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Synergy Effects by using SysML Models for the Lightweight Design Method "Extended Target Weighing Approach"

Albert Albers[1], Georg Moeser[1], Sven Revfi[1]*

[1]*Karlsruhe Institute of Technology (KIT) - IPEK – Institute of Product Engineering, Kaiserstr. 10, 76131 Karlsruhe, Germany*

* Corresponding author. Tel.: +49 721 608-46339; fax: +49 721 608-46051. *E-mail address:* sven.revfi@kit.edu

Abstract

Product engineering processes are multidisciplinary and comprise several methods and tools. These methods and tools often coexist and are not linked to each other. In order to come closer to a continuous coupling of models, this paper shows how SysML model data can be used for the execution of a lightweight design method called "Extended Target Weighing Approach (ETWA)".
The Extended Target Weighing Approach is a function-based lightweight design method for the systematic identification and evaluation of lightweight design potentials with regard to costs and CO2-emissions. It is based on a Function-Effort-Matrix, which quantifies the percentage contribution of each component to the fulfilment of the functions.
A model, which is created according to the FAS4M approach (with SysML/MechML), contains both functions and the components involved in its design. The mass, costs and CO2-emissions of the components can be specified and, if necessary, retrieved from a CAD model via an interface. A matrix can be derived automatically from the available SysML model data, in which each component is linked to the function realized by it.
This contribution shows how the Function-Effort-Matrix required for the ETWA can be automatically derived from models generated according to the FAS4M approach. This makes it possible not only to shorten the time-consuming preparatory work for the execution of the ETWA considerably with an existing SysML model but also to reduce possible sources of error, which occur during the filling of the Function-Effort-Matrix. In addition, further synergy potentials through the coupling of system modelling according to FAS4M and the ETWA like the reuse of existing SysML models or the reuse of discarded concept ideas will be demonstrated.

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Keywords: Design method, Conceptual design, Lightweight design

1. Introduction

The basic idea behind Model-Based Systems Engineering (MBSE; [1]) is to generate consistent and universally usable models describing the system to be developed, during its development and to use them continuously. This implies that it must be possible to carry out highly specialized activities with these models. If this is the case, a considerable increase in efficiency is achieved, as secure and extensively available information can be used (e.g. throughout the product lifecycle for production, maintenance, recycling, etc.). In particular, when it comes to model re-use across different product generations, there are inherent efficiency potentials (timesaving through effort reduction) [2].

This paper examines the synergy effects resulting from the use of system models according to the "FAS4M approach" (from the project "Functional Architectures of Systems for Mechanical Engineers"; in short "FAS4M"; [3,4]) for the Extended Target Weighing Approach [5], a lightweight design method, and shows that the models support the identification of lightweight design potentials.

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2. State of the Art

The following summarizes the current state of the art in research relevant to this paper. First, the PGE - Product Generation Engineering [6] is explained as a basic understanding of product development. Subsequently, the model-based system development will be introduced with a focus on the development of mechanical system components. Finally, the Extended Target Weighing Approach [5], which is the focus of this article, is explained.

2.1. PGE – Product Generation Engineering

The basic assumption of PGE - Product Generation Engineering according to ALBERS is that the development of new products cannot be explained by the "white-piece-of-paper" theory, but is almost always based on one or more reference products. Reference products can be company-internal predecessor product generations, competitor products available on the market as well as products from other industries. Of course, for company-internal reference products, all development data (including design rationales and evaluated other design options) are available which must first be acquired for external reference products. For the development of a new product generation, the activities carryover variation (CV), embodiment variation (EV) and principle variation (PV) are systematically combined within PGE [6]. The new development share of a new product generation can be determined by the amount of EV and PV in relation to the previous product generation G_{n-1} [6]. EV and PV differ in terms of development risk. This supports the selection of a suitable product development process. [7]

On the way to a new product generation, several development generations can be passed through, in which functional components and software are integrated by EV or PV [8]. A product generation is launched on the market, while a development generation is only known in the company. In the context of this paper, a development generation can be, for example, a finished 3D CAD design that is optimized with regard to the aspects of lightweight design after applying the Extended Target Weighing Approach (see section 2.3) and thus transferred to the next development generation.

2.2. Model-Based Systems Engineering with focus on mechanical development

Systems Engineering (SE; [9]) is an interdisciplinary approach to product/system development. The approach aims to define customer needs and the necessary functionality early in the development process [9].

For several years now, SE has been further developed into model-based system development (MBSE; [1]). This is the formalized application of modeling in all system life cycle phases to support SE activities [1]. Thus, in addition to the general tasks of a system engineer, highly specialized activities (in the context of this article: application of a lightweight design method) are also to be supported [1].

In the context of MBSE, there are three aspects to which a compatible selection must always be made. These three aspects are language, tool and method and are called modeling triple [10] or pillars of MBSE [11]. The Systems Modeling Language (SysML; [12]) is the most widely used (modeling) language [11]. Numerous (modeling) tools are available for modeling with SysML [13]. There are dedicated modeling methods for mapping system structures, behavior, requirements and corresponding parameters with SysML (e.g. SysMOD [14], OOSEM [15]). However, all other methods of the SE should also be feasible with the models and use or extend the database (see above).

The "FAS4M approach" [3,4] was developed for the development of mechanical system components. This approach involves modeling during development and mapping the content generated during development in four system views using MechML (a SysML profile [16]). These four system views are the function view, principle view, conceptual view and component view.

The function view is used to model a functional architecture with functions and sub-functions [17]. The result of the FAS method [14] can be used to support this [4]. In the principle view, possible principle solutions for implementing the functions are collected and selected. Conceptual detailing takes place in the conceptual view. Finally, the component view models components (assemblies and parts) with their properties (same structure as in the CAD structure tree). [3]

The work of the developers is also supported by the integration of free sketches [18,19], which are very similar to the mental models of the developers and show the contexts (system context/interactions) of the considered element [18]. The embedding of free sketches is already supported by a tool implementation [20]. The software is available online [21].

2.3. Extended Target Weighing Approach (ETWA)

In order to develop products with low mass, holistic, cross-component methods are necessary. The Target Weighing Approach (TWA) introduced by ALBERS et al. [22] is such a method supporting the systematic identification of lightweight design potentials. The potentials found can then be fully exploited with the various lightweight design strategies concept, material, form, manufacturing and conditional lightweight design [23]. The TWA itself can be classified as a method in concept lightweight design. The approach is based on "Value Engineering" [24] and "Target Costing" [25]. Their basic principles are abstracted and applied in the context of lightweight design: With the help of this method, each function is assigned its specific mass. Another approach based on functions, mass, mass distribution and mass moments of inertia was presented by Posner et al. [26,27,28]. As lightweight design solutions are often associated with high costs and CO2-emissions, ALBERS et al. [5] extended the mass-based Target Weighing Approach by the dimensions costs and CO2-emissions. The Extended Target Weighing Approach (ETWA) holistically supports the identification and evaluation of lightweight design potentials balancing the three factors (so-called efforts) mass, costs (estimated through green-field approach) and CO2-emissions (estimated by a life-cycle assessment) [5].

Fig. 1 shows the workflow of the ETWA. The starting point is a reference product of the product generation G_{n-1} in terms of PGE. Based on this reference product, the product functions are analyzed.

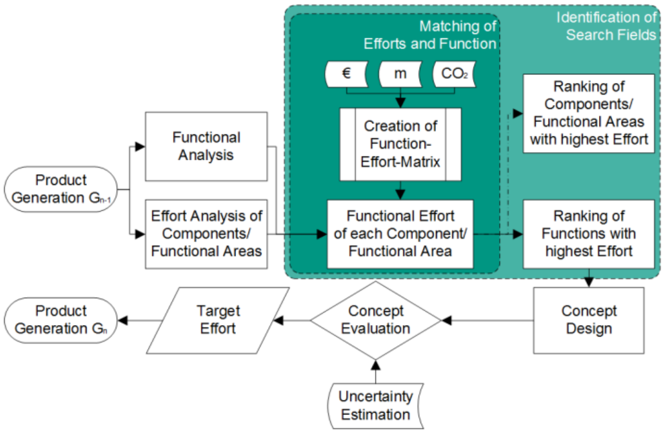


Fig. 1. Workflow of the Extended Target Weighing Approach (ETWA)

This first step is often time-consuming, but it has a significant influence on the achievable results, since the result of the functional analysis serves as the starting point for all following steps. In a further step, the efforts (=mass, costs, CO2-emissions) of the components or functional areas are determined. Functional areas are areas of the product (not necessarily following the structure of the assemblies and components) in which the analyzed functions are fulfilled [5]. The functional area-based approach is particularly suitable if there are not enough individual components in the observation area [5]. In this article, the component-based approach is discussed below.

With the determined functions, the components in the examination area and their effort, a Function-Effort-Matrix is created, which is exemplarily illustrated in Fig. 2.

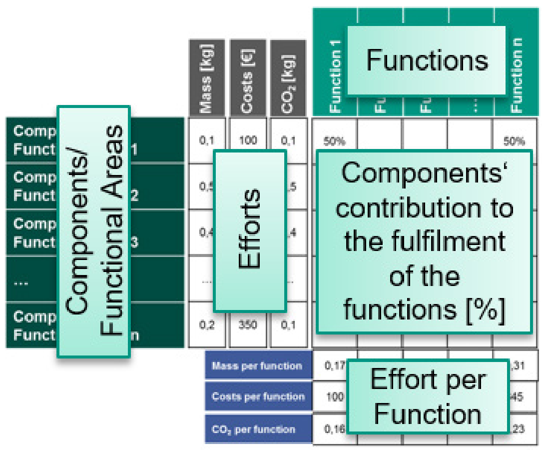


Fig. 2. Function-Effort-Matrix

The identified functions are plotted on the horizontal axis, while the product components and their corresponding efforts are listed on the vertical axis. Afterwards, each component is assigned its percentage contribution to the fulfillment of the function. This step is often time-consuming, since it is necessary to identify which functions the component actually contributes to. Expert knowledge and experience is very helpful in this context. Ultimately, the result of the assignment is a functional effort. The fact, that the ETWA is a cross-component approach, is represented by this, since one function can be performed by several components. Various evaluation methods, e.g. a function portfolio, can be used to determine "heavy" functions that offer lightweight design potential (see Fig. 3).

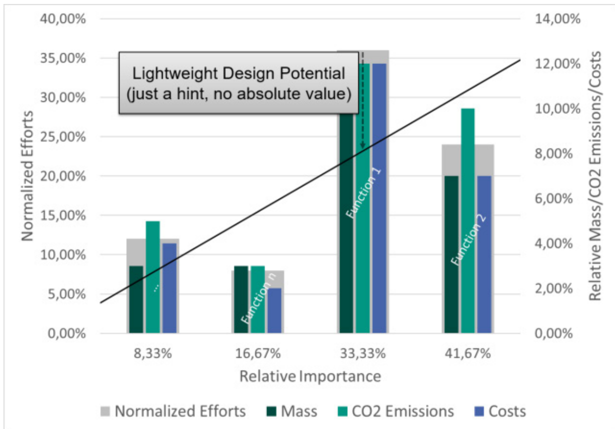


Fig. 3. Function portfolio

These functions can then be processed with the aid of various lightweight design strategies and alternative concept solutions can be generated. However, the creative process of finding new solutions is not the focus of this article (for more details see [5,22]). Normally the concept design phase starts with e.g. hand-drawn sketches, which are refined during the product development process until the final design. In order to assess the impact of a newly developed lightweight design concept, the sensitivity analysis uses the Function-Effort-Matrix in the reverse direction. In doing so, the effect on the weight can be observed directly in the Function-Effort-Matrix. Thus, the accumulated knowledge concerning the design concept increases and the efforts can be determined more exactly which allows a better evaluation of the new design.

3. Coupling system modeling according to FAS4M with the Extended Target Weighing Approach (ETWA)

A model created according to the FAS4M approach (with SysML/MechML) contains both functions and the components involved in their fulfillment. The efforts of the components can be assigned and, if necessary, retrieved from a CAD model via an interface.

A matrix can be derived automatically from the underlying model data, in which each component is linked to the function performed by it. This significantly reduces the initial preparatory work required to carry out the ETWA. The work effort required for function definition in previous projects is completely eliminated. By directly including the "mass", “costs” and “CO2-emissions” properties of each component, it is no longer necessary to retrieve this information manually from e.g. the CAD model. This reduces the workload even further.

The following step of assigning the percentage function fulfillment to the components is reduced by the error source of forgotten or incorrect assignments. The completeness is guaranteed from the model. The marked fields in the automatically derived matrix (see Fig. 5(b)) only have to be replaced by the corresponding percentage values.

The procedure is illustrated in the following example. A gearbox housing shown in Fig. 3 is being analyzed with regard to its potential for lightweight design. For reasons of clarity, only the essential elements are shown here. Fig. 3 shows four components "Lid Side (1)", "Mounting (2)", "Bearing Seats (3)" and "Centre Section (4)". These components are welded together.

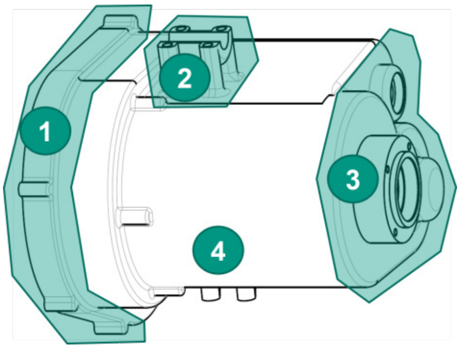


Fig. 4. Gearbox housing

The gearbox housing with its four components fulfils the following functions:

- Fix system
- Fix system components
- Absorb axial forces
- Absorb bending moments
- Seal against medium intrusion/leakage
- Dissipate heat
- Enable assembly

During development, the functions, principles, concepts and lastly the components in the four views of the MechML (see section 2.2) are modeled with the help of MechML [16]. The Cameo Systems Modeler (CSM) tool from the company NoMagic is used for modeling [29]. Fig. 4 shows an example of the model elements that are cross-linked with the function "Enable assembly" in the model: principle solution "Full side removable covers"; conceptual element "Cover concept" as well as the two components "Bearing seats" and "Lid side".

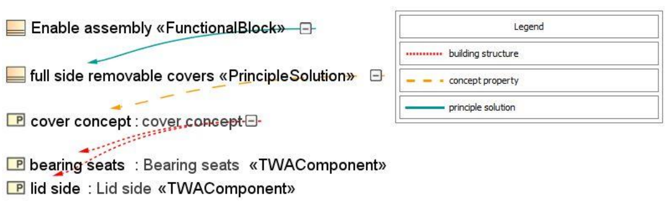
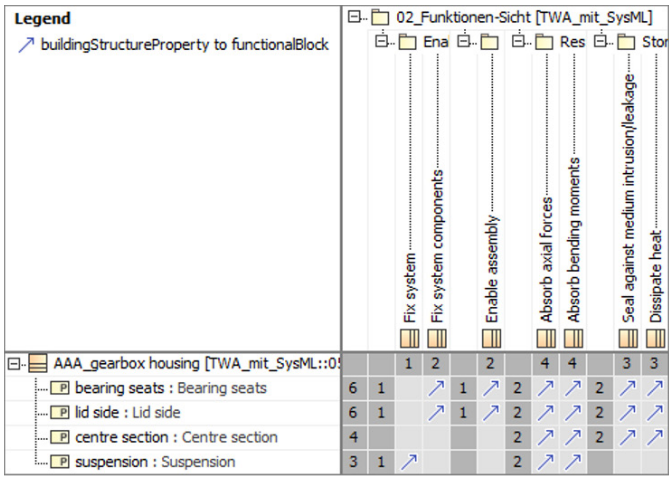


Fig. 5. Cross-linked MechML elements exemplified by the "Enable assembly" function

On basis of this cross-linking, the correlation between components and functions in the fulfillment of which they are involved can be mapped in matrix form. In addition to the view in CSM, it is also possible to export this data in matrix form e.g. to Microsoft Excel. Fig. 5 shows these two views of the cross-linked contents, which already have the (basic) structure of the Function-Mass-Matrix of the ETWA.

The automatically generated matrix from the MechML model and the assigned efforts of the components, significantly reduce the preparatory effort for the implementation of the Extended Target Weighing Approach: Based on the automatically generated Function-Effort-Matrix, the percentage allocation step is carried out without any further preparatory work.



a)

	Fix system	Fix system components	Enable assembly	Absorb axial forces	Absorb bending moments	Seal against medium intrusion/leakage	Dissipate heat
bearing seats		->	->	->	->	->	->
lid side		->	->	->	->	->	->
centre section				->	->	->	->
suspension	->			->	->		

b)

Fig. 6. Matrix "Component to Function" generated from the model
a) View in CSM and b) Data exported to Microsoft Excel

After identifying the functions with the greatest lightweight design potential (cf. [5,22]), a methodologically supported creativity process for generating new principle and/or design concepts follows. These can also be evaluated in terms of their lightweight design potential by updating the Function-Effort-Matrix – based on the new components.

Fig. 6 shows two of the concepts for a new generation of the gearbox housing, which have been developed with principle respectively embodiment variation.

Fig. 7. Gearbox housing concepts
a) with reinforcing honeycomb structure b) with sealing plastic cylinder

In both design concepts, the "Seal against medium intrusion/leakage" function was implemented with a lower mass than in the G_{n-1} product generation housing from Fig. 3. Fig. 6 a) shows a honeycomb housing with a similar stiffness and a lower wall thickness, resulting in a weight saving of approx. 9%. Fig. 6 b) shows the introduction of load-bearing structures in the middle section, while the sealing function is only fulfilled by a plastic cylinder (weight saving of approx. 15%).

4. Synergy effects through the coupling of system modeling according to FAS4M with the Extended Target Weighing Approach

With the Extended Target Weighing Approach (ETWA), the design of the previous product generation G_{n-1} can be investigated with regard to lightweight design potentials. In this case, there is great potential for effective development work through the further use of models of the previous product generation (see [2]): MechML models and CAD data can be used directly, as shown in section 3, to derive the Function-Effort-Matrix for the ETWA.

Furthermore, the Return on Investment (ROI) increases in the tension between modeling effort and model benefit, if through consistent pursuit of the PGE strategy the models according to the FAS4M approach [3] (as shown here on the example of ETWA) are used for specific development activities.

For the ETWA execution, there is a reduction in the initial effort since the correlations of functions and components are already defined in the model of the previous product generation or the current development generation and can be exported as a matrix. In addition, the use of the model, which was created during development, means that no correlations between functions and components can be forgotten.

Furthermore, the documented lightweight design potentials as well as developed but not implemented lightweight design concepts can be integrated into the SysML/MechML model and are directly available for the development of future product generations. This is particularly interesting if the technologies for the realization of lightweight design approaches have developed decisively up to the development of the respective future product generation. For example, a few years ago, some load-optimized components could only be manufactured with considerable additional effort. These solutions can now become attractive again - due to new production technologies such as additive manufacturing [30]. Of course, this re-use for a new innovative product generation can only be used if the discarded solutions from previous product development processes have been consistently archived with all boundary conditions according to the concept of the CIS - Continuous Idea Storage [31].

5. Summary and outlook

This paper has shown a concrete benefit of system modeling with SysML: The effort for the execution of the Extended Target Weighing Approach (ETWA) could be considerably reduced by using system models. A further dissemination of extensive system models with SysML is expected from the authors under the following circumstances: (1) increasing model use for specific methods, such as ETWA; (2) increasing model use across product generations [2] and (3) appropriate training of young engineers (see [10,32,33]). It is important that all referenced, coupled or (in cross-company communication) exchanged models follow a common metamodel [34]. It shows that the consistent pursuit of a PGE strategy is the key to success. This will also be examined in detail in future research.

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