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Target Weighing Approach: Study to evaluate the benefits of a methodical approach in comparison to classical company processes for the identification of lightweight design potentials

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Abstract

In order to achieve weight targets, the product developer can rely on the five lightweight design strategies concept, material, form, manufacturing and conditional lightweight design. However, lightweight design activities often focus on material and form lightweight design, i.e. the optimisation of individual subsystems. But a combination of subsystem optima does not inevitably lead to an overall system optimum. For this reason, the optimisation of the overall system must be carried out by cross-subsystem approaches (concept lightweight design).
One such approach, which serves for the systematic identification and evaluation of holistic, cross-subsystem lightweight design potentials, is the "Target Weighing Approach (TWA)". Thereby, the reference product to be examined is analysed with regard to its functions. Subsequently, the percentage contribution of the subsystems to the fulfilment of the functions is determined in a Function-Mass-Matrix and thus a weight per function is determined. Based on this, "too heavy" functions are determined which offer possible lightweight design potentials.
This paper presents the results of a study conducted as part of the Live Lab "IP - Integrated Product Development". In this Live Lab, selected students go through a product development process (in cooperation with a chosen industrial company) from the analysis phase through the generation of product profiles to the production of prototypes. The aim of the study was to identify lightweight design potentials of an application-oriented system (underbody of an automobile) and to develop related initial concept ideas.
For the study, 37 students were split into two groups of four development teams. One group was taught in the TWA and forced to use the method for achieving the goal. The development teams of the other group were organised by subsystem responsibilities in analogy to a classic corporate structure, i.e. one person per development team is responsible for one subsystem. As in real corporate environment, the individual members of the development teams were locally

separated and only allowed to interact at defined points in time. This simulates corporate-typical meetings where product developers from different departments exchange information about the project and make decisions.
At the end of the study, the most promising concept idea per development team was presented and a questionnaire with seven questions was handed out. Here, the influencing factors for the identification of lightweight design potentials (communication, distinct analysis phase, understanding of subsystem interactions, cross-system thinking, detachment from existing restrictions (interfaces) of the reference product) identified by the authors prior to the study were queried.
The results showed that the development teams supported by the TWA achieved a greater understanding of the overall system and were therefore able to recognise the lightweight design potential of the system more comprehensively. On the one hand, this was due to better communication and a more detailed analysis phase compared to the peer group. On the other hand, they had a better overview of subsystem interactions and were able to think independently of existing interfaces.

Keywords: Product Design, Lightweight Design, Design Method, Empirical Study

1 Introduction and Motivation

Current vehicle developments in the automotive sector are particularly affected by rising fuel consumption and emission requirements (Friedrich, 2017). In addition, customer requirements in terms of safety, comfort and driving dynamics are also increasing in a highly competitive environment. In order to develop vehicles to meet these challenges, special attention must be paid to highly networked and influential development measures such as vehicle weight (Friedrich, 2017). The vehicle weight influences both the design of the vehicle and customer-relevant properties such as driving dynamics or driving resistance. Vehicle weight must therefore be continuously reduced in order to compensate for weight increases through the constant growth in size of new vehicle generations and increased comfort and acoustic requirements (Friedrich, 2017). For this reason, the vehicle components have been optimised in terms of material and form with regard to weight over the past decades. Consequently, future significant weight reductions are more likely to be expected in the area of lightweight concept design (Henning & Moeller, 2011). The demand for cross-subsystem lightweight design methods is derived from this.
The Target Weighing Approach (TWA) is such a cross-subsystem method that has already been successfully implemented in pilot projects (Albers et al., 2013). In order to examine the functionality and efficiency of the method, the TWA was taught and carried out as part of the Live Lab "IP - Integrated Product Development" (Albers, Bursac, Heimicke, Walter, & Reiß, 2018). In this Live Lab, conducted in cooperation with a chosen industrial company, the participating students developed lightweight design concepts and eventually completed a questionnaire. To this end, the students were divided into two groups, with one group using the TWA and the other group applying conventional development processes. The results of this study are presented in the following sections.

2 State of the Art

2.1 PGE – Product Generation Engineering

A classification of the design types in the design methodology is usually carried out in new construction, adaptation construction and variant construction (Ehrlenspiel, 2009; Feldhusen, Pahl, & Beitz, 2013). In the industrial environment, however, it is often not possible to

distinguish clearly between the three types of construction, so Albers, Bursac, & Wintergerst (2015) developed the approach of PGE - Product Generation Engineering. This states that products are developed in generations. The basic assumption is that the development of new products is usually based on one or more reference products. Within the framework of PGE, a distinction is made between the activities of carryover variation (CV), embodiment variation (EV) and principle variation (PV). These activities are specifically combined for the development of new products. New development shares result from the activities embodiment variation and principle variation. (Albers et al., 2015)
An important aspect in the development of new products is lightweight design. In order to face this challenge, it is necessary to consider the entire product development process as well as interdisciplinary teamwork (Henning & Moeller, 2011). The Target Weighing Approach (TWA) is an approach that supports this cooperation by addressing the potential for lightweight design across subsystems.

2.2 Target Weighing Approach (TWA)

The Target Weighing Approach by Albers et al. (2013) is a function-based lightweight design method. Function and embodiment design are directly linked to each other. From embodiment design, the functions can be analysed whereas a function can be transferred into embodiment design in a synthesis step (Matthiesen, 2011). Abstraction on the functional level implicates that a cross-subsystem search for lightweight design potentials is carried out, since a function can always be fulfilled by several subsystems.
Therefore, the TWA can be categorised as a method in the lightweight design strategy "concept lightweight design" as one of five main lightweight design strategies (Henning & Moeller, 2011).
The TWA is based on the methods of Value Engineering and Target Costing: TWA allocates weight (according to Feyerabend (1991) and Posner, Keller, Binz, & Roth (2012)) and costs (according to VDI 2800 (2010)) to functions. The workflow of the TWA can be seen in Figure 1. Another approach for the estimation of mass target values based on functions, mass moment of inertia and mass distribution had been developed by Posner, Binz, & Roth (2013, 2014).

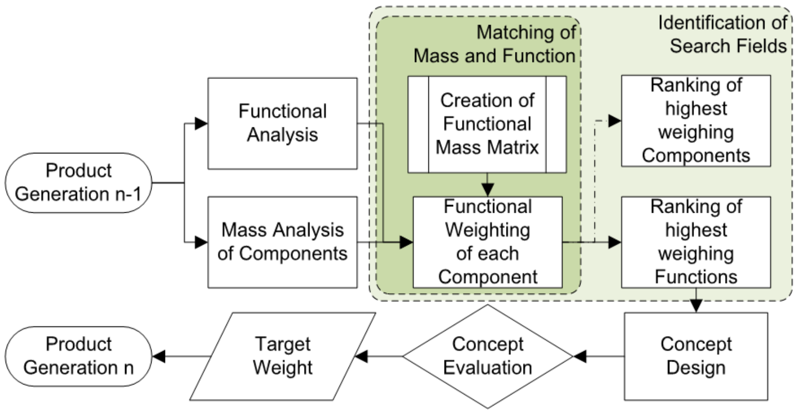

Figure 1. Workflow Target Weighing Approach (Wagner, 2015)

Due to a paradigm shift, which was also forced by legislation, it is unavoidable to consider CO2 emissions in lightweight design in addition to weight and costs (Friedrich, 2017). Therefore, in the meantime, the TWA has been extended by the factor CO2 emissions in order to also assess the global warming potential in the search for lightweight design solutions. Consequently, the

Extended Target Weighing Approach (ETWA) aims to balance weight, costs and CO2 emissions (Albers, Revfi, & Spadinger, 2017).
The starting point for the TWA is a reference product according to PGE. It is important to select the observation area correctly in order to consider all subsystems for the lightweight design tasks. The defined reference product is then optimised in its weight.
First of all, this reference product is analysed with regard to its functions, or if a description of the product functions is available, it is checked for consistency. This step is crucial for the success of the method as it provides the basis for the following steps. At the same time, the mass of the individual subsystems in the observation area is determined (e.g. using CAD data). Afterwards the subsystems are linked to the functions in which they are involved. This allocation takes place in percentages. In this way, a subsystem can contribute to several functions. This results in a mass (cost) per function (see Figure 2 (left)). Furthermore, a paired comparison is conducted in order to determine the relative importance of each function. The function mass together with the functions' relative importance can be plotted in a Function Portfolio to identify lightweight design potentials (see Figure 2 (right)).

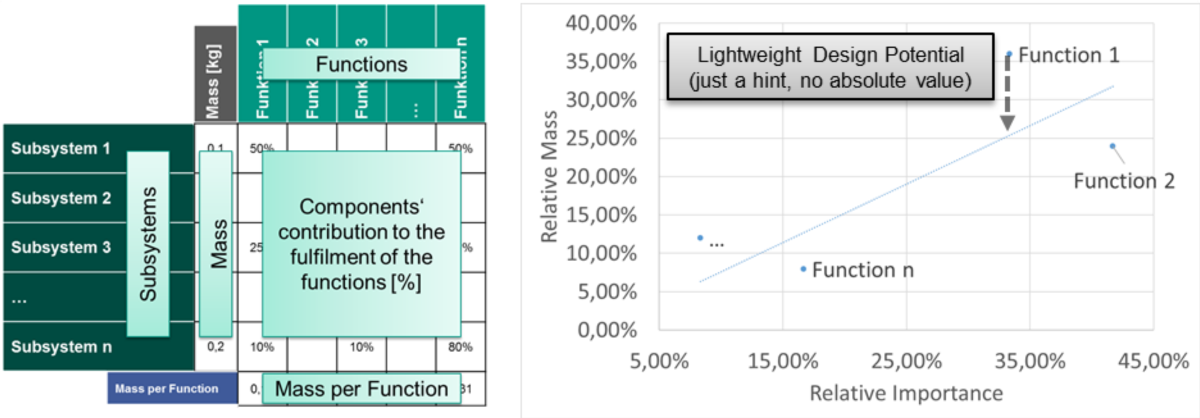

Figure 2. Function-Mass-Matrix (left) and Function Portfolio (right) according to Albers et al. (2013)

Based on the identified lightweight design potentials, new concept ideas are generated supported by various creativity methods (e.g. brainstorming, TRIZ, etc.). The challenge to be met by the product developer is to transfer - in a synthesis step - the "too heavy" functions into a "lighter" embodiment design.
After the identification of lightweight design potentials and the generation of new concept ideas, those concept ideas can be evaluated by using the Function-Mass-Matrix in a reverse direction. As this was not part of the study anymore, the authors refer to literature (Albers et al., 2013).

3 Aim of research and research design

In the following, the research objective is presented first. This is followed by a description of the research design.

3.1 Aim of research

The TWA has been developed five years ago and has been applied in a few projects (Albers et al., 2013). Although it has always been possible to achieve weight savings with the TWA, the value of the lightweight design method has not yet been shown in an empirical study. That means that there has been no direct comparison between the results achieved with the systematic, cross-subsystem approach and the results gained through a corporate-typical development with subsystem responsibilities.

Therefore, the aim of this empirical study is on the one hand to identify the benefit of the method and on the other hand to show that the systematic, function-based approach of the TWA specifically supports the achievement of holistic lightweight design potentials.

3.2 Research design

In order to conduct the study, the participants of the Live Lab "IP - Integrated Product Development" at IPEK – Institute of Product Engineering were selected (Albers, Bursac, Heimicke, Walter, & Reiß, 2018). The participants taking part in this Live Lab are master's degree students in Mechanical Engineering, selected through a selection process with an interview to ensure that they have a high level of expertise. Within the Live Lab, the students go through a product development process in cooperation with an industrial company until the first prototypes are built.

For the study, the 37 students were split into two groups of 18 (= group 1) and 19 (= group 2) students and further into two development teams of five and two development teams of four students resp. into three development teams of five and one development teams of four students. The task for all students was *the identification of lightweight design potentials and based on that the development of rough concept ideas (with reasonable costs)*. The system under investigation was chosen application-oriented and challenging at the same time, as it was the underbody of an automobile. The available time was 4.5 hours, split up as shown in Figure 3.

<table>
<tr><th>Group 1 (4 TWA-Teams)</th><th>Group 2 (4 Non-TWA-Teams)</th><th></th></tr>
<tr><td colspan="2">Introduction and grouping (objectives, boundary conditions, presentation of system under investigation, available documents) (20 min)</td><td rowspan="12">Experts always available as contact persons for both groups</td></tr>
<tr><td>Presentation TWA (30 min)</td><td>Work Phase 1 (35 min)</td></tr>
<tr><td rowspan="2">Function Analysis + Meeting with Experts (45 min)</td><td>Meeting (10 min)</td></tr>
<tr><td>Work Phase 2 (35 min)</td></tr>
<tr><td rowspan="3">Creation of Function-Mass-Matrix + Paired Comparison + Meeting with Experts (45 min)</td><td>Meeting (10 min)</td></tr>
<tr><td>Work Phase 3 (35 min)</td></tr>
<tr><td>Meeting (10 min)</td></tr>
<tr><td rowspan="2">Analysis of the Lightweight Design Potentials (20 min)</td><td>Work Phase 4 (35 min)</td></tr>
<tr><td>Meeting (10 min)</td></tr>
<tr><td>Concept Design (70 min)</td><td>Presentation TWA (30 min)</td></tr>
<tr><td colspan="2">Presentation of the best concepts (One each Development Team) (20 min)</td></tr>
<tr><td colspan="2">Survey (20 min)</td></tr>
</table>

Figure 3. Time Schedule

All students got the same basic information in the beginning (objectives, boundary conditions, available documents and a short introduction to the system under investigation). Afterwards, group 1 was taught in TWA at the beginning of the study and was forced to use the method during the study. The phases were split up in the similar sequence to the TWA workflow (compare Figure 1). As in real product development situations the application of the TWA is very time-consuming, the phases of group 1 were restricted in time. The meetings with the experts served to review the results of the students and bring them back up to the same stage. As group 1 was divided into four development teams, four concept ideas developed using TWA were presented in the final presentation.

The four development teams of group 2 were organised in analogy to a classic corporate structure in order to map the corporate environment in a university environment. That means that there was one person per development team responsible for one subsystem. Usually in real corporate environments, the subsystem responsibilities are organised in different departments which are often locally separated. So, in real world development processes the main communication and exchange of information are often done in meetings. Therefore, the individual members of the development teams of group 2 were locally separated and only allowed to interact at defined meetings (see Figure 3).

This procedure allows the evaluation of the benefits of a methodical approach in comparison to classical corporate processes for the identification of lightweight design potentials. Well knowing that this is only a modelling of the real environment in a university environment, it has to be noted that the investigations in a corporate environment could be slightly different.

The result was one best concept per development team chosen by the team members and presented in front of all study participants.

At the end of the study, a questionnaire with seven questions (see Figure 6) was handed out. The questionnaire addressed the influencing factors for the identification of lightweight design potentials (communication, distinct analysis phase, subsystem interactions, cross-system thinking, detachment from existing restrictions (interfaces) of the reference product) identified by the authors prior to the study.

Following the study, the concept ideas presented were evaluated by three experts from an automobile manufacturer with regard to predefined criteria.

The criteria were

- *Mass reduction* compared to the reference product
- *Costs* compared to the reference product
- *Degree of revolutionariness* in terms of design
- *Overall impression* of the developed concept idea.

4 Evaluation and Interpretation

In this section, the results of the study (i.e. the developed lightweight design concepts and the completed questionnaires) are presented, analysed and interpreted. In doing so, the boundary conditions and interfering factors of the study, e.g. the different expertise of the students, the short working time or the complexity of the system under development should be taken into account when interpreting the results.

4.1 Concept Evaluation

As mentioned above, the eight development teams have developed various lightweight design concepts. They presented the best concept (in terms of lightweight design with reasonable costs) in the form of a concept sheet at the end of the study. Such a concept sheet is shown as an example in Figure 4.

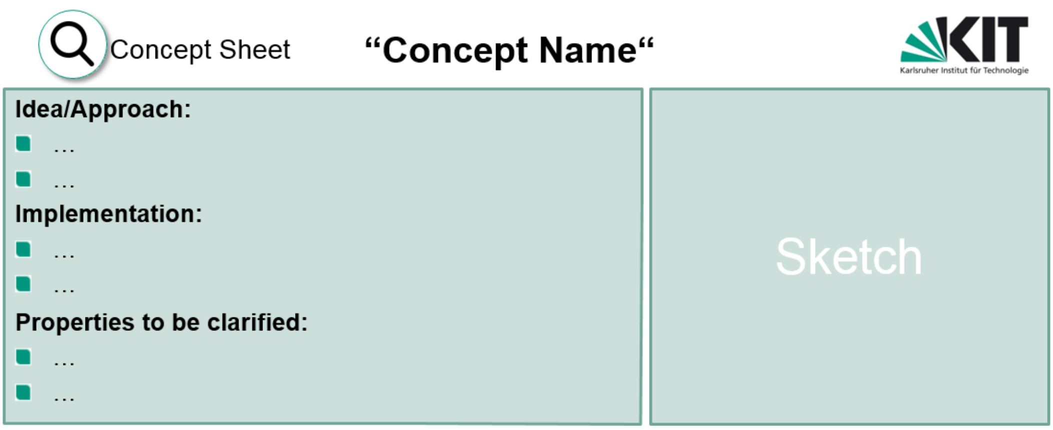

Figure 4. Concept Sheet

Since the evaluation of the underbody concepts with regard to mass reduction, costs, degree of revolutionariness and overall impression requires a high degree of expertise, this evaluation was not carried out by the students but by three experts of an automobile manufacturer. The experts came from the fields of body concept development, underbody simulation and lightweight design.

The evaluation logic consisted of a ranking of the eight concepts (1=best, 8=worst) in the four categories mentioned above. This means that the concept with the lowest average rank is the best and that the smaller the group average the better. An analysis and interpretation of the results follows the presentation of the results in Figure 5.

	Teams	Experts			Results	Average
		Lightweight design	Vehicle body simulation	Vehicle body concepts		
Mass reduction	TWA-1	8	8	1	17	
	TWA-2	1	2	3	6	
	TWA-3	3	4	2	9	
	TWA-4	7	7	5	19	12,75
	Non-TWA-1	2	3	7	12	
	Non-TWA-2	6	5	4	15	
	Non-TWA-3	4	1	8	13	
	Non-TWA-4	5	6	6	17	14,25
Costs	TWA-1	7	7	5	19	
	TWA-2	1	2	3	6	
	TWA-3	3	4	4	11	
	TWA-4	8	8	7	23	14,75
	Non-TWA-1	2	3	6	11	
	Non-TWA-2	5	5	1	11	
	Non-TWA-3	4	1	2	7	
	Non-TWA-4	6	6	8	20	12,25
Degree of revolutionariness	TWA-1	1	2	1	4	
	TWA-2	4	5	3	12	
	TWA-3	2	4	5	11	
	TWA-4	3	1	4	8	8,75
	Non-TWA-1	5	6	6	17	
	Non-TWA-2	7	7	2	16	
	Non-TWA-3	6	3	8	17	
	Non-TWA-4	8	8	7	23	18,25
Overall impression	TWA-1	8	8	1	17	
	TWA-2	1	2	3	6	
	TWA-3	4	7	2	13	
	TWA-4	7	4	4	15	12,75
	Non-TWA-1	2	3	6	11	
	Non-TWA-2	5	5	5	15	
	Non-TWA-3	6	1	7	14	
	Non-TWA-4	3	6	8	17	14,25

Figure 5. Concept evaluation by experts (1=best, 8=worst)

Even if the evaluation was carried out by only three experts and is therefore not based on statistical significance, it is still possible to derive some clear trends in the evaluation of the concepts.

Mass reduction
The mass reduction evaluation reveals very different assessments by the experts, especially for the TWA concepts. A main reason seems to be the very low level of detail of the concepts due to the limited workshop time. The more disruptive the concepts are, the harder it is to estimate the potential for mass reduction. This usually favours concepts that are based on the current design. Nevertheless, the two best-rated concepts were developed by the TWA teams and on average all TWA concepts were slightly better rated. It can be concluded that the TWA's cross-subsystem nature led to new solutions, whereas the conventional development approach has led to very similar concepts.

Costs
The consideration of the costs leads to similar results as the mass reduction evaluation. Since the costs are hard to estimate by the experts in such an early concept phase, the evaluation was primarily based on the complexity of the concepts. In most cases complex product structures are neither in the sense of costs nor of lightweight design, thus can the similarity to the weight evaluation be justified. As TWA concepts tend to involve a rather disruptive approach with a larger share of redesign, they were probably valued as slightly more expensive.

Degree of revolutionariness
As already mentioned, the TWA has led to cross-subsystem concepts. This is clearly reflected in this valuation category by the assessment. Each of the TWA concepts was rated better on average than the Non-TWA concepts. In this study, the TWA has thus led to significantly more integrative and revolutionary concepts.

Overall impression
Since the weight and cost ratings are almost identical, the evaluation of the overall impression is similar. It can be noted that one concept from the TWA group was clearly rated best, whereas the Non-TWA concepts were rated similarly because of their proximity to the reference product. The TWA has thus led to more revolutionary concepts, which has resulted in very different expert assessments reinforced by the low level of detail in the concepts. This approach can therefore support the development of completely new lightweight design solutions in the sense of an overall system optimum.

4.2 Questionnaire Evaluation

In addition to the concepts, all participants were also surveyed by means of a questionnaire on the study and the methods used. The questionnaire interrogated the influencing factors for the identification of lightweight design potentials (communication, distinct analysis phase, understanding of subsystem interactions, cross-system thinking, detachment from existing restrictions (interfaces) of the reference product) previously derived by the authors from literature (Albers, Reiß, Bursac, & Breitschuh, 2016; Friedrich, 2017; Henning & Moeller, 2011). The results of this questionnaire are shown in figure 6.

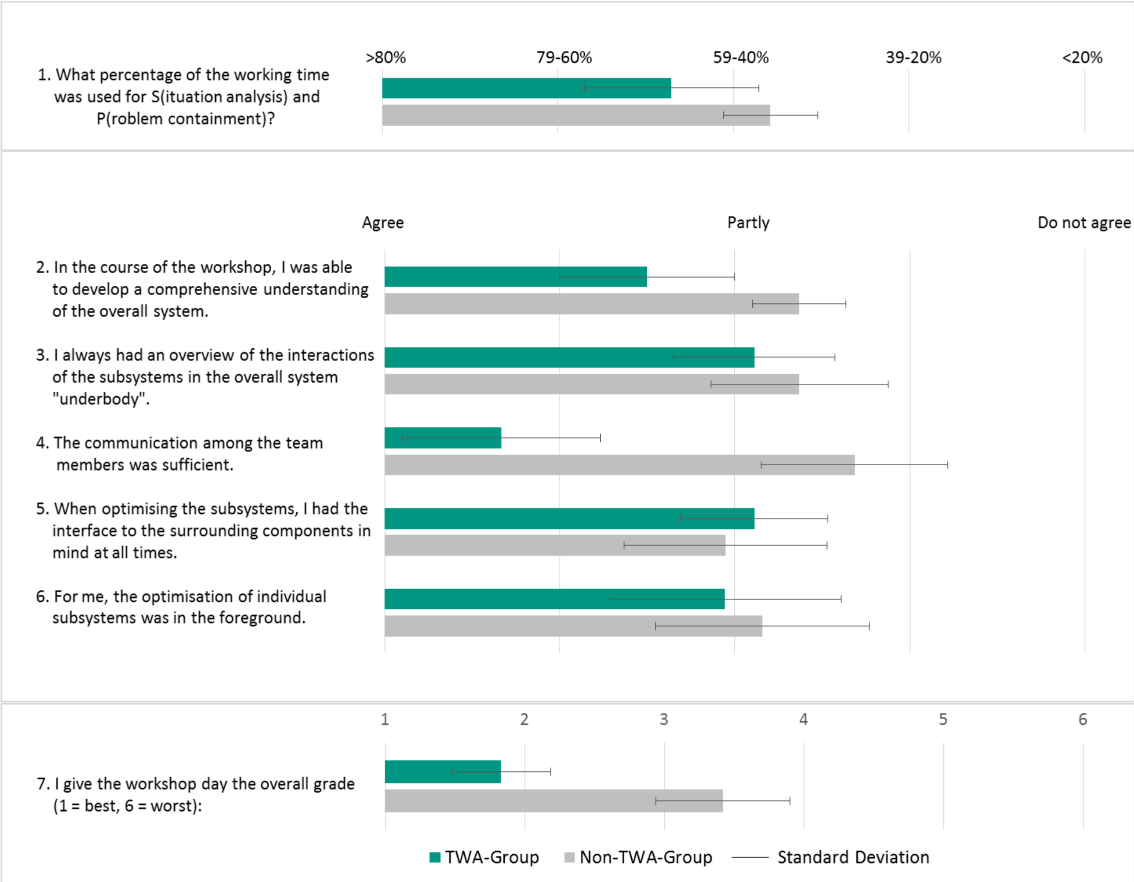

Figure 6. Results of questionnaire

Interpretation of question 1: *"What percentage of the working time was used for S(ituation analysis) and P(roblem containment)?"*

According to the SPALTEN methodology, situation analysis (S) and problem containment (P) are important for the success of a product development (Albers et al., 2016). If these two activities are not carried out properly, it will extend the total time required. Therefore, appropriate time should be spent on both activities (up to 70%) in order to address the right problem with the generated alternative solutions. It is shown that the TWA leads to a stronger focus on the phases S and P.

Interpretation of question 2: *In the course of the workshop, I was able to develop a comprehensive understanding of the overall system.*

The second question shows that the TWA leads to a better overall system understanding. This is mainly due to the Function-Mass-Matrix, which provides a good overview of the interactions in the investigated system. This question is a consequence of the first question, because a more intensive analysis of the system logically leads to a better understanding of the system. The underlying understated assessment can probably be explained by the complex system and the lack of students' expertise.

Interpretation of question 3*: I always had an overview of the interactions of the subsystems in the overall system „underbody".*

The positive effect of the Function-Mass-Matrix is also evident in this question. This provides an improved overview of the interactions in the system. Nevertheless, it must be mentioned that a larger difference could have been expected on this issue.

Interpretation of question 4*: The communication among the team members was sufficient.*

In the field of communication, this study reveals the biggest difference between the methods. One reason for this is that the team members of the TWA are forced to fill in the artefacts together like the Function-Mass-Matrix. Communication is therefore a core aspect of TWA. In contrast, the comparison group simulated a real situation in an automotive company. Communication was deliberately cut off and only allowed for certain meetings. This explains the poorly rated communication in the peer group. However, since communication is an obstacle in real companies due to the mostly subsystem-based organisation, this study design is considered suitable.

Interpretation of question 5*: When optimising the subsystems, I had the interface to the surrounding subsystems in mind at all times.*

At first glance, the students' response is surprising, as the TWA should lead to an improved overall system understanding. However, since the TWA transforms the component structure into a functional structure, no further value must be attached to the interfaces in the reference product. The resolution of these defined interfaces expands the creativity space and is an essential part of TWA.

Interpretation of question 6: *For me, the optimisation of individual subsystems was in the foreground.*

This shows a balanced picture for the two comparison groups. The TWA Group is focusing even more strongly on lightweight subsystem design. This is surprising at first, but the evaluation varies within the range partly. It is therefore hard to speak of a focus on lightweight subsystem design and the TWA does not categorically exclude lightweight component design, since this is also part of concept lightweight design (Henning & Moeller, 2011).

Interpretation of question 7: *I give the workshop day the overall grade (1=best, 6=worst).*

The concluding question shows above all that the students liked the TWA's approach very much. In spite of the sometimes complex methods, they found the procedure to be obviously helpful and effective. For the peer group, the valuation was only average, as the learning effect was reduced for them. The emerging feeling of being a peer group must have made a worsening contribution.

5 Conclusion and Outlook

The TWA promotes a cross-subsystem concept of lightweight design by transferring the entire system into a functional structure. In this way, it is possible to think freely of predefined interfaces from the reference system. As a result, completely new lightweight design solutions can be found in the sense of an overall system optimum. Within the scope of this study, this could be proven with the concept evaluation by automotive experts. Thus, the concepts developed by the TWA group were consistently evaluated as more revolutionary and more integrative compared to the peer group. Furthermore, the questionnaire underlined that the system analytic part of the TWA led to a stronger focus on situation analysis and problem containment. This and the TWA's cross-subsystem character leads to an improved overall system understanding and significantly improved communication between the engineers involved.

This study confirmed the benefits of TWA empirically. In order to further develop the TWA a follow-up study will be conducted to uncover optimisation potentials. For this purpose, engineers from industry as well as students who have already worked extensively with the TWA are surveyed about the individual steps of the method.

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