consuming iterations, especially, in the development process of the casting component. To avoid this coupling on the components level, function carriers could be re-arranged to components, for instance, by the application of a Design Structure Matrix method based on working structures (cf. [Albers et al. 2007]). Thus, extra adapters could be inserted to compensate possible design changes.

6. Conclusion and further work

The aim of the presented research is to increase the designer's understanding of effects of product architecture design in order to make suitable decisions in conceptual design. In this paper, a framework was presented, highlighting the variety of effects with an effect model and its connections to activities in the design process. To describe design activities, five levels of PA design were defined to which product models could be allocated. This was stated as a basis for describing the product architecture as a connection between product models on the different levels.

As the analysis of existing approaches has shown in chapter 2 and 3, the effects to be considered in PA design are well known and are addressed by established methods. The main issue is that methods often consider specific effects only, which could be explained due to the fact that specific basic principles (integration or modularisation) are applied and specific design activities are supported working with product models on few of the defined levels of PA design. The proposed framework should increase the transparency for the designer of possible approaches, considering specific product models – knowing full well that it is not possible to apply a large number of methods.

What the framework does not provide up to this point is an overview of specific connections between effects of PA design and product models on the defined levels. In industry projects it had been shown that the framework itself supports orientation, but the selection of product models was finally based on experience of the persons introducing the framework to designers. Thus, an important next step is to conduct an extensive literature review on product models describing effects of PA design on the defined levels. Results should be a catalogue providing a classification of development goals allocated to the effect model and its correlation with product models. As this catalogue will contain a diversity of cross connections, the first approach is to build up a graph database.

This step should be followed by the development of an applicable method presenting the framework's content to designers in an appropriate way. It should contain support for the identification of development goals with an extended effect model containing explicit descriptions of the effects. On this basis, a tool have to be created to make it possible to identify suitable product models for specific effects. This should contain appropriate descriptions of the proposed product models to enable the designer to make decisions on the most suitable approaches for individual requirements. Finally, it has to be ensured that different product models on the levels of PA design are connected in an appropriate way in order to obtain closed paths through the levels.

In summary, the presented work highlights the role of product architecture design as a key task within conceptual design. In order to fulfil this purpose, it is necessary for designers to obtain an extended understanding of what are the effects of decisions on product architecture design. The introduced framework is a first step towards this goal, while connections between effects and design activities (in terms of creating product models) are highlighted by a classification of product models to levels of PA design. This is the basis for next steps, in which the presented framework has to be concretisised by the elaboration of details on its elements of effects and product models and their connections.

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