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ENHANCING PRODUCT ARCHITECTURE APPLICATION IN EDUCATION AND INDUSTRIAL PRACTICE

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ABSTRACT
Creating good product architectures is one of the keys to designing configurable and successful products. As defined by Ulrich [1], product architecture is a scheme by which the function of a product is allocated to its physical components. Since product architecture is determined in an early phase of research and development, it is crucial to provide a solid framework that leads to both comparable and innovative results. Comparable results would require a strict set of rules, which at the same time impacts creativity and innovation, thus leading to a conflict. Our long-term goal is to improve understanding and application of product architecture in education and practice by creating a standardized framework that allows both. This paper intends to show the current stages of research towards this objective at RWTH Aachen University, and should be understood as an indicator concerning the direction of future research. It summarizes the experience we gathered by teaching product architecture and captures the problems we identified with present theory. Three lab studies with a total of 216 graduate engineering students have been carried out that clearly show the need for a standardized set of rules, since the same definition of both product architecture and tasks leads to a wide range of different results.

Keywords: Product architecture, product structure, function structure, lab study

1 INTRODUCTION

All required functions of a product are combined under the term “function structure” [2]. Similarly, product structure describes the hierarchical layout of physical components [2]. Product architecture is therefore the mapping scheme between function structure and product structure. By applying this systematic and modular approach in construction and assembly, a simpler product standardization process and more economic feasibility can be achieved, as first stated by Göpfert [3]. From our experience at teaching Advanced Engineering Design at RWTH Aachen University, there are some challenges to successful apply the concept of product architecture in practice. In Chapter 2, as an initial approach to this problem, a first lab study analyzed the shortcomings of present theory. Even though our graduate engineering students were given the same task, due to the lack of specific guidelines, the results of their work were not comparable. Therefore, in a second lab study, the same task with a stricter set of rules was carried out. This second test is summarized in Chapter 3. Since the effect of those stricter set of rules was largely positive, an extended third lab study was conducted, which is described in Chapter 4. This finally leads to a proposal on how to improve teaching and organizing of product structures and derived product architectures, as found in Chapter 5.

2 FIRST TEST

The application of methods to define product structures has not yet been extensively analyzed. To meet this challenge, a lab study was designed in which participants had to perform a multi-part engineering design task. Besides monitoring the participants’ success in the engineering tasks, the lab study also intended to examine the correlation between time restriction and quality of outcome. The amount of time available was varied systematically on four levels. A between-subjects design was chosen and no repeated measures were taken. The development tasks in the lab study dealt with the improvement of a set of gear wheels with treadles for a common bicycle.

2.1 Lab Study

2.1.1 A. Tasks

The tasks of the empirical study covered five of the seven steps from the “General Approach To Engineering Design” according to the VDI 2221 guideline [2]. In Task 1, participants had to evaluate a given product by breaking down the product into basic modules (Task 1a) and functions (Task 1b) (Figure 1). This corresponds to phases 1 and 2 of the VDI 2221 guideline, which state that the task has to be clarified and defined and the functions of the given product have to be determined and structured, respectively. In Task 2, improvements to the product based on a set of given deficiencies had to be developed and sketched in form of a principle solution. This matches phase 3 “principal solutions” of the VDI 2221 guideline. In Task 3, one part of the product had to be drafted using a CAD system (Task 3a) and subsequently put together with other provided parts to make up a digital assembly of the bike parts (Task 3b). This corresponds to the phases 4 “division into modules” (3a) and 5 “development of the layout” (3b) of the VDI 2221 guideline. Each of the five tasks can be further divided into subtasks, which are necessary steps to reach a satisfactory result.

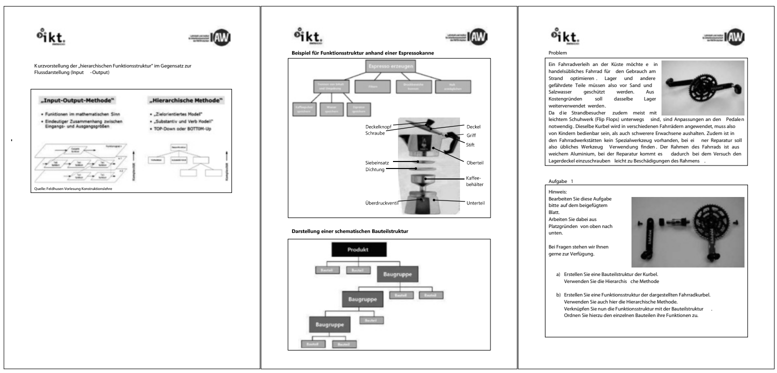


Figure 1. Task Indication for first lab study

2.1.2 B. Procedure

The experiment was divided into three parts: Pretests, main experiment and self-reflection. In the pretest phase, the participants had to complete questionnaires in which demographic data (age, gender etc.) as well as level of education and work experience (technical drawings, CAD, product knowledge etc.) were anonymously collected [4] and the participants carried out a part of the I-S-T 2000 R test to measure their spatial awareness [5]. In the main experiment the participants had to process the tasks described above in sequential manner. After each task, the subjective workload was measured based on the NASA-TLX assessment technique.

This multi-dimensional rating technique evaluates workload according to six subscales: Mental Demands, Physical Demands, Temporal Demands, Own Performance, Effort, and Frustration [6]. Finally, a 10-minute semi-structured interview was conducted, in which the participants were confronted with their own development results. They were given the possibility to evaluate the obtained design solution and comment on the experiment in general.

2.1.3 C. Participants

The group of participants consisted of 111 junior engineers, all of them students in higher semester engineering classes at RWTH Aachen University. They were mostly male (91%), had a mean age of 22.76 (SD=1.36), and generally evaluated themselves as “medium or highly experienced” in both, technical drawing (80%) and Computer Aided Design (68%), but only “little or not experienced” in the design of actual products (54%).

2.2 Results

The first experiment was kept very simple in its design task. Participants were only requested to identify components and assign functions to each component. This led to results that were varying widely and thus difficult to compare [7, 8]. In order to obtain more comparable and explicit results, the second experiment needed a stricter set of rules, e.g. of how to name functions and also give a full list of all components with their respective names. The goal was to reduce semantic variance. As nomenclature it was decided to use a “verb+noun” model [9] that has been used in lectures.

3 SECOND TEST

The aim of the second lab study was to obtain independent, but still comparable product architectures. The results of the first test showed the difficulty to compare the work of two or more people concerning the same product and its components [10].

For that reason the second lab study was improved by proposing a simplified task. All components of a simple mechanical system had been named and given to the participants. To make it more comparable and to reduce the probability of less solved tasks, there was no time limit set up in the second test.

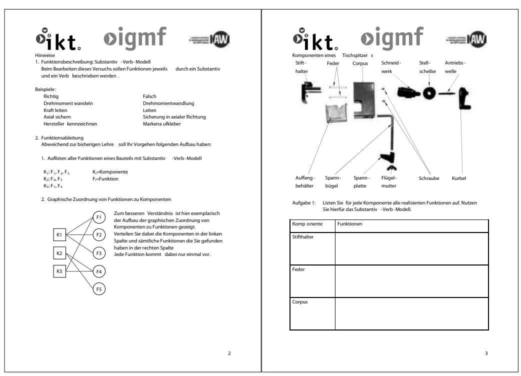
3.1 Lab Study

3.1.1 A. Tasks

In order to achieve similar results, the participants had to identify basic modules (task 1a) and functions (task 1b) as in the first lab study. For the first task, the given parts had to be defined by identifying their function. Secondly, the functions of the product were collected and assigned to the physical components. The third task contained the sketching of an improved solution.

3.1.2 B. Procedure

The procedure of the second lab study was similar to the first one concerning the phases. First, there was a short survey about the participant, followed by the task for a normal engineer’s workday. To avoid the less comparable results of the first test, there was a change in the nomenclature and the given task.


Hinweise
1. Funktionsbeschreibung: Substantiv -Verb-Modell
Beim Bearbeiten dieses Versuchs sollen Funktionen jeweils durch ein Substantiv und ein Verb beschrieben werden .

Beispiele:

Richtig	Falsch
Drehmoment wandeln	Drehmomentwandlung
Kraft leiten	Leiten
Axial sichern	Sicherung in axialer Richtung
Hersteller kennzeichnen	Markena ufkleber

2. Funktionsableitung
Abweichend zur bisherigen Lehre soll Ihr Vorgehen folgenden Aufbau haben:

1. Auflisten aller Funktionen eines Bauteils mit Substantiv -Verb-Modell

K_1: F_1, F_2, F_3 K_i=Komponente
K_2: F_4, F_5 F_i=Funktion
K_3: F_1, F_4

2. Graphische Zuordnung von Funktionen zu Komponenten

K1 K2 K3 F1 F2 F3 F4 F5

Zum besseren Verständnis ist hier exemplarisch der Aufbau der graphischen Zuordnung von Komponenten zu Funktionen gezeigt.
Verteilen Sie dabei die Komponenten in der linken Spalte und sämtliche Funktionen die Sie gefunden haben in der rechten Spalte
Jede Funktion kommt dabei nur einmal vor.

2

Komponenten eines Tischspitzer s
Stift-halter, Feder, Corpus, Schneid-werk, Stell-scheibe, Antriebs-welle
Auffang-behälter, Spann-bügel, Spann-platte, Flügel-mutter, Schraube, Kurbel

Aufgabe 1: Listen Sie für jede Komponente alle realisierten Funktionen auf. Nutzen Sie hierfür das Substantiv -Verb-Modell.

Komp onente	Funktionen
Stifthalter	
Feder	
Corpus	

3

Figure 2. Task Indication for second lab study

3.1.3 C. Participants

The second lab study was performed by 20 engineers, among them 14 junior engineers and 6 engineers working at the Chair and Institute of Engineering Design at RWTH Aachen University.

3.2 Results

In this chapter, the allocation of a function to basic physical components is analyzed. Overall it is to say that a number of different mistakes could be identified even though participants were provided sufficient time to finish the tasks.

The participants in the lab study are provided with a method to precisely describe functions, using pre-defined nouns and verbs (verb+noun system). This scheme is meant to improve the accuracy of descriptions.

Unfortunately by using this method, the participants also produced results that were difficult to compare. An example of that would be “guide force”, “create force” and “store force”, all of which used to describe the function of a spring. Also, some test subjects did not utilize the given

“verb+noun” model in some cases, as it did not describe the function properly. For example in the given model, “pull pencil holder to corpus” was used instead of the intended phrase “pull pencil holder” to specify a direction. That way, evaluating the results was difficult and time consuming as the description for the same function was often semantically different. In some cases, it was not clear whether the test subjects meant the same or different functions for the same component. This can be seen in “create preload [Vorspannung erzeugen]” and “create tension [Verspannung erzeugen]”, where both phrases describe the function of screws.
Next, the content was checked. The allocation of the given parts and their function were evaluated. This shows whether the chosen function is linked correctly to the specific part. On one hand, the completeness of this process is reviewed by verifying if all functions and components are correctly copied in order to prepare the next step. On the other hand, parameters to compare the participants' work including the line-up of the relations are established. Every component and function should be connected, precisely as they were defined in the first case. Thus, indicators are derived to compare the work of several participants.

Table 1. Excerpt of evaluation and resulting indicators

	1-01	1-02	1-03	1-04	1-05	1-06	1-07
number of components A3	12	12	12	12	12	12	12
components transferred A4	12	11	12	12	12	12	12
Quota 1	100,0%	91,7%	100,0%	100,0%	100,0%	100,0%	100,0%
amount of allocation A3	16	17	24	20	18	16	12
amount of allocation A4	17	14	25	22	18	14	12
notes			a)	a)			
Quota 2	93,8%	82,4%	95,8%	90,0%	100,0%	87,5%	100,0%
amount of b) mistakes	0	0	2	5	0	0	0
different functions of A3	10	16	22	13	17	13	11
amount of c) mistakes	0	0	3	1	0	2	0
different functions of A4	11	14	18	13	17	11	11
sum of mistakes	0	0	5	6	0	2	0
Quota 3	90,0%	87,5%	31,8%	40,0%	100,0%	64,6%	100,0%
Sum	94,6%	87,2%	75,9%	76,7%	100,0%	84,0%	100,0%

Table 1 shows an abstract of the evaluation of the work of the participants. The first mistake can be seen by examining Quota 1. Even though there was no lack of time, participants did not transfer all components from one page to the next page.
The second inaccuracy can be seen in Quota 2. The allocation the participants had defined in task A3 varied. Sometimes tasks were missing or getting even more. For the next step the product and the function had to be connected graphically. Quota 3 shows the effect of the working accurateness.

4 CURRENT LAB STUDY FOR EVALUATION

A new model was needed for the third experiment that would allow expressing the relation of the noun to the given components. An approach to that could be found in VDA 2006 [11], where requirements have to be “clear, comprehensible and verifiable”. The nomenclature used to ensure this is based on five components:

- Subject (the control unit)
- Auxiliary (has to)
- Action (deactivate)
- Object (the motor)
- Condition (when temperature reaches 20°C)

The idea was to use a similar set of components to describe the functions as means to ensure comparability (clear, comprehensible and verifiable).
The approach from the second experiment was extended to include three components: Subject, verb, object. Also, adjectives to further describe the object were allowed.

Table 2. Examples of the used method

Subject	Verb	Object
The screw	Transmits	A force
The label	Identifies	The manufacturer
The shaft	Transmits	Torque

It should be noted that the given nomenclature was translated from the German language and the benefits might differ when used in the English language. Therefore, the authors propose an adaption of the nomenclature to the English language, which is not part of this contribution.

4.1 Lab Study

4.1.1 A. Tasks

The tasks of the latest lab study were modified to obtain better comparability of the results. In the first task, the participants had to describe the main functions of the pencil sharpener and to sketch the functional structure of the product. For analyzing the product functions in a second task, an exploded view of the pencil sharpener was given and the components were clearly named to avoid misunderstandings. In the first part of this task, the participants had to describe the functions with the "Subject-Verb-Object-Model" for each component of the product. In a second step of Task 2, they had to connect the functions graphically with the components. Content of Task 3 was hand-sketching a redesigned product by adding new requirements to the product. In the last part of the test, CAD software was used to design the clamping plate of the pencil sharpener by using a given sketch, after that, an assembly of the pencil sharpener was completed using existing components. Between the four tasks, the participants were asked about their stress level during task execution.

4.1.2 B. Procedure

Strict time limits were set for each task. As the participants were forced to do one task after another, there was no possibility to choose a preferred task.

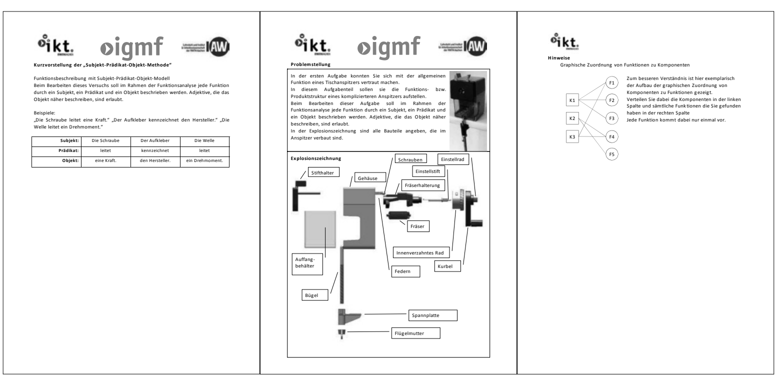


Figure 3. Task Indication for third lab study

4.1.3 C. Participants

In this third study, 85 participants performed the engineering tasks. All of them were higher semester engineering students and all had taken a class on Systematic Engineering design prior to the lab study.

4.2 Results

The evaluation has just been initialized and will be finalized in the close future. Therefore up to present, the effects and implications of this third lab study are subject to ongoing research. Equally, the insights to be derived from the subsequent series of the three lab studies can only be gained once the final evaluation is completed.

5 CONCLUSION AND OUTLOOK

This paper addresses the problem of successfully applying product architecture. It proposes an empirical approach to a better understanding of a method to obtain comparable product architectures. In this paper, a sequential development of this enhanced approach is presented.

As this paper's empirical research is situated within the field of engineering design education, insights gained in this paper were already and will continue to be transferred into future engineering design education at RWTH Aachen University. This paper introduces three steps of developing a nomenclature for enhanced application as well as teaching of product architectures. In a first attempt, junior engineers were requested to derive product architectures for a given product in a very informal way. As this proved to deliver rather unclear an incomparable results, the second lab study already introduced a formalized way to obtain product architectures by using a nomenclature. This nomenclature supported the design engineers' conception of product architectures along with setting boundaries for the variety of the results. Still there were inconsistencies in the execution of the product architectures. Therefore, for a third lab study, a more precise set of rules was defined. With this, even more comparable yet precise product architectures could be conceived.

Results of this series of lab studies enhance future design engineers' education at RWTH Aachen University. An application of the rules and the nomenclature developed in this research area and an adaption to more languages can definitely provide an improvement to future product development.

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