Representing the Effects of Product Architecture for Decision-Making in Conceptual Design

Timo Richter, David Inkermann and Thomas Vietor

Abstract The definition of the product architecture has a great impact on customer satisfaction, company strategy, and costs. Whereas these effects mostly become visible in later stages of the product development, most decisions on the product architecture are made early in conceptual design when allocations of functions to solution elements are determined. To support these decisions, many methodical approaches exist, for instance, for functional integration or modularization. However, a big part of those merely addresses single effects of the product architecture. This paper presents a comprehensive approach to draw correlations between targets derived from the specific development task and methods for product architecture design. Therefore, it contributes towards the structuring of existing methods in order to enable the designer to select most suitable methods for specific development tasks.

Keywords Product architecture · Conceptual design · Integration · Modularization

1 Introduction

Within the conceptual design, the designer is called to define the product architecture by allocating the function of a product to physical components [1]. Thereby, various product models can be used, representing information about the allocation of system elements of different concretization, e.g., sub functions and function

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carriers, and allowing deciding on its allocations [2]. These decisions on the product architecture have various effects on product properties impacting customer's satisfaction as well as company costs and strategic aims of a company.

However, existing methods for product architecture design are often set up with a specific purpose (e.g. controlling variety or reducing the number of parts) and focus on particular principles for product architecture design only, such as functional integration or modularization. Thus, product models merely represent information on specific effects. Therefore, the current research aims at the development of a methodical framework, enabling the designer to understand the wide range of effects of the product architecture and to define appropriate product models for design activities supporting specific goals. In this overall context, this paper focuses on answering the following questions:

- How do existing methods consider effects of the product architecture to the designer in conceptual design?
- How do product models of different concretization stages of the design process contribute to a comprehensive product architecture design?
- How can the designer be enabled to identify suitable product models addressing specific effects of the product architecture?

Following the structure of these questions, Sect. 2 will give a short overview of established approaches for product architecture design. In Sect. 3, the role of product models on different concretization stages will be examined regarding their given information for decision-making on the product architecture. Based on this, in Sect. 4, a new approach will be presented, enabling the designer to define appropriate product models for specific development goals. Finally, the results achieved will be summarized and discussed in Sect. 5.

2 Product Architecture in Conceptual Design

How do existing methods consider effects of the product architecture to the designer in conceptual design?

To support product architecture design, many methods exist. However, mostly, they focus on particular development goals and only consider specific effects. This section will highlight the scope of the product architecture decisions in conceptual design and its effects.

The product architecture describes the allocation of the product function to physical components [1]. Consequently, the product architecture defines in what way a component of the product interacts with others, for instance, by imposing geometry constraints or transferring forces, material, energy and/or signals to ensure proper functioning [3]. These interactions are mainly determined in conceptual design when based on functional structures and working principles, a principle solution (concept) is elaborated [4].

Defining the product architecture, two general strategies that are often referred to as mutually exclusive arise [5]. Firstly, functional integration aims at a reduction of the number of parts and/or an extension of the number of functions while sticking to the number of parts [6]. Secondly, modularization aims at clustering functions into modules while minimizing the coupling among the modules and maximizing the cohesion within the modules [7]. The decision on an appropriate strategy depends on the required product properties and has to be supported by suitable product models representing the effects of the product architecture.

Effects of the product architecture describe the relations between the characteristics of the defined product and its properties, c.f. [8]. Characteristics define the structure, dimensions, materials, etc. of the product. In product architecture design, the designer influences characteristics with the objective of fulfilling certain required properties in the best possible way. These properties describe the product's behavior and are related to stakeholders' interests, e.g., the customer or the manufacturer.

Like the required properties, the effects of the product architecture are also very wide ranging and can be assigned to various areas of the company [9]. However, besides a quantity of literature focusing on handling the wide range of effects of product architecture, most methodical approaches for conceptual design only consider a few of these and could be categorized after three main objectives: reducing variety (e.g., [10]), modularization for product-strategic reasons (e.g., [11]), and functional integration (e.g., [5]). Comparing objectives of these approaches, their considered effects show many overlaps and can be allocated to three main areas of impact (described by the authors more precisely in [12]):

- customer satisfaction, e.g., higher compactness or less weight through integration, higher adaptability or enhanced reparability through modularization
- company strategy, e.g., lean processes through less (integrated) components, higher flexibility and external variety through modular product systems
- company costs, e.g., less material consumption and high interdisciplinary development effort for integrated mechatronic solutions, less manufacturing effort and purchase costs through the use of standardized modules.

For product development, this wide range of effects results in the challenge of defining appropriate product models supporting analysis (evaluating effects on product properties) and synthesis (determination of the product architecture) as single product models only represents some of those effects.

3 Product Models in Product Architecture Design

How do product models of different concretization stages of the design process contribute to a comprehensive product architecture design?

To communicate a comprehensive picture of the effects of product architecture design, product models used in the design process are central as they supply the basis for decision-making. In this section, the use of product models in design in general will be highlighted, before a framework for structuring product models for product architecture design is proposed.

3.1 Progressing with Product Models

A product model (also referred to as design model) is a model of the product being developed, representing sufficient properties of the product in an adequate form to support specific design activities [2]. In product design, a large number of different product models is applied, for instance, requirements lists, function models, product structure models, prototypes, etc. These product models are often assigned directly to design stages. Thus, during the design process, several product models are used that merely represent a small part of all available information about the current design stage in order to support only those decisions to be made [13]. For instance, models of early stages do not represent geometrical arrangements or materials but the required logical behavior. Consequently, the design process could be described as a progressing from product model to product model—from problem to solution [2]. In order to choose appropriate product models, a thorough understanding of modeled properties and the modeling purpose is required [13].

Since product architecture integrates the functional and physical view on the product [1], product models supporting its definition require containing information of different design stages. For instance, when defining the module structure of a product, components have to be combined in modules considering function structures. An applicable product model is, for example, a Design Structure Matrix [14], representing components and their functional interactions. The same applies for functional integration, when, for instance, several function carriers are realized by one component [2]. In previous publications of the authors [15], it has been shown that several product models of product architecture design could be distinguished by its represented types of elements of different design stages and its represented effects. Thus, there is a need for an overarching framework.

In literature, approaches with similar objectives can be found. For instance, Otto et al. [16] present a generic sequence of steps of product architecture design in order to enable combining different methods of modularization in order to make use of the various potentials due to its specific focuses. Krause et al. [17] developed a methods toolkit to identify methods regarding, e.g., design for variety and life phase modularization. Similar to that, Ziebart [6] argues that functional integration requires a comprehensive understanding of different methods to be used and proposes a target model integrating objectives of various methods for functional integration in order to enable the designer to select suitable methods based on identified objectives. However, both approaches only focus on modularization or integration, while it is argued that objectives for both need to be considered simultaneously [1, 5]. For this reason, the approach of this research work is to describe product architecture design on overarching levels in order to allow structuring and goal-oriented application of existing methods for both modularization and integration.

3.2 Levels of Product Architecture Design

In order to systematize product models describing product architecture decisions, the authors have conducted a literature review, examining established approaches regarding their concretization level and considered effects. Extracts from the results have been presented in [11]. It has been found that system elements represented in the product models could be systematized by five levels of product architecture design, shown in Fig. 1.

Based on the established literature, five types of system elements on these levels could be defined:

- Functions describe the teleologies of objects, i.e. what they are for [18]. Functions could be of technical, semantic, symbolic or aesthetic type [19].
- Principles are basic laws from which effects to fulfill functions could be derived [4], for instance, physical working principles.
- Function carriers are technical elements to fulfill a function [4]. Described as working bodies and working surface pairs, they form a working structure.
- Components are individual physical parts from which the system can be assembled [20].
- Modules constitute a decomposition of a product into building blocks with specified interfaces, driven by company-specific strategies [10].

Within one level, system elements are linked by interactions, for instance, an energy flow between functions or physical connections between components. Between levels, system elements are linked by allocations, for instance, a function is allocated to a principle realizing that function. System elements from

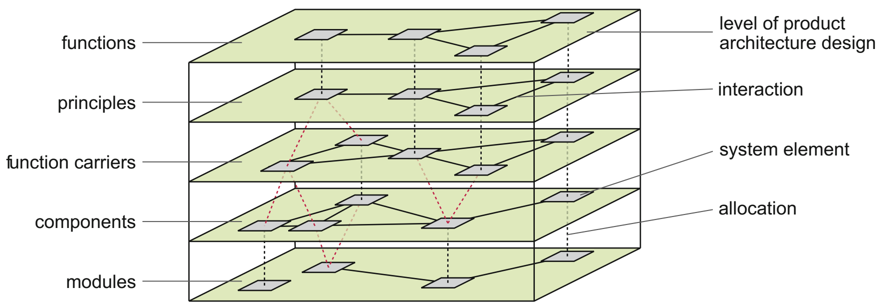

Fig. 1 Product architecture described as allocations between system elements of five levels

non-adjacent levels are also linked in this way over several levels. Thus, every function is allocated to at least one module as well.

The levels themselves are well known in product design. Besides several product models supporting decisions within one level (e.g., variation operations for functional structures), many product models exist to support decisions on the transition between the levels (e.g., deciding for working principles to realize functions, for instance, in a morphological box). However, an overarching concept with a focus on the explicit definition of the product architecture is missing. Therefore, the new approach aims at structuring existing product models regarding their contribution to product architecture design. Thus, principles for functional integration as well as modularization can be described in the same model in order to make use of the desired effects of both.

4 Representing Effects of the Product Architecture

How can the designer be enabled to identify suitable product models addressing specific effects of the product architecture?

As shown in Sect. 2, the product architecture affects a quantity of product properties. To be able to address these effects, the designer needs to identify the most suitable product models (Sect. 3). Therefore, in this section, a modeling approach is proposed to draw correlations between effects and product models.

4.1 Meta Model for Integrated Product Architecture Design

The basis for the determination of the most suitable product architecture in conceptual design is the designer's comprehensive understanding of its effects on different product properties. Product models can help to break down these effects by providing manageable information on the relation between design alternatives and product properties in order to support analysis and synthesis, see Fig. 2.

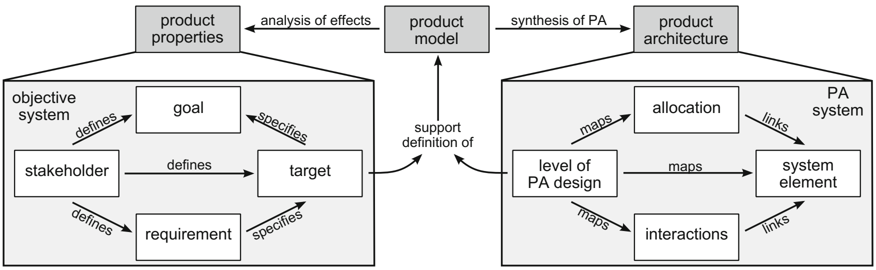

Fig. 2 Meta model for integrated product architecture design

However, the scope of a product model is limited. Therefore, its objective and extend of represented product information has to be defined clearly. Thus, the main idea of the presented approach is to increase the understanding of objectives (objective system) and the product architecture (PA system) to enable the designer to define appropriate product models to support design activities, see Fig. 2.

The PA system describes system elements and their allocations on the five levels as defined in Sect. 3.2 (levels of PA design). These levels provide the basis for the identification of appropriate product models supporting design activities. However, for that, development goals have to be specified within the objective system in order to create links to design activities. Therefore, a hierarchical modeling approach proposed by Stechert and Franke [21] is applied. According to that, requirements are modeled as specifications of targets and superior goals. In this way, objectives of the design task are described on three levels: goals, targets, and requirements:

- A goal describes the basic idea of what is developed, for instance, minimizing internal variety.
- A target specifies a goal as a principle to be applied to a specific level of product architecture design and describes objectives for allocation decisions of system elements in the PA system, for instance, reducing variety of used principles to realize the same function. (The target of this example is directly linked to the level of principles, since decisions on the allocations between functions and principles are made there.)
- A requirement specifies a target with concrete target values. Since every requirement is connected to targets and goals, a goal orientation of defined requirements is ensured, for instance, the desired number of applied principles to realize the same function.

In this modeling approach, targets are highlighted as the connecting element to the levels of product architecture design. On this basis, the designer is able to decide on suitable levels to carry out design activities to determine desired properties (for instance, by deciding for the level of principles to address the target of reducing internal variety). In order to support the definition of appropriate product models, existing product models, for instance, from approaches for functional integration or modularization, could be identified, that are categorized by targets and levels of product architecture design.

To demonstrate the application of the approach, Fig. 3 illustrates examples of goals (left), related targets (middle) and proposed applications of design principles in the PA system (right). The goals represent typical challenges of companies: Facilitating the testing prior to delivery of products, minimizing the final assembly effort of variant products, and limiting production costs by reducing the number of components. Related to these goals, four targets are shown that are derived from methodical approaches for product architecture design, e.g., the differentiation of function carriers in order to realize them as several components to be tested independently (c.f. [11]). Likewise, other targets could also aim at allocation principles of differentiation or integration (c.f. [6, 10]).

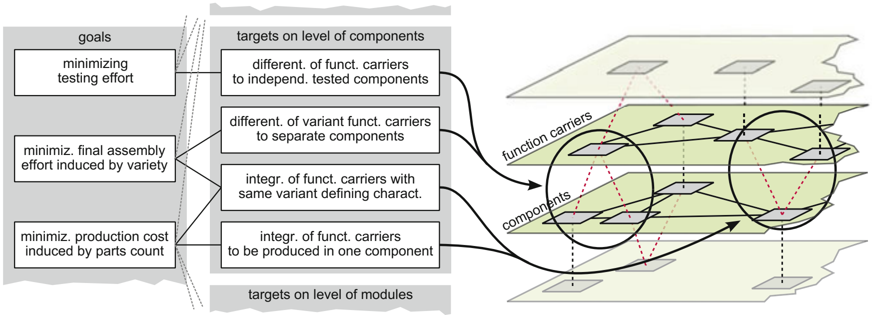

Fig. 3 Examples of goals and related targets aiming at allocation decisions on the components' level of product architecture design

This example only presents targets on the level of components, i.e., targets that aim at reconsidering allocations between function carriers and components. However, the dashed lines show that goals could be connected to targets aligned to several levels of product architecture design. For example, the goal of minimizing the testing effort could also be addressed by reducing the number of function carriers to be tested, thus, by integrating principles to be tested (level 2) into a reduced number of function carriers. Therefore, the proposed approach supports both the identification of suitable levels of product architecture design as well as the application of different targets within one level.

4.2 Application Scenario in Conceptual Design

The application of the proposed modeling approach in design projects require three steps to be executed: (1) Identification of goals related to product architecture design, (2) specification of goals by targets, describing concrete objectives for design tasks on levels of product architecture design and (3) definition of product models representing information for the implementation of the earlier defined targets. The application is suitable, in particular, for design projects with unclear objectives or various effects of product architecture decisions to be considered by the designer. In this case, steps 1 and 2 provide a basis for the explicit definition of appropriate product models.

Although the proposed modeling approach has not been implemented in a tool for industry use yet, its basic idea was used for several workshops in small and medium size enterprises dealing with the ideation of new product concepts. At this point, the example of the development of an air preparation unit will briefly be introduced in order to give an insight into the designer's problems in conceptual design when defining the product architecture.

Air preparation units are applied in pneumatic systems between the compressor and air driven devices. Since the air leaving the compressor often contains contaminations and does not have the appropriate pressure, it needs to be prepared. Therefore, air preparation units fulfil several functions such as filtering, regulating, lubricating, and other. Traditionally, these products are structured modularly, allowing a configuration regarding the required functions. However, the realized modularity of the air preparation unit entails certain disadvantages: The high number of interfaces between the modules causes extra costs for additional connection parts and results in a great installation effort for the manufacturer and customer. Furthermore, the robustness is noticeably reduced and the flow resistance is increased because of many redirections caused by interfaces.

Therefore, the application of the proposed approach supported the clarification of development goals affected by the product architecture. In doing so, targets could be identified aiming at differentiation or integration on the levels of principles, function carriers, or components, while previously the company had been considering a module definition only regarding main functions of the product. In this way, product models were created representing a decomposition of functions and its allocations to principles and function carriers, c.f. [22]. Using this product models and applying identified targets, new concepts were created in which solution elements for auxiliary functions were differentiated from modules fulfilling the main functions. Thus, for instance, the housing protecting the system against mechanical damage was differentiated from the modules for filtering, regulating, etc. and realized as one housing for all other modules. Therefore, by applying the proposed approach, the focus on product architecture design was expanded from previously only differentiation by including integration principles. In this way, development goals were achieved by decreasing the total number of parts and facilitating the mounting.

5 Conclusion and Further Work

The objective of the research work presented is to increase the transparency between effects of the product architecture and product models to support design activities in conceptual design. The focus was lain on the presentation of an approach for modeling the goals of product architecture design (as determination of required product properties). Thereby, targets that could be linked to levels of product architecture design are formulated, which has been presented in previous publications. This was stated as the basis for defining appropriate product models to support the decision-making on the product architecture in conceptual design.

Something that has not been shown in this paper is how exactly product models can be defined. Examples were given of using product models from existing approaches for product architecture design. It remains an unanswered question how the designer can be supported if no existing product models are appropriate for the specific design task. In this case, new product models have to be created; in doing so, it must be ensured that all necessary information is included to obtain a verified basis for decision-making. Therefore, further work aims at the elaboration of a catalogue of targets of product architecture design and the subsequent linking of product models. Therein, descriptions of targets should clearly define which information is essential for its implementation.

Moreover, the modeling approach needs to be implemented in a tool for industry. Hence, based on existing requirements modeling tools, a prototype based on SysML should be created. In this tool, a catalogue of goals and targets should be integrated, that were derived from literature and case studies in industry projects dealing with re-designs or new product developments in the fields of consumer goods, automotive engineering, and industrial mechanical engineering.

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