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A Framework for Integrated Product Architecture Design

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Abstract

Product architecture design is a key challenge within conceptual design, effecting a wide range of development goals like adaptability, compactness, upgradability, as well as product cost and strategic aims of the company. However, existing methods for product architecture design are often facing a limited number of these effects. Thus, only specific goals are addressed, whereas others are not taken into account. A comprehensive understanding of the effects of the product architecture is not given. In this paper, an approach is presented allowing the comparison methods regarding specific effects of the product architecture as well as the product models considered. Five different levels of product architecture design are defined: functions, principle solutions, function carriers, components and modules. The application of methods describes the transitions of product models between these levels and, therefore, the product architecture. It is highlighted that existing methods only represent a limited view on product architecture design and often do not exploit the full range of design possibilities. Thus, framework is proposed to widen this view on product architecture design.

Keywords: product architecture, modularization, functional integration, conceptual design

1 Introduction

Product architecture (PA) describes the allocation of product functions to physical components including their interactions. Within the conceptual design, the designer is called to define the product architecture by structuring partial solutions of different design states such as functions, principle solutions or function carriers. Thereby, decisions on the allocation of these elements are made, for instance, by choosing a principle to fulfil one single function and integrating its function carriers into one separated module – instead of using a solution integrating various functions in one module. These decisions have a great impact on the customer's satisfaction (weight, compactness, upgradability, etc.) as well as the efficiency of the product realization (number of parts, assembly effort, etc.) and strategic aims of a company (product variety, flexibility, etc.).

However, there are various methods to support product architecture design. These methods are set up with a specific purpose (e.g. controlling variety or reducing the number of parts) and often focus on particular principles for product architecture design such as functional integration or modularization. An integrated approach addressing the wide range of effects and contributing towards a comprehensive understanding of product architecture design is missing. This results in the main question to be addressed in current research work:

How can the designer's understanding of the effects of product architecture be increased in order to make most suitable decisions in conceptual design?

To answer this question, three intermediate objectives have to be achieved:

(1) The variety of effects of product architecture design concerning customer's satisfaction, company costs and company strategy have to be analyzed in order to represent them in an effect model. First steps towards this aim have been made in previous work and will be summarized in section 2.

(2) Since principles of product architecture design proposed by existing methods are described with different product models, a comprehensive understanding of the product architecture has to be established. Therefore, in section 3, five levels of product architecture design are introduced: functions, principles, function carriers, components and modules. By means of these levels, methods for product architecture design could be classified regarding their considered information in product models and their approaches for product architecture design.

(3) A framework has to be developed supporting the understanding of relations between effects (1), levels of product architecture design (2) and methods – as an applicable behavior pattern. This ensures a comprehensive understanding of product architecture design by highlighting potentials and limitations of methods due to its considered product models. The concept of this framework will be presented in section 4.

In section 5, applicability and value of the proposed concept will be discussed and next steps towards achieving referred aims will be derived. The contribution will close with a conclusion in section 6.

2 Effects of product architecture design

The product architecture model intends to integrate two views on the product: the functional and the physical view. The functional view is described by function structures, which arise due to the decomposition of the overall function of the product in sub functions and their interactions, for instance, regarding energy, material and information flows. The physical view describes the product structure including all physical parts of the product as components, assemblies as well as their interfaces. The integrated model of the functional structure and the product structure is called product architecture (Ulrich, 1995).

When defining the product architecture, two general strategies arise: functional integration on the one hand and modularization on the other, which are often referred to as "conflicting requirements" (Erens, 1997). Integration means that one component fulfils more than one function. Superior goal of functional integration are a reduction of the number of parts or an extend 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. Modularization, on the contrary, aims at clustering the functions into modules while minimizing the coupling among the modules and maximizing the cohesion within the modules (Fricke et al., 2005). Reasons for modularization are various and could be described by module drivers focusing on the whole product life cycle (Blees, 2011), for instance, considering development processes, distribution or recycling.

These basic strategies of integration and modularization show the wide range of impacts of the product architecture to product development – or, put in a more general way, the company's success. Often, the company's success is described by cost, time, and quality. This traditional factors could be expanded, adding service, flexibility and product diversity (Kaluza, 2005). Based on this general factors and an analysis of aims of existing methods to support product architecture design, the authors of this paper have introduced a model to describe different fields of effects of the product architecture (Richter et al., 2015), derived from established literature like (Ulrich, 1995; Yassine, 2007; Ericsson et al., 1999; Renner, 2007; Ziebart, 2012), see Figure 1.

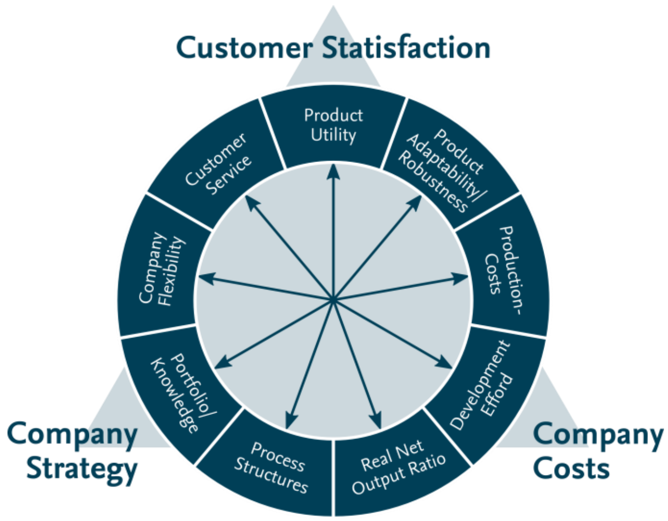

Figure 1. Effects of product architecture design on the company, cf. (Richter, 2015)

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, being addressed with modular structures for higher adaptability or more integration that could contribute towards 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 organizational 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 configurability of products by the help of modular product systems (“Baukasten”). By modularization, also process structures could be addressed, for instance, if assembly steps are considered defining component interfaces.

Company costs are directly effected by costs of product production and development. Product architecture could contribute to this, for instance, if high integrated mechatronic solutions require 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.

This effect model provides an overview of the wide range of effects of product architecture design, which will be referenced in the following sections. Obviously, it does not present a tool for task clarification or concept evaluation. Rather, it could serve as an basis for the development of a requirements model for product architecture design.

3 Levels of Product Architecture Design

As the effects of product architecture design are diverse, many methods to support the designer defining the product architecture exist with different goals (often referred to as "Design for X" methods). In this section, the focus will be on a comprehensive understanding of recurring patterns of these methods. For this, product models are analyzed regarding their role in product architecture design, and levels are derived in order to provide a basis for classifying product models.

3.1 Product models in product architecture design

Roth (Roth, 2000) describes the development process as progressing from one design state to another. In each state, product models are used containing specific information representing different aspects of the product like requirements, functions, effects and physical or logical arrangements. In order to navigate the designer through the design process, prescriptive procedure models for product development propose the stepwise creation of these product models. In Weber's Property-Driven-Development (Weber, 2007) the use of product models is described as the relation between the required properties of the product and the characteristics of the product. Thus, product models are the basis for the use of methods for analysis and synthesis.

The product architecture – combining the functional and physical view on the product – includes different product models, and is itself a product model describing the transitions between specific views on the product. Thus, methods for product architecture design (e.g. for integration or modularization) consider specific information from different product models (e.g. function structure and component structure), varying these models and defining allocations between elements of the models (e.g. allocating a function to a component). Thereby, methods support the understanding of the effects (analysis) or the determination of product structure considering the effects (synthesis).

This emphasizes the close link between product models and methods: Methods for product architecture design provide information about the product architecture and its effects in order to support decision-making. Basis therefore are product models containing a limited view on to product according the fulfilment of the method's purpose. However, in order to gain a comprehensive understanding of a method's goals (considered effects of product architecture design) product models have to be categorized regarding their support for specific design goals. For this purpose, based on an analysis of existing methods from literature, five levels of product architecture design were defined in (Richter et al., 2016). To those levels, product models could be allocated as they support the variation of classified product models and/or the transition in between. This is illustrated by Figure 2.

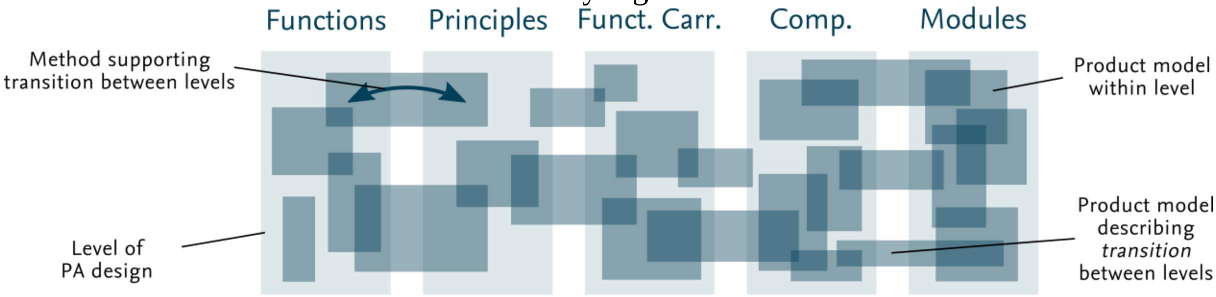

Figure 2. Product models within and in between levels of product architecture design

These proposed levels themselves are well known from established approaches of product development and are often referred to as concretization stages. However, in this context, the levels do not give an hierarchical order of stages to be passed through in one direction in conceptual design. Rather, the levels provide classes of product models that could be used at any stage, for instance, as module structures could be considered when defining functions. Table 1 gives definitions of the levels and examples of product models used within the levels.

Table 1. Levels of product architecture design

Level	**Definition of level**	**Product models within level**
Functions	Teleologies of objects, i.e. what they are for (Gero et al., 2004)	function tree, function structure, flow chart, requirements list, use cases
Principles	Principles from which an effect to fulfil a function could be derived (Pahl et al., 2007)	effect structure, mathematical expressions, principle catalogue
Function Carriers	Technical elements to fulfil a function (Pahl et al., 2007)	working structures (working surface pairs/working bodies), principle sketches
Components	Individual physical parts from which the system could be assembled (Hubka et al., 1988)	technical drawing, parts list, component tree, CAD model
Modules	Decomp. of a product into building blocks with specified interfaces, driven by company-specific strategies (Ericsson et al., 1999)	modular product system/*Baukasten*, platform system, assembly tree

Thus, describing product models with these levels is nothing new in itself. However, new is the approach, to use this levels as a comprehensive basis for describing product architecture design instead of using methods only focusing on some of these levels. Thus, in the following, methods are classified to these levels.

3.2 Classification of methods regarding levels of product architecture design

As stated before, methods are linked to product models describing the product on the proposed levels of product architecture design. The proposed action behaviors of the methods result in varied or new product models. For instance, a function structure could be varied by variation patterns („Variationsoperationen“, cf. Roth, 2000). However, the focus of methods for product architecture design lies not on the variation of product models on single levels, but on the transition between elements of different levels.

Thus, to examine the relation between methods and the introduced levels of product architecture design, a literature review has been conducted. It could be shown that analyzed methods for product architecture design
(1) consider information regarding the effects of the product architecture from product models of at least two levels,
(2) support the transition between at least two product models on different levels and
(3) in many cases, consider further information from other design states (product models on other levels or strategic aims, requirements, etc.).

Table 2 shows an extract of the literature review undertaken. Different methods with the main goals of integration, modularization and *Baukasten* development are assigned to the levels of product architecture design, between which the transition is supported. For instance, the Design Structure Matrix (Eppinger, 1994) supports the clustering of components into modules. Thereby, functional and geometrical relations between the components are considered without explicitly using models or varying solutions on these levels. In comparison, methods for *Baukasten* development (Renner, 2007; Pahl et al., 2007) focus on the allocation of functions to modules („Bausteine“) without considering the levels in between like principles, functional carriers or components. The only method listed here considering the transition between more than two levels is the variety oriented design introduced by (Kipp, 2012), that proposes an incremental approach focusing on variety of functions, (working) principles and components.

Table 2. Considered product models allocated to levels of product architecture design

Method	Main Goal	Levels of PA Design				
		Functions	Principles	Funct. Carr.	Comp.	Modules
Principle variation [Köckerling et.al. 2003]	integration for max. principle exploitation	● ↔	●	○	○	○
One-piece machine. [Ehrlenspiel 1995]	integration to reduce number of parts	◑	○	● ↔	●	○
Integration of work. princ. [Roth 2000]	integration to reduce number of parts	○	○	● ↔	●	○
Modular funct. deploym. [Ericsson et.al. 1999]	modularisation for life cycle optimisation	◑	○	○	● ↔	●
Design structure matrix [Eppinger et al. 1994]	modularisation to reduce complexity	◑	○	◑	● ↔	●
C&CM Dependency Matrix [Albers et al. 2007]	modularisation to reduce complexity	◑	○	● ↔	↔	●
Variety oriented design [Kipp 2012]	modularisation to reduce variety	● ↔	● ↔	↔	●	○
Funct. orient. *Baukasten* dev. [Renner 2007]	*Baukasten* to reduce company complexity	● ↔	↔	↔	↔	●
Baukasten dev. [Pahl et al. 2007]	*Baukasten* to reduce variety	● ↔	↔	↔	↔	●

● *considered product model(s)* ◑ considered to some extend ○ not considered ↔ *supported transition*

This representative selection shows that methods' scope of application is mostly limited to the consideration of specific product models onto few levels of product architecture design. A reason for this may be, that these methods are integrated into superordinate approaches for product development and only partially support single steps, for instance, the layout of the product. An iteration to earlier steps, as the determination of functional structures, is not explicitly provided. That is, however, the main intention of the proposed framework towards an integrated product architecture design.

4 Towards integrated product architecture design

It was shown that product architecture design is a complex task affecting various properties of the developed product (see section 2). Existing methods are pursuing different targets regarding those effects of product architecture design. Therefore, different levels of product architecture design are considered, between which allocations of elements like functions or principles are made (see section 3). Based on these levels, a framework to support the designer's understanding of the variety of effects of product architecture design and the selection of suitable methods for specific development tasks will be introduced.

4.1 Framework for integrated product architecture design

A basic assumption for a framework for integrated product architecture design is that the determination of the product architecture could be described as allocations between the defined levels of product architecture design. Methods as classified in section 3 support the decision-making regarding the selection of suitable allocations based on principles such as integration or modularization. However, existing methods are based on various product models on different levels of product architecture design and have to be standardized for comprehensive application. Furthermore, the goals of methods differ widely, and thus, different effects are considered. Therefore, a certain transparency of methods and goals has to be enhanced. These interactions are shown in Figure 3.

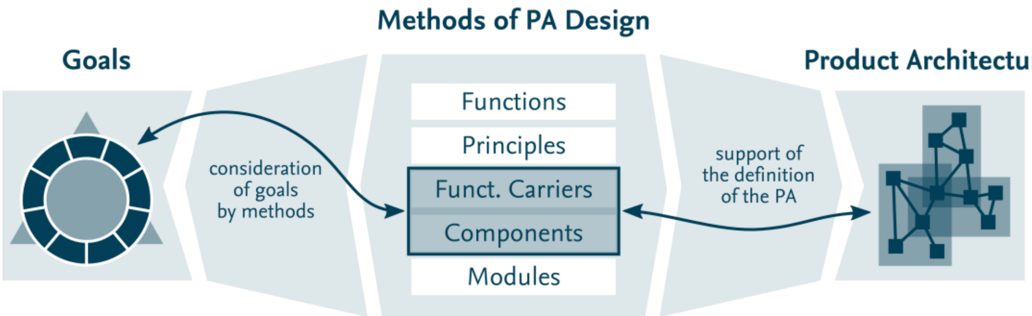

Figure 3. Methods of product architecture (PA) design basing on defined levels as link between goals of the development project and the product architecture

The objective of the framework is to standardize basic principles of existing methods with regard to addressed levels of product architecture design and considered effects. The framework supports the creation of new product concepts as well as the optimisation of existing concepts by providing key levers concerning effects of the product architecture. Thus, the core approach is the identification of suitable starting points and assisting the application of methods. Basis therefore are the levels of product architecture design, by which the selection of appropriate product models is supported. For instance, improving the producibility of the product as a goal of the product development, allocations between function carriers and components could be considered in a first step, see Figure 3. Thus, suitable methods of product architecture design could be selected and applied.

4.2 Product architecture design on different levels

Two possible scenarios arise for the application of the methods:
(1) For specific effects of product architecture design (reducing variety, reducing number of parts, etc.), methodical support is needed. The designer identifies associated levels and select suitable methods. For instance, if a product concept exists and the parts number has to be

reduced, as starting point working structures on the level of function carriers could be analyzed and the transition into the component's level be supported.
(2) At a specific point in product development, product models contain information about the product up to a certain concretization. However, effects of next steps in which a transition from this product models into models of other concretization are not known. With consideration of the proposed framework, methods could be identified to support this transition with a comprehensive understanding of its effects. Instead of an implicit product architecture design, an explicit approach is performed resulting in a more suitable product architecture.

For both scenarios, the main idea of the application of the framework is that the product architecture effects are considered making decisions on the transitions between various of the above defined levels. Figure 4 shows an examples of the benefits of the application of the framework describing a product concepts with its elements on the levels of product architecture design (squares) and allocations between the levels (lines).

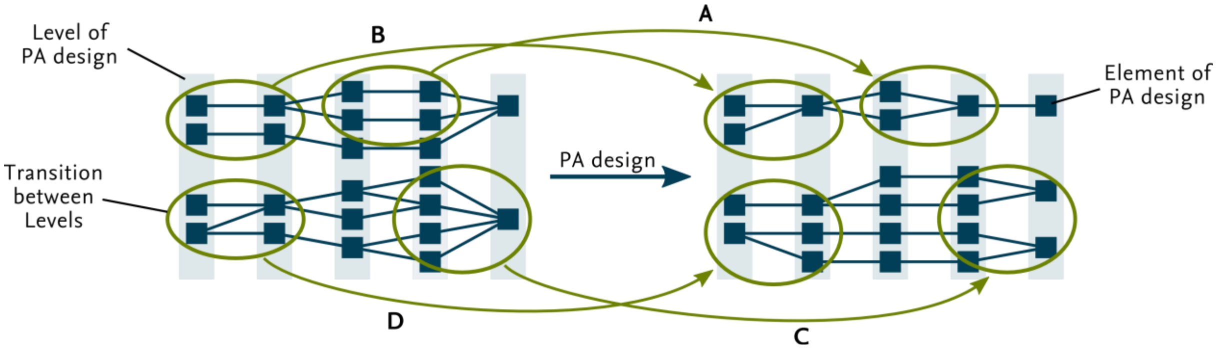

Figure 4. Product architecture design on different levels

In the illustrated example of a product architecture, four areas are highlighted describing possible variations that could be addressed by different methods. For instance, if the design goal is a reduction of the number of parts and assembly effort, a common approach is to optimize the product on the level of components, for instance, supported by methods of Roth or Ehrlenspiel (A). Beyond these methods, the framework proposes to look out for optimizations of the product architecture on other levels, like principle solutions (B). Thus, the method of Köckerling could be applied, supporting the identification of solution principles that could fulfil various functions in order to reduce function carriers and components. The same could be described for an example of modularization: Whereas a modularization on the components level, for instance, by applying the Design Structure Matrix (C), achieves an optimisation of the physical structure of the product, methods on the level of functions and its fulfilling principles could restructure functional relations between components (D).

Thus, the proposed framework could increase the designer’s understanding of effects of the product architecture by providing a comprehensive view on levels of product architecture design. While the application of single methods only has limited impact on the diverse effects of the product architecture, the framework aims on exploiting potentials on different levels.

5 Discussion and future work

The presented framework provides the basis for a comprehensive understanding of the effects of product architecture design and the application of methods. However, up to this point, it only describes and justifies the interrelations between product architecture, methods for product architecture design and its effects in general. To obtain an applicable approach, its elements have to be described in a standardized way. For instance, in Figure 4, the transitions between levels of product architecture design are described as connections between the elements on these levels. But how exactly do these elements and their allocations need to be modelled? By which product models could the levels be described? For this, a standardization of product models is needed before principles to support the transitions could be derived from methods what is part of future work. Furthermore, the effects of the product architecture need to be described in a more detailed way as presented in this paper. Therefore, a modelling approach based on SysML is being developed, providing a basis for tools to support goal clarification and the implementation to development processes by applying above mentioned principles.

This gives rise to a next question: In what way do principles (as standardized recommended action patterns derived from methods) need to be described? To answer this question, the input and output of methods have to be understood. The Design Structure Matrix, for instance, has a clear defined input in form of interrelations of different kinds between components. The output is a recommendation for clustering components to modules. However, for other methods, this input/output relationship is not that easy to describe. For instance, Tjalve (Tjalve, 1978), describes a method to support the composition of form elements regarding aesthetics as an effect of the product architecture. The golden ratio is a proposed tool to define harmonizing modules, but final decisions are mainly based on the designers individual competencies and action patterns are not formalized. Further challenges brings the integration of technological innovations into conventional products. For instance, adaptronic solutions, cf. (Inkermann, 2016), or additive manufacturing, cf. (Laverne et al., 2015) offer alternative solutions for functional integration.

After clarifying these issues, the framework needs to be brought into application in industry. Different projects with SME are initiated, e.g. (Richter et al., 2016), to get a first feedback of designers regarding the basic concept. Therefore, the framework will be introduced in workshops with interdisciplinary teams in different stages of the product development process. Initially, the focus will be laid on the applicability of the levels to explain the key issues of product architecture design. The products considered in these projects range from small industry consumer goods, like air preparation units, up to complex facilities, like drilling rigs.

6 Conclusion

Product architecture design is a key challenge of product development. By structuring partial solutions and allocating functions to physical components, many success factors of the product and the company, like customer satisfactions, company costs and strategy, are affected. Existing methods for product architecture design are facing this variety of effects and support the designers in defining suitable product concepts. However, most of the existing methods focus on very specific effects of the product architecture, such as reducing the variety of the company’s products or reducing the product weight. Thus, only specific goals are targeted, whereas others are not taken into account. A comprehensive understanding of the effects of the product architecture is not given.

In this paper, an approach was presented allowing a comparison of methods regarding the specific effects of the product architecture as well as the design states considered. For this, five levels of product architecture design were defined, namely: functions, principle solutions, function carriers, components and modules. The application of methods describes the transitions between these levels and, therefore, the product architecture. It was shown that existing methods only represent a limited view on product architecture design and do not exploit the full range of design possibilities. A framework was proposed to widen this view on product architecture design. Core element are the defined five levels of product architecture design allowing a classification of product models used by methods. By taking the considered effects of product architecture design into account, the framework could support designers to use the most suitable method for specific design tasks.

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