ICED13
INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED13
19-22 AUGUST 2013, SUNGKYUNKWAN UNIVERSITY, SEOUL, KOREA

TARGET WEIGHING - A NEW APPROACH FOR CONCEPTUAL LIGHTWEIGHT DESIGN IN EARLY PHASES OF COMPLEX SYSTEMS DEVELOPMENT

Albert ALBERS (1), Daniel WAGNER (2), Anne RUCKPAUL (1), Benjamin HESSENAUER (1), Norbert BURKARDT (2), Sven MATTHIESEN (1)
1: Karlsruhe Institute of Technology, Germany; 2: BMW AG, Germany

ABSTRACT
This research suggests a new approach in early stages of product development, aiming at a lightweight orientated functional concept design. Based on the systematic approaches of target costing and value engineering a functional analysis is proposed to match mass and function. This allows the identification of where the most promising weight reductions could be achieved without focusing single components. Search fields for further investigation are identified based on the resulting weight of functions. By including the significance of functions for internal and external customers this approach points out opportunities for product optimizations. Furthermore, the created data enables a systematic way to evaluate the target weight of new concepts and makes a selection easier. This proposed approach was validated in two projects regarding a car climate control system and a high voltage battery for plug-in hybrid electric vehicles. This method raises the awareness to lightweight potential within early product design and determines target values for weight, cost and volume of new concepts.

Keywords: lightweight design, target weighing, design methods, functional modelling, early design phases

Contact:
Prof. Dr. Ing. Albert Albers
Karlsruhe Institute of Technology
IPEK - Institute of Technology
Karlsruhe
76131
Germany
albert.albers@kit.edu

1 INTRODUCTION

Fuel efficiency targets in Europe – set by the EU climate commissionary – are very challenging. The allowed amount of emitted CO_2 by 2020 will be 95 g/km averaged over the whole fleet of cars manufactured by one OEM. This target poses a glaring contrast to the advancing demand and need for safety and comfort of the passengers and pedestrians.

This contrast is leading to alternative drive train concepts as well as to efforts to reduce the overall vehicle weight. There is the need of a structured design process in order to identify possible search fields for lightweight design and to improve the estimation of the final component weight. “Lightweight design is a mind-set” says Heinrich Timm[1]. This quote emphasizes the importance of consistent identification and use of lightweight potentials in a total system. Therefore, the whole development process has to be considered for new methods and tools which deal with the specific problem of weight saving.

The usual activities in a lightweight design centric product development process are specified in Figure 1.

Figure 1. Activities in a lightweight design development process

Each activity listed has to be supported with the right set of tools and methods in order to derive an optimal solution to the posed problem. In this work, a new method is proposed, which deals with the problem of finding hidden potentials for weight-saving activities.

There are five main strategies of lightweight design (Moeller and Henning 2011) which can roughly be used in the following order in the product development cycle:

- Conditional/environment
- System
- Material
- Shape/form
- Manufacturing.

This work mainly deals with system lightweight design and the activity “situational analysis – potential for lightweight design in total system”. This combination is usually found in early stages of the product development processes, when there is little knowledge about the system. Ideally though, a predecessor system exists and is in use.

The goal of the proposed method is the identification of lightweight potential in a total system (e.g. a battery system). To this end, “heavy” functions are identified in a similar manner to the target costing method. Target costing begins with the question: “What should a product’s cost be?” (Feil et. al., 2004) and breaks these costs down to the individual functions which should be fulfilled. In a similar manner, the question which should be answered with the approach presented here is: “What should a

[1] Heinrich Timm, Leichtbaugipfel 2012, Würzburg, Germany. Timm is the intellectual father of the Audi aluminum space frame

product's weight be?" and additionally: "What amount of mass should each function contribute to the total system mass?"
In order to answer that question, a bottom-up-analysis is used on a predecessor system – in this case, for demonstrating the approach, two relevant systems are used: a high voltage car battery (plug-in hybrid electric vehicle) and a car climate control system (HVAC – heating, ventilation and air conditioning). The approach matches functions to their respective mass by functionally dividing each component of the total system.

2 BASICS

2.1 Target Costing

The target costing approach was introduced in Japanese companies in the 1960s as a proactive cost management tool on top of the just-in-time (JIT) production systems. After JIT reduced the costs in the production stage there were efforts to achieve cost reductions in earlier phases of the development process. As a result the target costing is an activity to reduce life-cycle costs of new products by identifying opportunities in the product planning and development (Kato 1993). It is a reverse costing methodology to determine the tolerable costs for a new product (Zengin and Ada 2010). As showed in Figure 2 this process determines an estimated or target selling price for the product which consists of the desired profit and the target costs. Based on the market, customer needs and competitors the desired profit margin is derived. Together with target selling price the maximum costs for the product are calculated. These costs are distributed to material and component level to control the costs while developing the new product. The amount of the target costs has to include all expenses like production, purchase, marketing, R&D etc. (Ellram 2002).

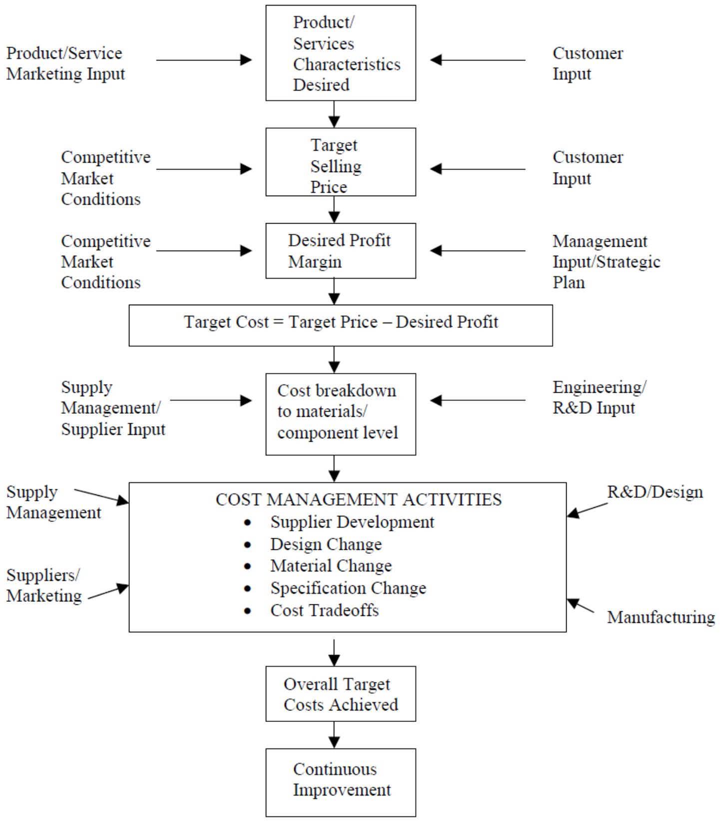

Figure 2. Target costing process (Ellram 2002)

Forthcoming market changes demand cost reductions of new products while ensuring quality and functionality in order to gain market share and experience economic success (Cooper and Slagmulder 2000). According to (Monden 1996) the first main objectives for target costing therefore is to reduce the costs of new products to ensure a company profit while satisfying the market and customer needs. The second objective is the orientation of all employees to cost aware development. Overall this approach focuses customer attribute satisfaction (Ibusuki and Kaminski 2007) and in contrast to traditional approaches costs are an input in the development rather than a result (Cooper and Slagmulder 2000).

2.2 Value Engineering

The value engineering (VE) process is complementary to the target costing approach. While target costing shows company targets to be achieved for future profitability the value engineering identifies possible cost reduction in the product development. In the majority of cases VE is used to increase the value of a product by improving existent functions without increasing any costs (Ibusuki and Kaminski 2007). According to the standard procedures DIN 2800 and DIN EN 1325-1 the value engineering approach serves as a development and improvement process for products, technical processes, science and management. The application of the value analysis achieves an advancement and value increase of the considered objects. Simultaneously the needed effort is reduced especially regarding costs. In the DIN 2800 (2010) there are ten steps described within a value engineering project. A major step is the function analysis in order to define the functions to which the costs are assigned. A possible systematic approach for function determination is the Function Analysis System Technique (FAST) diagramming (Younker 2003).

Also the Society of American Value Engineers (SAVE International, 1998) proposes similar steps in their VE work plan:

- Preparation: product selection, target formulation, work group and activity planning
- Information: collection of general product information (details about costs and values)
- Analytic: identifying functions and their costs, determine critical functions and compose the problem (this step is examined in more detail in 2.3 Cost of functions)
- Creative: gather, classify and select new ideas
- Judgment: developing alternatives for technical and economical solutions and selection of the best alternative
- Planning: presentation of the proposal, work plan for implementation
- Execution.

The central measure for all the decisions in the VE is the value that is defined by benefit divided by effort. This value should generally be > 1 and increased through VE projects (VDI-Gesellschaft Produkt- und Prozessges. 2011). Summed up, value engineering is a structured approach to increase different values of a product by introducing a creative, function orientated design process (Marchthaler, Wigger and Lohe 2011). The focus is corresponding to the target costing on costs and the relevance for the customer. This approach is embedded in the leadership theory called value management.

2.3 Cost of functions

An essential part in the approach of VE is the functional analysis in order to relate component costs to their functions. The assignment with the component costs adds up to the cost of functions. A possible procedure is to deploy the product system in the main subsystems and identify their components main functions (Marchthaler, Wigger and Lohe 2011). The functions get classified as main (essential for the product functionality) or secondary (supporting the main functions) (Ibusuki and Kaminski 2007). In order correlate the functions with their costs it is necessary to prepare the actual component costs of the predecessor system. In some cases it is required to estimate system costs or to find eligible share of costs (e.g. development costs of modular parts) through reverse engineering. To calculate the cost of functions the relevant functions need to be linked to the components that provide them. That means for each component the effective influence to provide the function need to be assessed. The different cost shares of one function summed up result in the cost of this function (VDI-Gesellschaft Produkt- und Prozessges. 2011). This principle is one major basis for the proposed method.

3 OBJECTIVES AND APPROACH

3.1 Matching of mass and function

Similar to the target costing and value engineering approach, the presented approach ties the functional requirements of a system to the weight of each function in order to raise awareness to lightweight potentials in an early product development phase. Extending the value engineering approach, a function analysis is used in order to derive the weight of each function. Differently to the functions in value engineering projects, here the functions of the product are examined in a more technical view. With this approach, two distinctive objectives can be achieved:

Objective 1: Exposing hidden potentials

In its simplest form, one objective of the proposed method is to gain knowledge about a predecessor system in order to expose hidden potential for weight saving activities such as new concepts for existing functions. Therefore, the functions and components of a system have to be analyzed and ranked according to their weight. Afterwards, groups of functions can be clustered and be used as potential search field for e.g. a brainstorming session. The process for analyzing the predecessor system is presented in Figure 3:

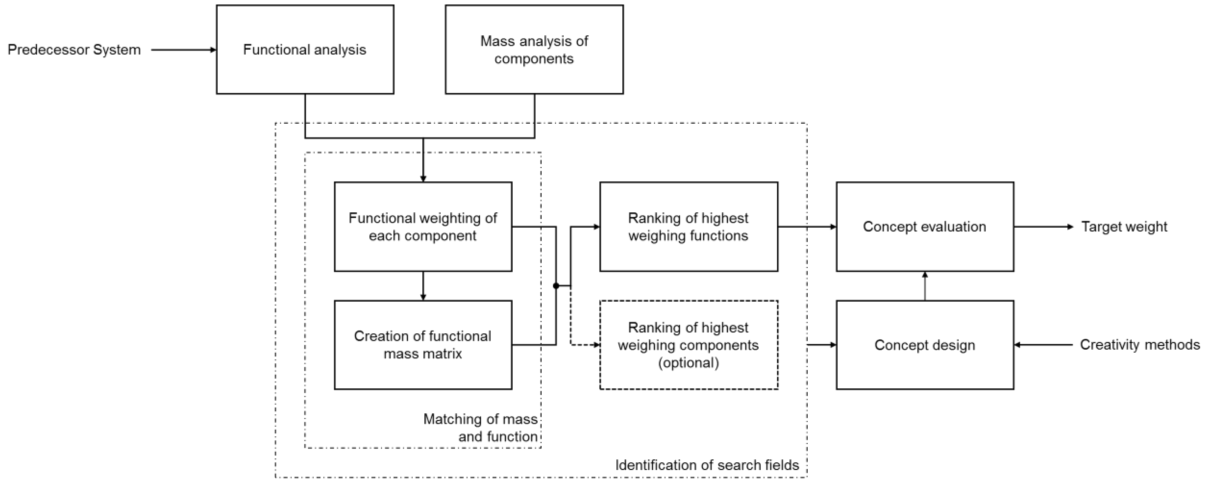

Figure 3. Target weighing process

In this case, the process starts with a functional and a mass analysis of each component of the predecessor system. This leads to a functional hierarchy similar to the one depicted in Figure 5. The resulting functions are applied to the columns of a functional mass matrix (see Figure 6), whereas the components are applied to the rows of this matrix. Each component attributes a certain percentage to the fulfillment of a specific function. This percentage is applied in the matrix. The percentages itself are derived by an approximate break-down of each component. This practice proved to be accurate enough for this kind of problem, where only a rough ranking of each function is necessary. In order to involve the complete system weight the summation of every row has to be 100 %. It is of course also possible to rank for the heaviest components, but this is rather trivial. This whole process then leads to an identification of new search fields, which can be used for concept design and concept evaluation. In order to create concepts within one search field it is practicable to use methods like TRIZ to find new solutions for the contradictions of the selected function.

Objective 2: Include significance of functions and additional examinations

The investigated question "What portion adds this group of components to the fulfillment of the function?" helps to evaluate the percentage of each matrix field. As this procedure is not focused on just one value it is possible to match not only the weight to the functions but also their costs and volume. The creation of the matrix consequently is a one-time effort that is used for several outcomes. This is important for the subsequent quantified evaluation of concept ideas by sensitivity analysis (chapter 3.2). In addition the significance of the functions for internal and external customers is helpful to identify development potentials. The rating of functions among each other for example by pair wise comparison or analytical hierarchy process (AHP) method is resulting in a prioritization list. The combination of the function weights with their relative importance is showed in a portfolio diagram (Figure 8). By analyzing the portfolio several potentials could be identified. When there is a heavy function that has no high significance for the customer then the weight of the components fulfilling this function should be reduced. By integrating the function significance this approach is adapted to the fact that some functions for example concerning mechanical loads need more weight for their structural relevance.

Additionally the matrix of functions and components is helpful to identify further variations in system design. In this table functions that are highly integrated or differentiated can be detected. For example when one component is fully achieving one function (100 %) that is relatively heavy. In this case a possible stimulus in the creativity phase could be to try to split the function in more than one component. When there is a heavy function that is separated on several components (<5% each) a possible concept could be to try to integrate it more into one component. This information is useful for a structured direction in the creativity process.

3.2 Sensitivity analysis and concept evaluation

The exclusive view on component level ignores their task and relevance in the system context and produces in most cases just evolutionary development steps of the single components. With the presented approach, it is easier to identify the source of weight, costs and volume in the system. Hereby, not only the allocation of functions to components could be redefined in new product concepts but also the gained correlations could be used for concept evaluation. After a new concept idea is created in one of the search fields, it is useful to analyze its impact on the system values. The practice of a stepwise concept selection proved to be a structured and efficient way to find the most promising ideas after a broad idea gathering. In order to rate concept ideas a three step evaluation is suggested. First, a rough preselection reduces according to experience almost two-thirds of the ideas. Possible criteria for sorting out ideas are conflicts with physical laws, the technical feasibility or the goals of the project. However these ideas are important in the creativity phase to induce other ones or to discuss the reasons within a interdisciplinary team. In the next step a qualitative rating considering weight, functionality, costs and technical feasibility creates a ranking list for the actual project targets. Usually it is necessary to detail the best concept ideas after this step to facilitate a more precise evaluation.

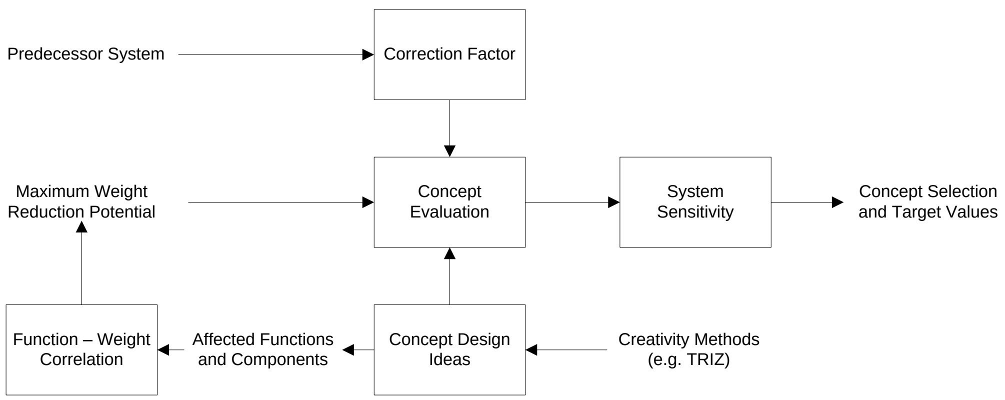

Figure 4. Sensitivity analysis for concept evaluation

For the last step to choose the ideas that get further developed this approach uses a quantified impact analysis on the system (Figure 4). For this purpose it is necessary to identify the components that would get changed and the functions that are affected by the considered concept. With this indication the matrix (Figure 6) can be used again in the opposite direction as described before. Here the maximum impact on the weight results from the matrix by adding up the quantified figures in the matrix fields (intersection points between the changed components and the affected functions). Of course these figures need to be reduced to a realistic level as the maximum impact is just a theoretical value. For this reason an individual correction factor is set by experienced data (e.g. similar past improvements or degree of change to the components) and the qualitative evaluation from the step before. These correction factors need to be derived over time and represent a company’s experience. The final target values result from the maximum impact values multiplied by the correction factors. By this, it is ensured that the best improvement on system level is focused and not only a local maximum (strong improvement of a light function). This is important as the ideas in the creativity phase often don’t stay just strictly in the search field. In the end every concept that passed the preselection process gets clear values for the expected improvement. One the one hand this is the decision basis for the final concept selection and on the other hand these values serve as target values (e.g. target weight) in the further realization. So this approach helps to develop early phase concepts in the most promising direction, to choose concept ideas for implementation and to estimate their quantitative target weight, costs and volume. The target values additionally reduce the risk of losing the aim in the implementation of new concepts.

4 APPLICATION

4.1 Climate control unit

As part of a research project the light weight potential of a climate control unit had to be exposed. Climate control units are used to provide a specified climate in e.g. vehicles. It normally consists of an air suction, a filter, an evaporator, a heating and a unit for directing the refreshed air to several air valves. Aim of the project was to expose hidden light weight potentials of the unit without losing any functional quality in comparison to the predecessor system.
In the first step the unit was analyzed according to its main functions, auxiliary functions and sub-functions. The functional analysis was deliberately conducted independent from the parts and elements of the system. Outcome of the analysis was a function tree with over 60 functions and sub-functions.

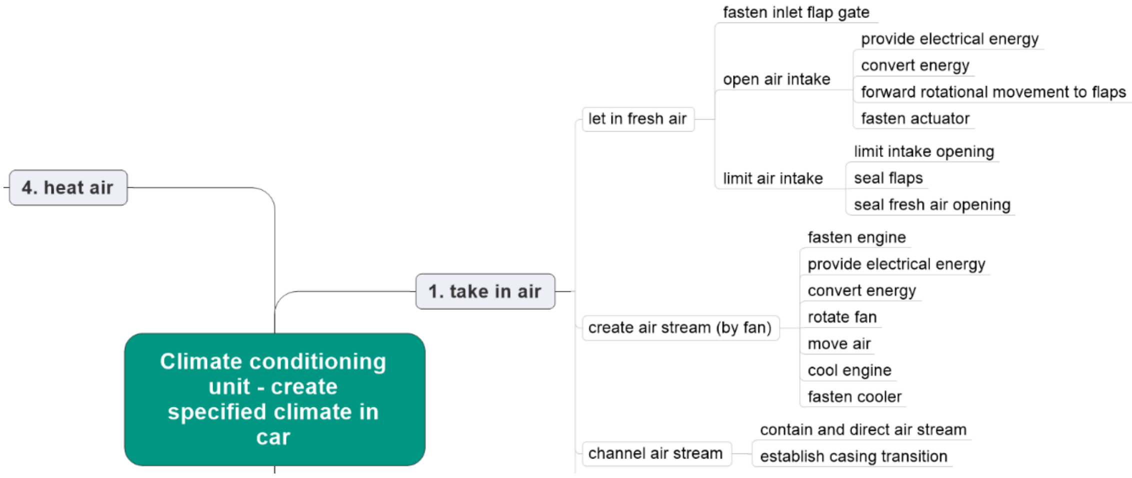

Figure 5. Function tree climate control unit

The function tree was transferred to the columns of a table. The rows were filled with the single parts from the structure tree of the climate unit (Figure 5). The mass of all parts was determined and entered into the functional mass matrix behind each part.

	functions	1.) take in air																							2.) filter air	
		take in fresh air								create air stream							channel air stream		take in circulating air						filter air	
																	616,0		216,0						430,0	
Functions from function tree																			open air intake 116,0							
components	mass in gram	fasten inlet flap gate	provide electrical energy	convert energy	forward rotational movement to flaps	fasten actuator	limit intake opening	seal flaps	seal fresh air opening	fasten engine	provide electrical energy	convert energy	rotate fan	move air	cool engine	fasten cooler	contain and direct air stream	establish casing transition	provide electrical energy	convert energy	forward rotational movement to flaps	fasten actuator	limit intake opening	fasten intake flaps	fasten filter	filter air
mass per function	9835	10	40	50	20	16	118	22	20	86	40	900	300	150	150	46	500	116	40	50	10	16	90	10	130	300
Parts from structure tree																										
fan control	0																									
filter cover	50																								100%	
feeder	0																									
hexagon bolt	0																									
hybrid filter	300																									100%
numberplate	0																									
casing	200	5%				5%	5%	5%									50%	10%				5%	10%	5%		
fresh air flap	120						90%	10%																		
air casing: circulating air flap	70																						100%			
cam plate	10				100%																					

Figure 6. Function-mass-matrix

The most important step followed as the parts were assigned to functions. The mass of a function was portioned in percentage to the functions it participates in. The assignment was easy for e.g. a lever which fulfills only one function, to forward a rotational movement to the flaps. For other parts, e.g. the casing, it was more complicated due to the integration of several functions in the single part. The main function of the casing is to contain and direct the air stream but it also provides fastening points for flaps and actuators and adds to the stability of the whole system.

After assigning all components of the system to the functions the “mass per function” could be calculated (Figure 6).

Two groups of light weight potentials could be extracted directly from the functional mass matrix, the heaviest components and the heaviest functions which are:

- Convert energy and rotate fan (sub-function of “take in air” and “create air stream”)
- Contain and direct the air stream (sub-function of “take in air” and “channel air stream”)
- Precipitate humidity (sub-function of “cool air”)
- Exchange heat (sub-function of “heat air with fluid”)

The lists of heaviest components, functions and heavy functional clusters comprise the main light weight potentials. Based on the lists four search fields were defined as background for a following creativity workshop. The search fields were named “channel air”, “contain air”, “control air gates” and “provide the supporting structure”.

Based on the predefined functional mass matrix and the identified search fields in total 99 new ideas on light weight design were generated during the creativity workshop. After selection of ideas, three main concepts were summarized which hold a great potential for lighter weight of a successor climate control unit.

4.2 High voltage battery (BMW Group)

The high voltage battery system of a plugin hybrid electric vehicle (PHEV) was subject of a value analysis project within the BMW Group. According to the VE work plan, the electric energy storage system (EESS) of a sport utility vehicle was selected as demonstrator system. An interdisciplinary team (Pre-Development, R&D, Production, Company Strategy, After Sales etc.) was chosen. The objective of this project was a reduction of weight by 20% without increasing the costs. In the information phase different sources were used to collect relevant data. Benchmarks of competitor products searched their strengths in comparison to the own product. Furthermore, technical solutions for different functions were analyzed in practice. By breaking down the EESS components regarding costs, weight and volume first pareto analysis were possible on a component basis (Figure 7). In internal workshops the customer needs were examined with the expertise of after sales colleagues.

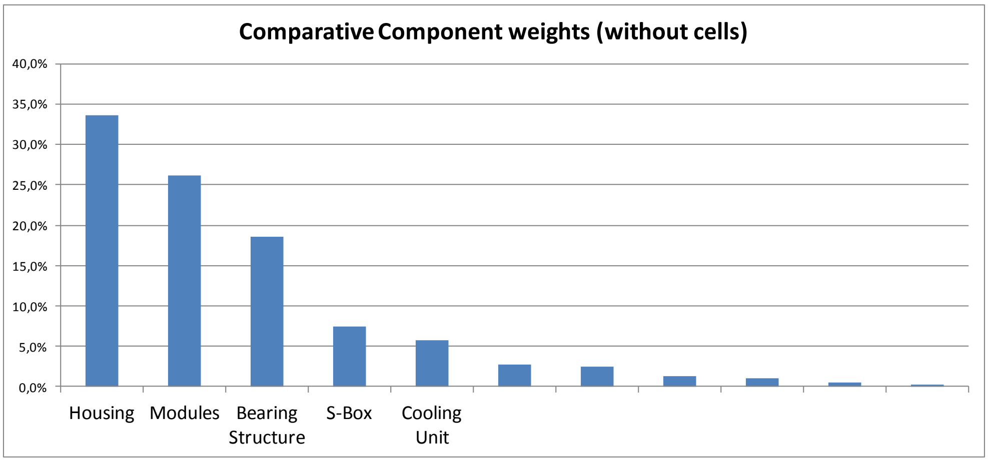

Figure 7. Pareto Analysis EESS

The next step consisted of identifying the necessary level of functional abstraction. The study was simplified to a list containing only functions with higher relevance in order to keep the effort manageable. Of the same tenor the components were grouped for practicability. Therefore, a list of 15 different functions of the EESS were formulated and matched to their technical requirements (e.g. crash loads of 60 g for 45 ms in x/y/z direction). Before the functions got aligned to their costs they were rated from a customer's view regarding the fulfillment degree. As the end customer is not directly affected by all selected functions, the customer view implied also internal customers such as production. Depending on the actual performance of functions, rough optimization directions were set. Overachieving functions (fulfillment degree > 100%) can be reduced and then again underperforming ones (< 100 %) need to be enhanced. As functions that satisfy discrete requirements typically are hard to rate regarding their performance, the focus here lies on scalable functions.

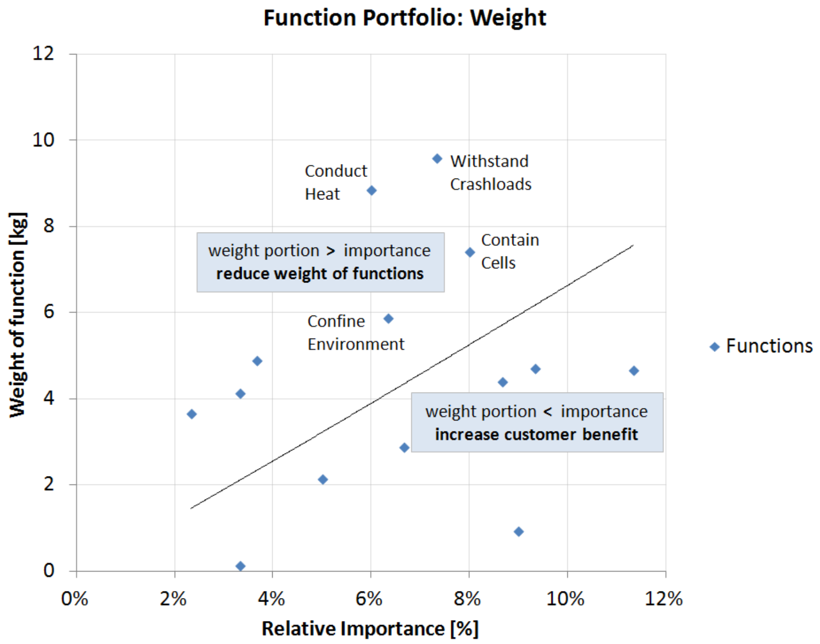

Figure 8. Function Portfolio regarding weight and relative importance EESS

In the following step the cost of functions were derived as described in chapter 2.3 in the form of a matrix table. Following the approach described in chapter 3.1 and 3.2 the mass per function got compared to their relative importance in a portfolio diagram (Figure 8).

This diagram reveals opportunities in the EESS on functional level. Regarding the function analysis and the matched mass of the functions the following search fields were identified: Confine Environment, Withstand Crashloads, Conduct Heat and Contain Cells. These functions could be identified as over dimensioned regarding their weight. Especially the function of withstanding loads in case of a crash is identified as biggest optimization opportunity. Reasons for this could be the conservative approach considering high-voltage safety in hybrid vehicles as well as manufacturing restrictions like minimal wall thicknesses.

In these search fields 275 ideas were created with creativity methods and idea workshops. For example new crash safe designs for the battery were generated by a well-directed movement of components. Also some components could be significantly improved by reducing their functions and assign them to a new structural component. In these interdisciplinary workshops the data of the function analysis was used to stimulate new ideas. After a rough preselection, 62 % of the ideas were rejected and the remaining were qualitatively rated considering weight, functionality, costs and technical feasibility. After this, 16 ideas were chosen for further elaboration. By the quantitative evaluation described in chapter 3.1 four of the concepts were selected for final implementation. The described approach was the basis to reach the project goal and delivered promising new concepts. Now the target values are used while detailing the concepts and implementing them into the EESS. The gained experience in this process is then reused to adapt the correction factors described in section 3.2.

5 CONCLUSION

In this paper, a new approach is proposed which allows for conceptual development of lightweight systems. This methodology is following the approaches of target costing and value engineering. It uses functional analysis as a tool in order to gain a weight of each function. With this approach, new concepts for lightweight systems can be derived and evaluated fast and efficiently. This is shown in two different examples. The proposed method also allows for rising awareness to lightweight potentials within the product development process. Furthermore, it can be used to include the significance of functions for the customer to fortify the development in early phases of product design. Finally, the data gained in this method is useful for concept evaluation and selection as well as determination of target values for weight, cost and volume.

Especially the development of electric drive trains is facing disruptive steps in product design while requirements (e.g. safety, electric range and power) increase. The suggested method helps to discover hidden opportunities and to justify research fields. As R&D budgets in the automobile industry are under pressure because of dropping sales, a systematic approach for new concept design makes it possible to overcome market challenges and to fulfill future emission laws. The advantage of the target weighing lies in the extraction of system knowledge and the combination to quantitative results. In addition, this is a simple was and easy to use for design engineers to understand concept chances and their impact on the system.

ACKNOWLEDGMENTS

Dieter Ziegltrum (R&D - Value Management, BMW AG)
Dr. Thomas Höfler (R&D Battery – Mechanical Design and Calculation, BMW AG)

REFERENCES

Cooper, R. and Slagmulder, R. (2000). Develop profitable new products with target costing, *IEEE Engineering Management Review*, Vol. 28(1), 79–88.

Ellram, L. M. (2002). Supply management's involvement in the target costing process, *European Journal of Purchasing and Supply Management*, Vol. 8(4), 235–244.

Feil, P., Yook, K. H. and Kim, I. W. (2004), Japanese target costing: a historical perspective, *International Journal of Strategic Cost Management*, Vol. 11

Ibusuki, U. and Kaminski, P. C. (2007), Product development process with focus on value engineering and target-costing: A case study in an automotive company: Scheduling in batch-processing industries and supply chains, *International Journal of Production Economics* 105(2), 459–474.

Kato, Y. (1993). Target costing support systems: lessons from leading Japanese companies, *Management Accounting Research*, Vol. 4(1), 33–47.

Marchthaler, J., Wigger, T. and Lohe, R. (2011), Value Management und Wertanalyse.

Moeller, E., Henning, F. (2011), Handbuch Leichtbau, Methoden, Werkstoffe, Fertigung, München, Wien, *Carl Hanser Verlag GmbH and CO. KG*

Monden, Y. (1996), Cost reduction systems: Target costing and kaizen costing, *Journal of Product Innovation Management*, Vol. 13(2), 187.

VDI-Gesellschaft Produkt- und Prozessges. (2011), Wertanalyse - das Tool im Value Management, Berlin, Heidelberg: *Springer-Verlag Berlin* Heidelberg. (VDI-Buch).

Younker, D.L (2003), Value Engineering: Analysis and Methodology, *Marcel Dekker*.

Zengin, Y. and Ada, E. (2010). Cost management through product design: target costing approach. *International Journal of Production Research*, Vol. 48(19), 5593–5611.