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Weight Optimization Approach for Conceptual Design – Requirements, Functions, Working Principles

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Abstract
Lightweight design and weight optimization in general are seen as one promising of many approaches to create products and services in a sustainable and resource efficient way. However, most of the methods proposed for lightweight design are applied late in the development process (embodiment and detail design) and mostly locally for specific components and subsystems without regarding the system as a whole. For today's sustainability challenges, the traditional weight improvements are not sufficient anymore. A transfer and an establishment of weight optimization methods to earlier design phases, especially the concept design stage, is needed because of the important influence on product properties in these phases. Moreover, a methodology of weight-optimization for innovative, interdisciplinary products, especially mechatronic products and systems, is missing.
In this contribution, a method for the consideration of weight optimization during the creation of function structures, working principles and principle solution structure is presented.

Keywords: Weight Optimization, Requirements, Function Structure, Principle Solution

1 Introduction

Common product development processes support the task of weight improvement, for example weight reduction and weight distribution, only insufficiently and unsystematically. Weight reduction for example is seen as one possible approach to a resource and energy conserving realization of products during production, usage and recycling lifecycle phases. The weight optimization task is mostly applied at the end or in the late phases of the design process with the consequence that the whole system/product is not covered and sufficiently focused on. Moreover, a large number of macro-iterations with design changes are necessary which results in increasing development costs and time. First approaches from different industrial sectors, e.g. aviation, automotive or rail motive, are aiming at monitoring weight properties throughout the whole development process. In contrast to weight-optimization, growing customer demands of comfort, a call for shortened development time and a not negligible need for safety often induce an increase of weight and deterioration of weight distribution and thus a change of the performance of the product.
Due to the application of traditional lightweight methods in late design phases (embodiment and detail design) there is no method existing which supports the early phases in the product

development process (task setting and conceptual design). Especially in the conceptual design stage (function structure, working principles and principle solution structure), lots of important product properties are pre-determined and limited to a specific solution space. Nevertheless, in these early design phases there are the biggest possible influences on product properties (cf. Figure 1).

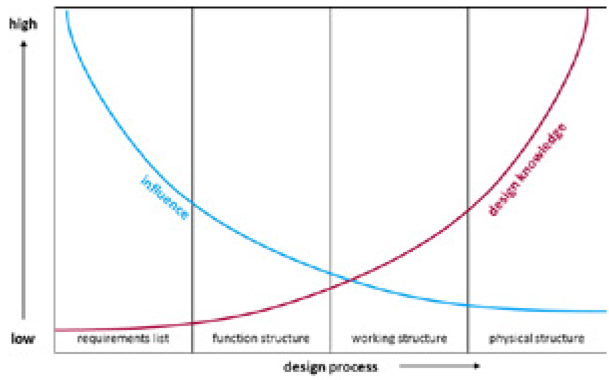

Figure 1. Product knowledge and innovation potential during product development process ("design paradox"), similar to [1]

During the design process the determination of weight and weight-related properties (weight distribution, center of gravity, …) is changing. In the early phases, most of the properties are estimated, for example from benchmarking or reviews of predecessor products, or roughly calculated. Despite this fuzzy and vague information about weight properties, there is a big chance to bring weight improvements further than the traditional, in late phases applied measures when taking especially the conceptual design phases as the most important influence area on weight into account.

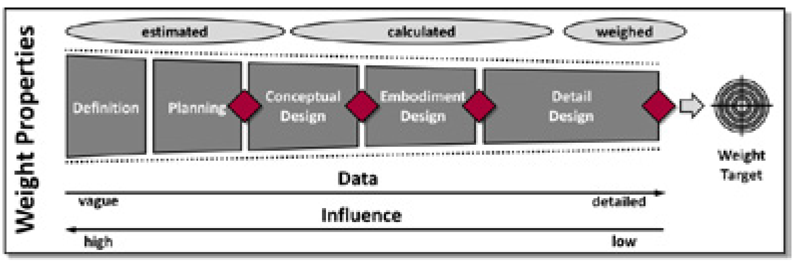

Figure 2: Weight Properties during Design Process, similar to [2]

Thus, it is necessary and inevitable to take the early design phases into consideration to exploit the full potential of lightweight solution for product development. The purpose of this contribution is a first approach taking function structure, working principles as well as principle solution structure into account for weight optimization of mechatronic products. A method for weight optimization is proposed which supports designers during the conceptual design stage.

2 State of the Art

In the following, a short review of the state of the art is given for optimization possibilities in the early concept stage, especially for weight optimization.

2.1 Optimization during Functional and Principle Solution Stage

General applicable sub-functions (elementary sub-functions) do not directly play an important role for the optimization of function structures. However, they have to be in consideration because they are decisive first for the variation of function structures and second for the search for working principles or physical effects. In many cases, the volume flows within the function structure are optimized during function structure variation.

In the literature, collections of function variation possibilities and optimization potentials are given [3, 4], adapted and further developed [5].

During the principle solution stage (working principles, working structure, …) the working principles often are afflicted with ranking characteristics and properties for variation. Moreover, with the help of design catalogues and thus characteristics for working principles and principle solutions, for example Roth [6], they can be compared against each other and thus evaluated.

2.2 Weight Optimization during Functional and Principle Solution Stage

In general, functions are not weight-afflicted [7]. Thus, there is no (or less) weight information in the functional stage available existing. In principle, only a few lightweight strategies are suitable to be applied in this early design stage: conditional, conceptual and systemic lightweight design [8]. The other strategies (manufacturing, material and structural lightweight design) are only applicable and executable when a physical structure (an embodiment) of the product is existing, and therefore in the late design phases.

Posner [5] proposes that an enhancement of the lightweight potentials is possible with a variation of functions as well as the use of generally applicable sub-functions and that the lightweight potentials have to be customer-based. Another research approach [4] suggests that it have to be clear during the function structure establishment which functions are spatially interconnected to achieve a best possible product weight. The functions which the product flows are going through one by one have to be arranged close together. Based on this, a function weight analysis which is an adapted „House of Quality“ facilitates a weight ranking order for functions. This approach is further developed by Posner [5]. Moreover, Schmidt [7] considers that the function structure must not be too specific in order not to exclude eventually favorable solutions from the very beginning.

The weight optimization on principle solution level does not provide many solutions. Only Ponn [4] states that on this level the flows within the product (material, energy, information) have to be into consideration because the kind of energy and information carrier are chosen. The choice of working principles and the interconnection within the functions have a substantial influence on product weight and product weight distribution. However, a method how to consider weight in principle solution level is not given.

3 Approach and Optimization Method

3.1 Proceeding for the Creation of Weight-Optimized Function and Principle Solution Structures

In the following a proceeding for a consideration of weight and weight-related properties during the early phases of the design process (task setting and conceptual stage) is presented. The proceeding is partially based on the process model of Pahl/Beitz [3] and VDI 2221 [9] and adapted. Moreover, some steps from the approaches of Ponn [4] and Posner [5] are taken into account and adapted. It is built as follows supported by different lightweight strategies (see also Figure 3):

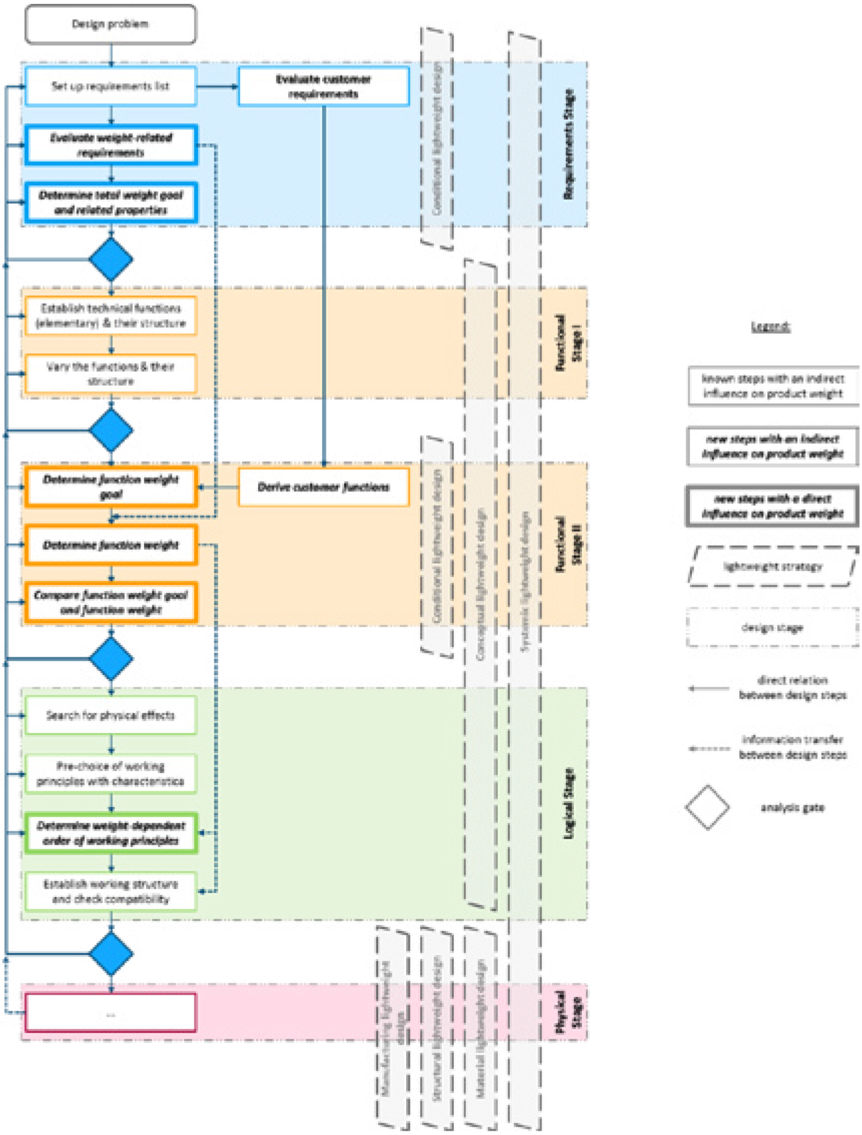

Figure 3: General Proceeding

3.2 Detailed Description of the Single Creation Steps

3.2.1 Requirements Stage

The requirements setting up stage comes along with the two lightweight design strategies of systemic and conditional lightweight design. It consists of the usually known task of clarifying the design problem and new set up steps which are important for further development and tracking product weight.

Evaluate weight-related requirements

With the aid of a quantitative explicit description of the requirements (e.g. weight < 10 kg) and determination to importance factors weight-relevant requirements can be illustrated. Moreover, relations between different properties have to be filtered out to illustrate occurrent goal conflicts. Potentially, it can be promising to depict the requirements related to the product weight as well as the interdependencies and the effects in a separate refined requirements list. Furthermore, it is important to create the requirements list with the task of weight reduction and distribution as a main requirement because lightweight design is only implicitly mentioned in conventional lists. A method for the identification of requirements which are critical to mass reduction is proposed by McLellan [10]. After a requirement pre-processing and a mapping of these requirements to components, requirements can be identified which are highly mass intensive and uncoupled from other requirements.

Determine total weight goal and related weight properties
A decisive factor for monitoring and tracking weight and relevant weight-related properties is the determination of a total weight goal. It is necessary to have sound estimations of weight-relevant properties and impacts within a system/product early in the design process and available before key design details are freezed [11]. For the definition of total weight goals different product and technology analyses as well as benchmarking of concurrent or predecessor products are very helpful and are normally used. Moreover, some methods linked to weight optimization are known and partially established, for example the "Value Analysis Weight" [12] transferred from the known value analysis or the "Lazy Part Indication" [13] where subsystems or components with an impact on product weight, but a low impact on product performance are identified. With the help of these methods and different types of analysis, a total weight goal of the product can be derived to which the further weight influence steps are issued. If there are no product analyses and benchmarks available, the total weight goal has to be estimated by experience. It can be expected that the experience-based value of the total weight goal is fuzzier than the analysis-based one.
Beside the determination of the total weight goal, further properties related to the weight have to be set with estimation. Based on products' analyses the weight distribution and the position of the center of gravity are roughly determined. With the help of these values the product to be developed has to be optimized concerning these factors.

Evaluate customer requirements
Parallel to the evaluation of weight-related requirements the establishment and comparison of customer requirements and their weighting by importance are applied, for example with a pair-by-pair comparison. The results from the customer questioning will be used later in Functional Stage II for the comparison of customer and technical functions.

3.2.2 Functional Stage 1 – Technical functions
The functional stage is distributed in two parts: the "technical" functional stage where known methods are applied in a new context and with other conditions and the "customer-/weight-afflicted" functional stage where customer requirements are taken into account and weight and weight properties are assigned to specific functions. Although the function structure provides less and fuzzy information about weight properties it seems possible to influence future product weight and related product properties early in this design phase because the solution space is limited when omitting functions. But from experience and from research [4, 5] it is known that the consideration of the function structure and the single functions is relevant for the implementation of "Design for X" criteria. Especially the conceptual lightweight design is present in this stage. With a variation of the function structure the concept of the future product is not limited as well as more or less determined.

Establish technical functions and their structure
Starting point here is a known function structure which is derived from existing solutions or which is established in a new way or for a new product. The flow-oriented perspective seems

to be best fitting one for the creation of the functional model because energy flow, material flow and signal flow in a system are considered. Moreover, it is helpful to take the generally applicable sub-functions (for example "link material to material" instead of "connect x to y") into account and here only these sub-functions which are significantly contributing to the overall function. In this case all necessary technical sub-functions have to be depicted.

Vary the functions and their structure

Based on the given function structure different variation possibilities have to be taken into account. The conceptual lightweight design strategy applied in this design stage can be interpreted in this way that a varied and thus a changed function structure can provide new solution possibility which can initiate product weight optimization. For weight optimization suitable variation possibilities of the function structure could be the following:

- Variation of functions
    - Substitution: A function is replaced by another function which is more suitable to the design problem. A function substitution often produces a change within the flows between the functions (from material to energy flow for example).
    - Integration: Several functions are integrated to one function. Thus, the weight optimization potential can be enhanced because it can be expected that less functions cause less weight. [4]
    - Separation: On the first sight, this possibility seems to deteriorate the weight optimization potential. However, a split from one function to several functions could be an asset if energy flow and material flow could be reduced. Moreover, a decentralized function fulfillment provides a higher weight optimization potential under certain circumstances, for example for modularly applicable functions.
    - Exclusion: Aim of this variation possibility is the exclusion of the elementary functions "flow" and "store" out of the system/product to be considered. These sub-functions are not able to be changed in their kind, size and number; they can only be changed in their time and place. Thus, they are not meant for an increase of weight optimization potential. A checking of this type of variation is best practicable when the function structure is built in a best possible abstract way. That means that the function structure only consists of generally applicable (elementary) sub-functions.
    - Elimination: Secondary functions which are not directly contributing to the main function but are a prerequisite for the fulfillment of the main function could be eliminated.
- Variation of flows: Because material flows as is generally known directly cause weight, it is very advisable and beneficial to change them into energy flows which are only indirectly or less directly connected to weight.

When applying the variation possibilities in the way described above the function structure should be optimized in terms of weight. Normally, a more transparent function structure should be obtained what is reflected in the reduced number of flows and functions.

3.2.3 Functional Stage 2 – Weight afflicted functions

Based on the results of the previous analysis gate and previous stage as well as aspects from the requirements stage this stage provides a direct connection/relation between functions and weight as well as related weight properties. The strategy of conditional lightweight design is applied in that way that weight-related and customer requirements seek to influence the determination of function weights and function weight goals.

Derive customer functions
The customer functions are derived from the customer requirements in order to compare with the technical functions. With the rating of the requirements from requirements stage it is possible to generate a function importance ranking which will be used in further steps.

Determine function weight goals – Comparison of customer and technical functions
The determination of function weight goals is derived from the comparison of the technical functions and the customer functions. With the help of an adapted "House of Quality" from the method "Quality Function Deployment" technical and customer functions ranked after importance are compared. The ranking percentage of the customer functions/requirements and the proportional fulfillment of the technical functions with the customer functions is used to gain the single functions weight goals out of the total weight goal determined in the requirements stage. From now on, the function structure is weight afflicted. The importance value of the technical functions will be used later when working principles are searched.

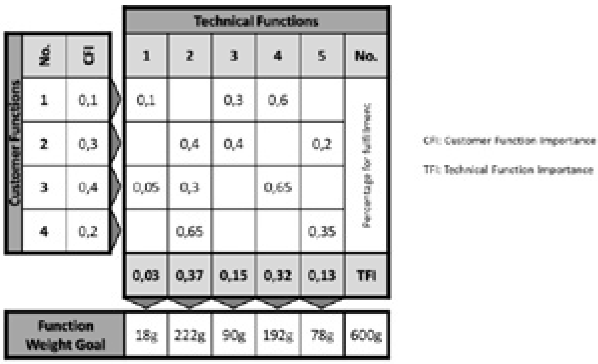

Figure 4. Determination of function weight goals

Determine function weights – Comparison of predecessor components and technical functions
To achieve the function weight goals another "House of Quality" has to be set up. But here, components of predecessor products are compared with the technical functions. A function weight results from the percentage of fulfillment of this specific function with a set of components and their respective weight [4, 5]. Thus with the QFD method and two Houses of Quality, weight can be connected to the function based on predecessor product information and customer demands.

Compare function weight goals and function weights
The comparison of weights and weight goals of every single function indicates the weight optimization potential of every function. If a function weight does not match its function weight goal it has to be considered how to solve this problem. On one side, there is the possibility to rethink the customer requirements or on the other side to hold the function.

3.2.4 Logical/Principle Stage
The search for working principles for the sub-functions defined in the function structure, the combination to a working structure and its concretization to a principle solution structure is part and parcel of this stage in conceptual design.

Search for physical effects
The first step after the functional stages is the search of physical effects for fulfillment of the sub-functions. If the search after effects and effect solution principles for a specific function is

difficult, it could be advantageous to allocate the function into several elementary, more abstract sub-functions. The ranking aspects and characteristics of these effects in physical, geometric and material-based levels facilitate the preparation of various solution alternatives which can be methodically accessed with a morphological matrix.

Pre-choice of working principles with characteristics
The physical effects found are compared with characteristic properties (for example effect intensity, realization possibility, …) to narrow down a pre-choice of working principles. Helpful here could be design catalogues which offer many possibilities to evaluate and choose suitable solutions. Exemplary design catalogues are from Roth [6] with general solutions or Luedeke [14] where especially mechatronic solutions for weight improvement are stored. Criteria for pre-choice are for example the magnitude of producible forces or the characteristic geometry. Often it is very helpful for introducing the characteristics which are relevant for the specific case. With the application of the relevant characteristic criteria for pre-choice a large amount of physical effects and thus the associated working principles can be reduced and depicted in the morphological matrix introduced in the step before.

Determine weight-dependent order of working principles
The pre-chosen working principles are arranged according to their weight dependency. The working principle taken from a predecessor product gets the value of 100% or 1,00. The other working principles found are accordingly ranked with a weight ratio in dependency of the weight of the predecessor working principle. Thus, the result is a weight proportion order. Moreover, the function weights introduced in the Functional Stage II give an insight on the weight relevance of the function which the working principles have to fulfill. On the other side, other information sources like designer experience or design catalogues can be used for the determination of the weight proportion and the order within the working principles solution set for one function. Thus, the working principles in the morphological matrix can be labeled with a weight relevance order in two dimensions (first order after function weight relevance and second order after working principle weight relevance within a solution set) and an estimated or even perhaps fuzzily determined weight.

Establish the working structure and check the compatibility of the working principles
Based on the weight relevance order introduced in the previous step, the working structure is established which is derived from the function structure and the search for working principles. For the fulfillment of the functions it is very necessary that the working principles are compatible to each other. Thus, different aspects (for example energetic, material or geometric factors) play an important role and have to be considered. The weight optimization in this step is based on the following criteria: first, the global weight optimum of the product/system dominates the choice of the working structure to be built (influence from conceptual and systemic lightweight design). Second, the working principles with the lowest weight relevance within their solution set and the highest weight relevance in the function weight order have to be preferred. Is the best possible working principle not compatible to others in different solution sets, the next working principle in the weight relevance order has to be chosen.
With the combination of the functional importance taken from the comparison of customer and technical functions and the working principle weight proportion in reference to the predecessor product, the weight relevance value *WRV* for a set of working principles can be determined which fulfill the technical functions from the function structure. The multiplication of the single function importance values and the proportion of the selected

working principles are summarized for generated working structures. Thus, different working structures from this morphological matrix can be compared.

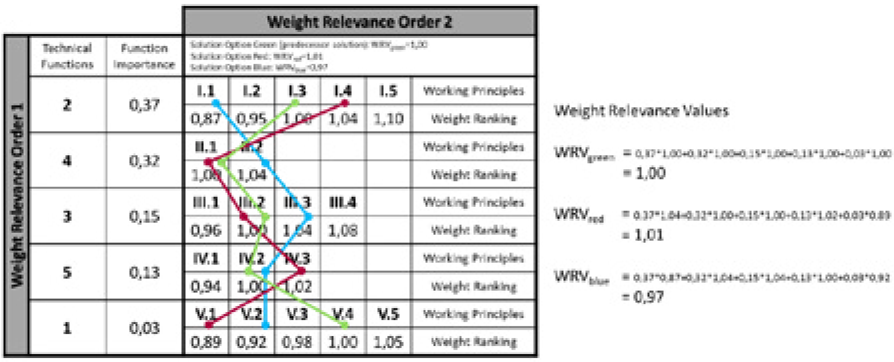

Figure 5. Morphological Matrix with Weight Relevance Order

For example, the value for the working principles combined in the red structure ($WRV_{red} = 1{,}01$) is higher than the value for the working principles generated in the blue structure ($WRV_{blue} = 0{,}97$) whereat the green solution option is the solution from the compared predecessor product ($WRV_{green} = 1{,}00$). Thus, the blue working structure is in this respect better suitable for a weight-optimized product. It unifies working principles compatible to each other with the best weight ranking value for the overall solution combination although not all single working principles are better than the traditional solution.

3.2.5 Further Design Steps

After evaluating the logical/principle solution stage the embodiment and detail design refines and concretizes the principle solution to the definitive layout of the product to be designed. For weight optimization in this phase the known strategies of manufacturing, material and structural lightweight design are applicable because the physical structure of the product is taken into consideration (geometry, material, …).

4 Example

An exemplary application of the methods and proceeding presented was executed with an electrical cork screw system for which a weight optimization of about 20% could be achieved. The predecessor weighs about 600g and shows some deficits discovered by the customers (for example energy consumption, high noise level during usage). Beside an adaption of the requirements list the original function structure could be optimized in that kind that the number of functions could be reduced from 11 to 8. Moreover, “lighter” working principles lead to a considerable undercutting of the total weight goal. The “electrical” working principles (battery, electromagnet and gear transmissions) are mainly replaced by “mechanical” principles (metal spring, pneumatic piston). A further weight optimization should be possible in later design phases when the strategies of manufacturing, structural and material lightweight design are applicable.

5 Conclusion and Outlook

The contribution proposes a proceeding for taking weight optimization into account in the early design phases (conceptual design). In general, it is known that the most influence on product properties (performance, weight, cost…) exists in this early design phase. The proceeding provides methods which are supporting weight optimization in the abstraction levels of requirements, functions and working principles. With their help, functions and working principles which are not weight-afflicted until today receive “function weights” and “weight ranking values”. With these values, different structures generated in one abstraction level could be compared and evaluated for best weight optimization. Further research deals with the further development of these methods presented here and definitive integration into the development process for mechatronic products.

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