AGILE LIGHTWEIGHT DESIGN - THE EXTENDED TARGET WEIGHING APPROACH IN ASD - AGILE SYSTEMS DESIGN USING FUNCTIONAL MODELLING WITH THE C&C²-APPROACH

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ABSTRACT

The context of product development can be understood as transformation of needs into technical solutions under the continuous handling of uncertainties. These result particularly in early development phases from a lack of technical knowledge. In order to counter the uncertainties, companies are increasingly implementing agile approaches, which mostly originate in the area of software development. Although these are suitable for flexible handling of project management activities and lead to an increased reactivity of the development team, they do not address the early and continuous integration of technical knowledge into the process. With the aim of optimizing mechatronic systems with regard to their lightweight design potentials, in this article a method is developed that supports agile development with the goal of lightweight design. Therefore, it combines a method for functional modelling with a function-based lightweight design method. The targeted integration of technical knowledge has shown that lightweight design potentials can be optimized iteratively in agile approaches. As an initial validation, the applicability of the method was demonstrated in a development project.

Keywords: Lightweight design, Embodiment design, Design methodology, Agile Mechatronic System Development, PGE - Product Generation Engineering

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1 INTRODUCTION

The development of mechatronic systems is a problem-solving process that requires a continuous handling of uncertainties (Albers *et al*., 2018a). These are caused by unclear and contradictory goals and requirements, which, due to their high dynamics (Schmidt *et al*., 2017), make development projects a complex task with unclear interactions between necessary but partly unknown information, goals and results (Snowden and Boone, 2007). Additionally, requirements and boundary conditions are often changed or extended in the course of a development project (Morkos *et al*., 2012). Current trends are creating additional boundary conditions from the context of lightweight design. These increase the potential for conflicting goals (e.g. lightweight design targets vs. customer wishes) and thus the uncertainties regarding customer satisfaction through the developed solutions (Unselt *et al*., 2004). Especially in early development phases, in which the embodiment parameters of the product are partly undefined, it is difficult to make predictions regarding lightweight design potentials. Many decisions in a development project have to be made based on vague assumptions (Meboldt *et al*., 2012). According to the rule of 10, early gain of insights is important, as changes become more and more expensive with the maturing of the product (Ehrlenspiel und Meerkamm 2017). However, since early decisions in the product development process have a decisive influence on downstream processes (Albers *et al*., 2019a), it is necessary to derive potentials and limits from the context of lightweight design at an early stage and to continuously concretize and consider during the process. This is contrasted, however, by the fact that lightweight design methods like topology optimization usually require a parameterized product and therefore can't be used in early phases. In order to minimize uncertainties in development by continuously reviewing results, to increase transparency in the development process and to make processes adaptable and teams reactive, companies are increasingly using agile development approaches (Schmidt *et al*., 2017; Gloger, 2016). Although these approaches (e.g. Scrum (Gloger, 2016) or Design Thinking (Plattner *et al*., 2011)) are generally suitable for dealing with uncertainties regarding project management (Scrum) or creative problem solving (Design Thinking), they do not aim at the technical interpretation of the embodiment of products. In order to identify and implement lightweight design potentials early in the development process, technical knowledge regarding the relations of embodiment and function is essential. This knowledge mostly results from experiences of employees whereby another challenge for today's companies arises, as implicit knowledge is becoming less effective as a result of increased employee turnover (Schmidt *et al*., 2013). In the dynamic and complex context of product development, a high reactivity of the development team is a decisive ability with regard to the early and continuous validation of development results. In the context of mechatronic system development, technical questions are particularly relevant. At the beginning of each development project, the low degree of product maturity and the necessary technical understanding with regard to embodiment function relations are contrasting elements with regard to early and continuous development towards lightweight design goals. The aim of this article is to support product developers in generating the necessary knowledge regarding the identification of lightweight potentials at an early stage in the development process. By means of this knowledge, lightweight design potentials are to be implemented iteratively into a concept during an agile process. The technically necessary knowledge is based on the modelling of the correlations between embodiment and function. The resulting method enables development teams to handle uncertainties in the achievement of lightweight design targets, especially in early development phases.

2 STATE OF THE ART

In order to solve the described problem, it is necessary to link modelling methods for embodiment function relations with a lightweight design method and to integrate it into an agile process. Existing methods of these three aspects are described in the following.

2.1 Process modelling of agile mechatronic system development

The process of product development can be understood as the transformation of needs into technical and commercial solutions. Each product development process is unique, but all processes have similar and recurring elements. (Smith and Morrow, 1999) In order to support the stakeholders involved in the product development process in navigating and managing the process, there is a multitude of process models, which differ in their purpose, their perspective on the process, the granularity of their description and the disciplines addressed (Wynn and Clarkson, 2018). In the context of mechatronic system development, the VDI 2221 (VDI 2018) or the Stage-Gate Process (Cooper, 1990), are established representatives in process modelling. In addition, companies are also increasingly implementing agile approaches in the field of mechatronic system development (Schmidt *et al.*, 2017), which make development teams more responsive to dynamic changes in contrast to the plan-driven approaches (Boehm and Turner, 2003). However, since all products are developed in generations (including those, which are understood as completely new ones), with each generation being developed on the basis of references, it is appropriate to integrate this idea into a process model with regard to the cross-generational use of knowledge. The basis for this is the understanding of product development as PGE - Product Generation Engineering. The PGE model is based on the hypothesis that each product is developed on the basis of references (previous product generations, existing products, their subsystems or principle solutions that do not necessarily have to be on the market and can originate from competitors or research) which are combined in the reference system. The reference system is continuously further developed by adapting, changing or enlarging its elements based on new gained knowledge during the process of product development. (Albers *et al.*, 2019a) This idea is taken up in the agile approach of ASD - Agile Systems Design and in its process model the iPeM - integrated Product engineering Model. It models the integrated and cross-generation development of products, the associated validation and production systems as well as the strategy. The agile development is achieved by separating phases and activities in the iPeM. (Albers *et al.*, 2018a) Each activity of product development in the ASD is understood as a problem-solving process, resulting in a matrix with different development situations within which different development methods are recommended according to the situation and requirements. This involves an iterative and continuous transformation of a system of objectives into a system of objects by the operation system - the system triple of product development (Albers *et al.*, 2018a; Ropohl, 1975). In this way, an agile development process can also be modelled over time and be supported by an iterative alternation between synthesis and analysis activities (Ruckpaul *et al.*, 2014). ASD models product development in a meta-process containing two phases, followed by up to four sprints (see Figure 1) (Albers *et al.*, 2018b).

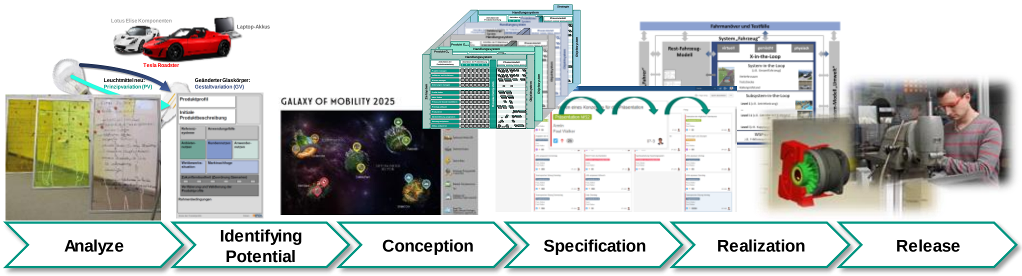

Figure 1: Meta-process and elements of ASD - agile systems design (Albers et al., 2018b)

In the *Analyze* phase, a broad analysis of existing technical systems and further potential reference elements is carried out to enlarge the reference system The reference system is continuously extended during the whole process (Albers *et al.*, 2019a). Based on the knowledge gained, product profiles are generated in the *Identifying Potentials* phase, which are iteratively converted into technical systems in the following sprints by using elements from the reference system. The phases and sprints of the metaprocess serve as chronological structuring elements within which the activities for synthesis and analysis of the technical system are carried out iteratively and in parallel. The generated increments are continuously validated with potential customers, and the reference system as well as the product profile are detailed. ASD supports developers in the development of mechatronic systems according to the situation and their demands. It is based on the principles (Albers *et al.*, 2018a, 2018b):

1. *the developer is the centre of product development*
2. *each process of product development is unique*
3. *situation- and demand-oriented combination of flexible and structuring elements*
4. *understanding of product development according to the system triple of product development*
5. *modelling of product development activities as problem-solving processes*
6. *development of products on the basis of references*
7. *innovation consists of profile, invention and market launch*
8. *early and continuous execution of validation activities*
9. *fractal and scaled modelling of mindsets, methods and processes*

2.2 Modelling of embodiment function relations

For modelling of embodiment function relations in early phases of embodiment design, approaches like the Characteristics Properties Modelling (Weber, 2014), Axiomatic Design (Suh, 1998) or the Function Behaviour Structure Ontology (Gero and Kannengiesser, 2014) can be used. To support thinking processes, the visualization of the products embodiment is important. For this, the Contact&Channel-Approach (C&C²-A) can be used, as it is based on a depiction of the embodiment (Albers and Wintergerst, 2014; Matthiesen, 2002). The C&C²-Approach is a meta-model and consists of elements and rules to build up explicit models. It can be compared to a language that contains words and grammar to express knowledge. This meta-model consists of three key elements and three basic hypotheses that define the usage of its key elements. Its key elements are the Working Surface Pair (WSP), Channel and Support Structure (CSS) and the Connector (C). A WSP describes the interface, where parts of the system connect while it fulfils its function. The CSS runs through system parts and connects the WSP. A CSS can include parts of components or whole subsystems, according to the modelling purpose (Matthiesen, 2002). The C sets the system boundary and transfers effects from outside the boundary into the system (Albers and Wintergerst, 2014). It considers the interactions of the environment with the system in development. These elements contain parameters of the embodiment that are relevant for the function fulfilment. For example, a friction coefficient is a parameter of a WSP, the stiffness of a component or subsystem is a parameter of a CSS. These parameters cause the functions of a system and are therefore relevant for simulation models. The C&C²-Approach supports the documentation of these parameters and their relation to functions in the system. The basic hypotheses describe possibilities and boundaries of modelling with the C&C²-Approach (Matthiesen, 2002). The first basic hypothesis states, that function always needs interrelations of components through WSP. The second basic hypothesis states that a function is fulfilled through a minimum of two WSPs that are connected by a CSS and integrated in the environment by the C. The third basic hypothesis describes the fractal character of modelling and shows how the created C&C²- Model of a system differs according to point of view and purpose of modelling. These hypotheses as well as the modelling elements are shown in Figure 2. (Matthiesen *et al*., 2018)

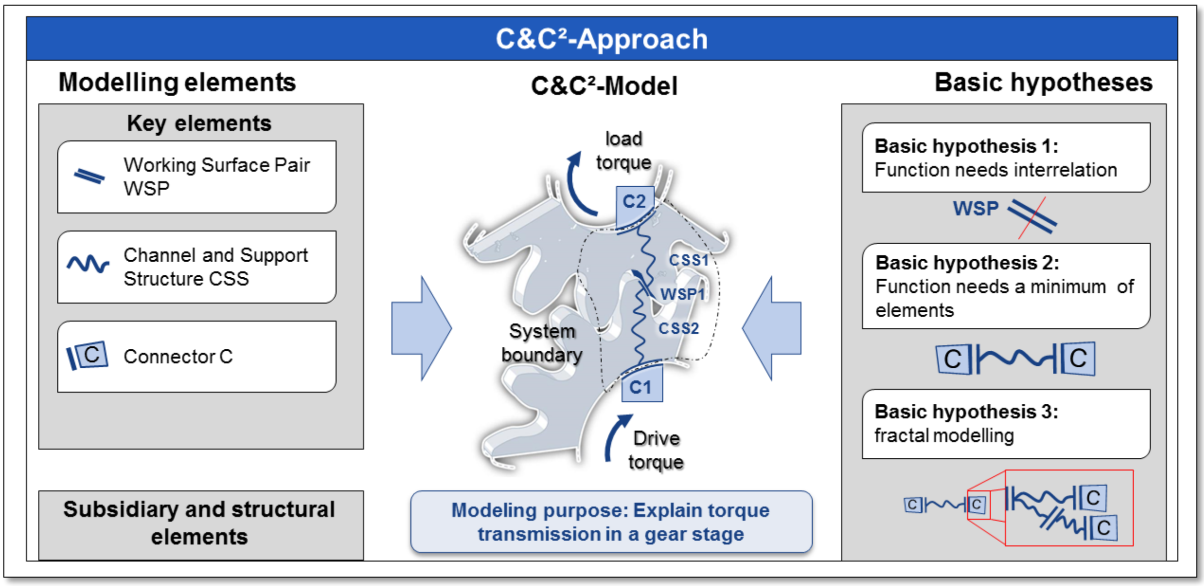

Figure 2: C&C²-approach and its elements according to Matthiesen et al. (2018)

2.3 Lightweight design strategies and methods

In order to realize lightweight design in the product development process, various lightweight design strategies are available to the development teams, which can be individually combined. These strategies are: system lightweight design, condition lightweight design, material lightweight design, form lightweight design and production lightweight design (Kopp *et al*., 2019). None of the strategies is to be considered in isolation, but always their interaction to achieve the highest weight reduction potential.

80 percent of the weight of a product is already set by the product concept or design and thus in the early phase of product development (Leichtbau BW, 2017). The reason for this is that product concepts can still be changed at this stage and the greatest lightweight design potential can often not be realized by

optimizing individual components but by optimizing the overall system. Therefore, the lightweight design strategy *system lightweight design* is decisive. In contrast to the component-based optimization, function based lightweight design methods were developed (Feyerabend, 1991; Ponn and Lindemann, 2011; Albers *et al*., 2013; Posner *et al*., 2013), which aim to address the lightweight design potential in the overall system by abstracting the product to the functional level. In order to address economic and ecological lightweight design not only by reducing mass, but also by taking into account lifecycle costs and CO2 emissions from cradle to grave, Albers *et al*. (2017b) presented the Extended Target Weighing Approach (ETWA). The workflow of the ETWA is illustrated in Figure 3 (left).

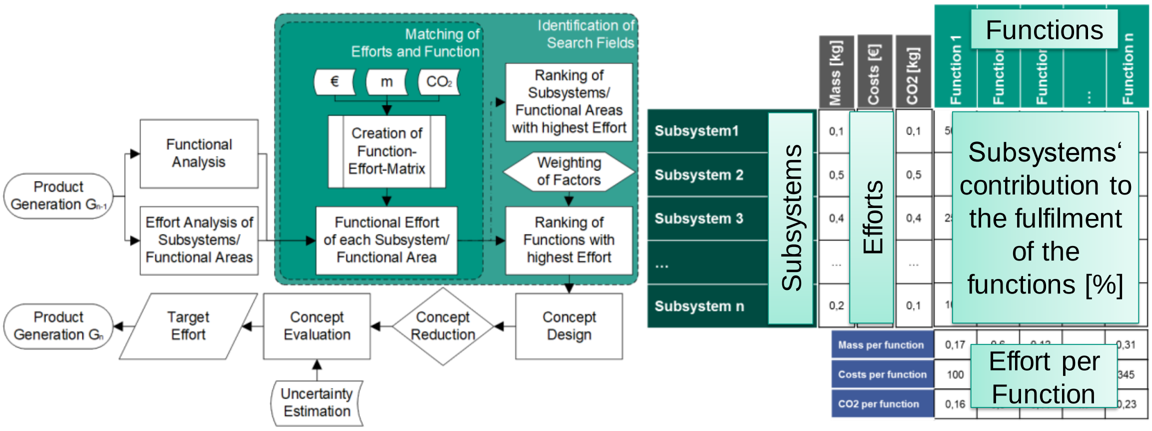

Figure 3: Workflow of the extended target weighing approach (left) according to Albers et al. (2019b) and function-effort-matrix (right) according to Albers et al. (2018c)

The first step is to define the elements of the reference system to be optimised in their mass (e.g. a previous product generation). Therefore, it is necessary to choose the right level of detail. If there are large component quantities in the area under consideration, it makes sense to combine them into subsystems. However, the ETWA can also be used for individual components by dividing the component into functional areas. Afterwards the product's functions need to be analysed what can be decisively supported by the C&C²-Approach (Albers *et al*., 2017b). The level of detail of the functional description has to be selected according to the level of detail of the system description. Due to the modular design of the ETWA, it must then be decided which target values are to be considered in addition to the mass. E.g. for the automotive industry, this can be costs and CO2 emissions. This data as well as the determined functions are then transferred to the next step of the method: the creation of the Function-Effort-Matrix. Here, the subsystem's contributions to the function fulfilment are assigned on a percentage basis. This estimation, which is crucial for the outcome of the method, is mostly done with expert knowledge. Assigning the subsystems to the functions results in an effort per function, which, plotted against the relative importance of each function, can be visualized in a 2D function portfolio (Figure 4 (left)).

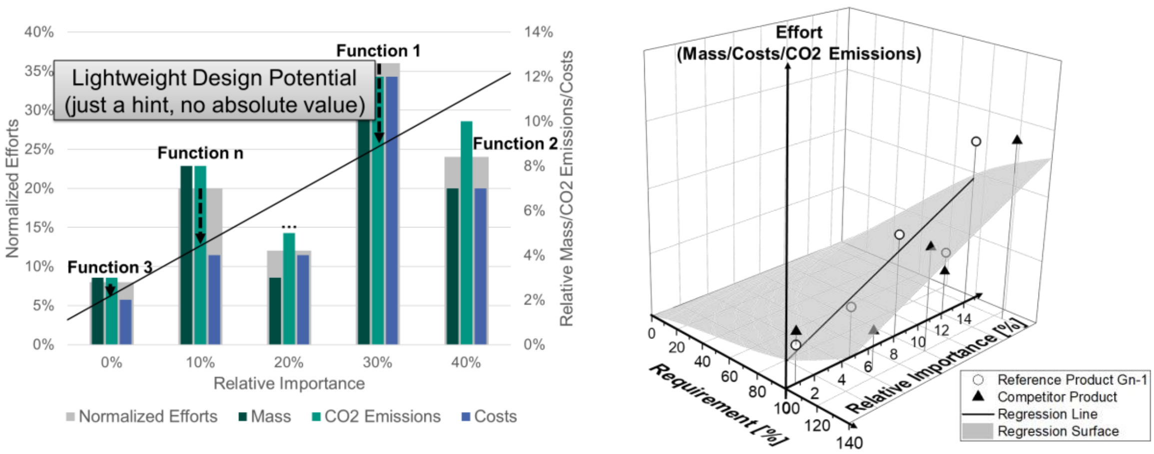

Figure 4: Function portfolio (left) according to Albers et al. (2018c) and function portfolio for benchmarking (right) according to Revfi et al. (2019)

By the possibility to use the ETWA for benchmarking (Revfi *et al*., 2019), this diagram has been extended by another axis (see Figure 4 (right)). On this axis the fulfilment of the requirement, which is linked to each function, is displayed. Hereby the own product on the axis is at 100%. As a result, it is possible to use the ETWA to disclose competitor-based lightweight design potentials of the own product. Based on the identified functions, which are "too heavy" compared to their relative importance, new concepts are generated using a combination of different lightweight design strategies.

3 AIM OF RESEARCH

The identification and use of the product knowledge necessary for the development of products with regard to lightweight design, especially in the early phases of the development process, poses challenges for engineers, particularly in agile development projects. In order to compensate the lack of technical knowledge at the beginning of the process, which is due to the low degree of product maturity of early development generations, the combination of methods from the fields of embodiment function relation modelling and lightweight design as well as their integration into agile development approaches can be used. In the absence of expert knowledge in the agile process, the early application of lightweight design methods is either impossible or very difficult. The knowledge would first have to be built up through lengthy research, for example. This inhibits the ability to react and thus the agility, which is why it is necessary to integrate a mechanism into the method that compensates for the lack of knowledge in the best possible way. This means that the method can also be applied by inexperienced employees. The state of research shows that all necessary elements already exist, but have not yet been combined. Accordingly, the aim of this publication is to develop a method to support the development teams in lightweight design activities in the early phase of the product development process by combining the ETWA (see section 2.3) and C&C²-A (see section 2.2) and integrating them into the ASD (see section 2.1). For this purpose, the following research question will be answered:
How can a method support gaining technical knowledge in agile development projects to identify lightweight design potential using the ETWA?

4 AGILE METHOD FOR THE EXTENDED TARGET WEIGHING APPROACH

Based on the Aim of Research, a method is developed to support the integration of the lightweight design method ETWA into the agile development process of ASD. As the agile development in ASD as well as the ETWA always rely *on a reference system* (ASD - Principle 6), the method needs to contain modelling of the embodiment function relations of the relevant elements of the reference system. Up to now, the ETWA needs implicit knowledge from experts for completing the Function-Effort-Matrix which makes the ETWA not reactive if these knowledge is lacking. However, being reactive is crucial for agile product development. Therefore, a model is needed that provides explicit knowledge of the embodiment function relations - already in early development phases where the application of the ETWA as a methodology for solving lightweight design problems (ASD Principle 5) is most effective. This is why the developed method is based on the C&C²-Approach, which provides necessary knowledge to support the completion of the Function-Effort-Matrix of ETWA. Depending on the available time and the level of detail of the required knowledge, this method can be applied either as a consideration of area ratio using WSPs (WSP-Approach) or as a consideration of volume ratio based on CSSs (CSS-Approach) according to ASD-Principle 3. By the developed method (Figure 5), explicit knowledge is built up and documented early, which reduces the dependence on experts and the uncertainty in the development project.

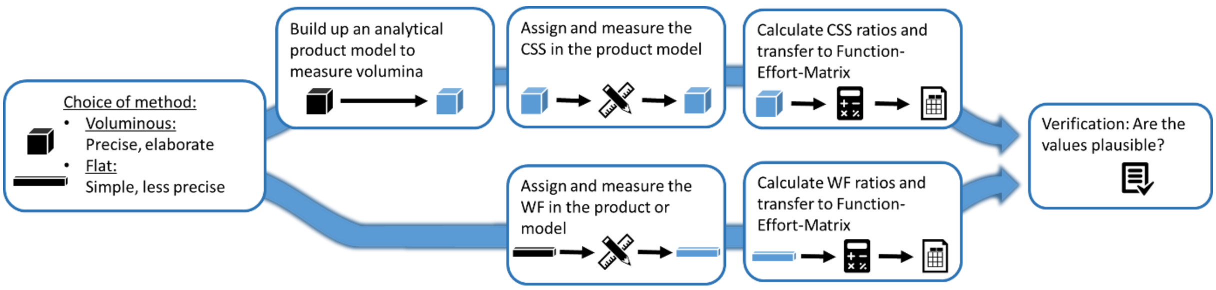

Figure 5: Choice of modelling method for embodiment function relations

Using the C&C²-Approach, a model of the embodiment function relations is created by identifying WSPs and CSSs of an element under interest from the reference system and considering its environment through connectors. An example of a C&C²-Model is shown in Figure 6.

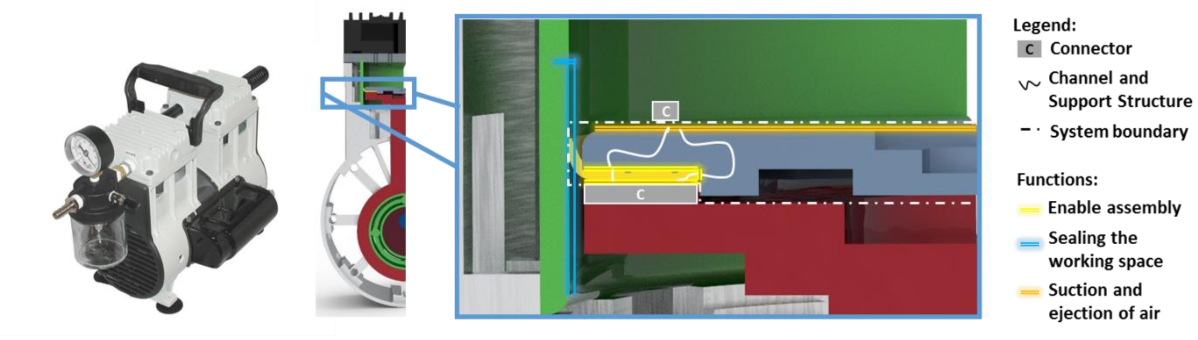

Figure 6: Modelling of embodiment function relations in an element of the reference system

Based on this model, it is possible to determine which areas are involved in the considered functions. Dividing these determined areas through the whole surface results in an area ratio which is involved in each function. This ratio is used to complete the Function-Effort-Matrix. For this purpose, the WSPs are measured in the virtual model (CAD, drawing) or in the physical reference element as part of the reference system. This analysis provides a first quick approximation to the percentage shares of the components contribution in the function fulfilment. This WSP-Approach is suitable when mainly flat components are considered or a rough overview of the lightweight potential is sufficient for the projects task.
The consideration of the volume ratios is also based on the C&C²-Model. Here, the volumes relevant for fulfilling the function are derived from the components of the reference system containing the CSSs. For this purpose, the CSSs are considered, which connect the WSP through the respective subsystem, and the volumes of the subsystems are measured. The CSS-Approach requires a higher effort, since volume calculation of subsystems is complicated by the fact that a CAD model of the system is necessary, in which volumes can be calculated. Elements of the reference system that are not available as 3D models in the company must be modelled in a suitable environment. The methods can be varied iteratively, so that detailed knowledge can be generated according to the situation and requirements. Based on these considerations, the percentage shares of the components in the fulfilment of the functions are evaluated. This can also be carried out as benchmarking to evaluate concepts and identify relevant elements for the reference system.

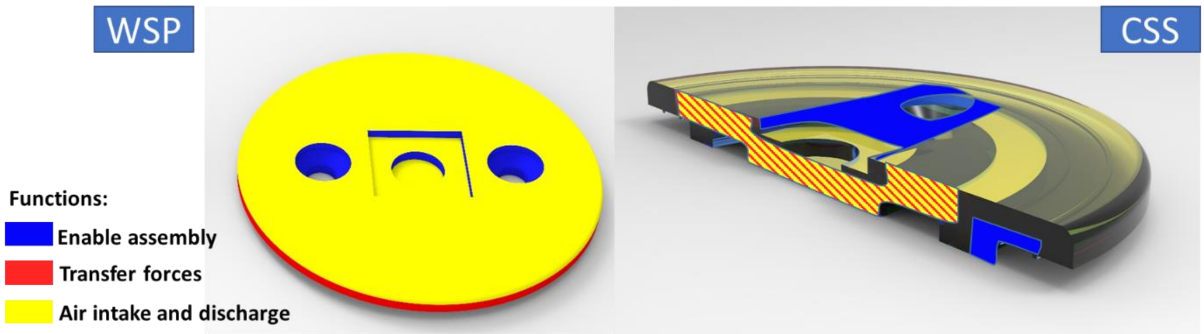

Figure 7: Comparison of WSP-approach and CSS-approach

5 INITIAL VALIDATION IN A DEVELOPMENT PROJECT

In the early phase (*Analyze* and *Identifying Potential*) of an agile development project of an oil-free piston pump, the ETWA was used to identify lightweight design potential. A product from the company as well as a competitor product were investigated to identify lightweight design potential. Based on the gained technical knowledge and the derived lightweight design potentials, product concepts were generated and iteratively optimized.
Figure 8 shows an extract of the Function-Effort-Matrix of the CSS-Approach and the WSP-Approach in comparison. In this case, only the mass reduction was in the focus, costs and CO2 emissions were

neglected. Due to the different area-volume ratios of the components, inaccuracies occur in the WSP-Approach. However, it can be seen that good approximations to the CSS-Approach can be achieved with plate-like components such as the piston ring (green boxes). For components like the cylinder cover or the piston, that have complex geometric structures (cooling fins), however, the approaches show large differences (red boxes). In a direct comparison, filling out the Function-Effort-Matrix using the WSP-Approach took about 6 hours for the vacuum pump. The CSS-approach took about 9 hours.

		WSP					CSS				
	Mass [g]	Air intake and discharge	Sealing the working area	Transfer forces	…	Allow assembly	Air intake and discharge	Sealing the working area	Transfer forces	…	Allow assembly
Housing	912			34%	2%	64%			44%	1%	55%
Piston	38	42%		9%		49%	83%		10%		7%
Piston ring	6		10%	14%		76%		15%	8%		77%
…	…				100%					100%	
Cylinder cover	315	29%			56%	15%	80%			17%	3%
Mass per function [g]		431	79	808	…	901	836	116	968	…	683

Figure 8. Function-mass-matrix for CSS-approach and WSP-approach in comparison

To identify competitor-based lightweight design potentials of oil-free piston pumps, another pump was analysed using the method, whereby analyzed components of the competitive product became part of the reference system for the own product development. C&C²-Models were derived to complete the Function-Effort-Matrix. In order to perform a benchmarking between the two pumps and to identify lightweight design potentials, a three-dimensional Function Portfolio was generated (see Figure 9). By introducing a third axis to the Function Portfolio, the search field for lightweight potentials can be expanded and the developer has more degrees of freedom to optimize the product. In order to optimize the vacuum pump, the product developer now has the opportunity to reduce the mass of functions through new concepts or to increase the specification of the requirement. Based on the identified lightweight design potentials, concepts for weight-optimized vacuum pumps could be generated (see Figure 9).

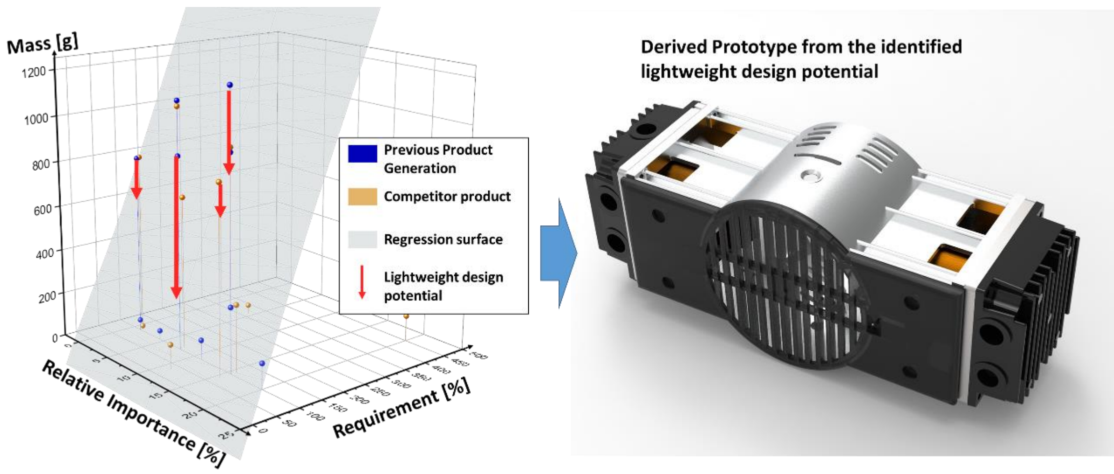

Figure 9: Function portfolio for benchmarking both pumps, which were elements of the reference system (left) and a concept for a new pump (right)

6 DISCUSSION AND CONCLUSION

The aim of this contribution was to support product developers in the early and continuous generation and use of relevant knowledge for the identification and implementation of lightweight design potentials. In the core, the lightweight design method ETWA, which represents a problem-solving process for the solution of lightweight design problems, was extended by a method using the C&C²-Approach. This method enabled the usage of the ETWA in agile projects through the possibility to derive technical solutions in early concept phases. The development and integration followed various principles for the agile development of mechatronic systems. This made it possible to support development teams early in the process in the generation and use of the necessary technical knowledge for the identification of lightweight design potentials on the basis of reference products.

The completion of the Function-Effort-Matrix was supported by the developed method to compensate the lack of expert knowledge. The method also supports the iterative implementation and continuous validation of lightweight potentials in a technical system. In a first application of a real development project, it was shown that lightweight design potential could be investigated without needing experts. From this, first concepts to implement these potentials have already been developed and iteratively optimized. They are currently being followed up within the company, which means that no statement can currently be made about any possible product success. In addition, with regard to the applicability of the method, it is already possible to deduce that the results of the method application correlate strongly with the quality of the embodiment function relation models. This method contributes to closing the gap in technical usability of agile approaches in early project phases of product development. In an application in the development of an oil-free piston pump, the method enabled development teams to gain the necessary knowledge to derive concepts and iteratively optimize them. In future, a study is planned where novice product developers use the method and are compared to intuitive approaches of experienced product developers for internal validation of the method according its usefulness. To gain a larger return of investment of the generated models, it will be investigated how the C&C²-Models support synthesis activities in embodiment design within the ETWA.

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