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SUPPORTING LIGHTWEIGHT DESIGN POTENTIAL ASSESSMENT IN THE CONCEPTUAL PHASE

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Keywords: lightweight design potential, function mass analysis, assessment of lightweight design potential

1. Introduction

Lightweight design is becoming an increasingly important aspect of product development. The advantages include, for example, the reduction of energy consumption and CO_2-emissions of vehicles, the reduction of physical strain on the users who have to carry the products, the increased maximum possible acceleration of industrial robots, as well as many others [Ponn and Lindemann 2011].
The literature of lightweight design proposes different lightweight strategies, such as material, condition or manufacturing lightweight design [Henning and Moeller 2011]. However, the high potential of the early design phases in particular is not exploited systematically. In the early stage of the conceptual phase of the product development process as described by Pahl et al. [2007] for example, the functions, their sub-functions, the working principles and the whole working structure are determined. For instance the sub-function of "torque transmission" can be fulfilled by a shaft. In order to fulfil the function with regard to lightweight design, the shaft can be drilled hollow and it can be created using fibre-reinforced plastic. However, the sub-function "torque transmission" can in some cases also be carried out using another working principle, for example a V-belt. This solution can potentially be much lighter and also cheaper. The idea of switching the working principle can offer new opportunities for lightweight design. In addition, mechatronic solutions can be initiated by changing the working principle. Not respecting lightweight design when choosing the working principle for example, can waste great lightweight potential. However, in order to select the appropriate working principle with the highest lightweight design potential, the assessment of the lightweight design potential of different solutions during the conceptual phase has to be supported.

2. Problem statement and goals

In the conceptual design phase there is often a huge variety of solutions which cannot be fully assessed [Heller 2013]. This huge variety could be used as a basis for selecting the solutions with the highest lightweight design potential. Thus, the lightweight design potential of this early stage could be exploited. The problem with choosing the function structure, working principle or working structure that has the highest lightweight potential is the missing information about the mass required to realise it. At the abstraction level of a function structure, working principle or working structure, there is no information about the shape, material or density of the material and therefore no information about the mass required to fulfil the sub-function or working principle. The Function Mass Analysis [Posner et al. 2013] is a method which supports developing the mass aims and the analysis of the lightweight design potential of functions, but for example does not yet support the decision, which working principle has the higher lightweight potential compared to another. One idea of the Function Mass

Analysis is to consider the product and its functions in terms of their structure and sub-solutions in order to analyse them with regard to the importance of the sub-functions and the mass required for their fulfilment. In order to perform that analysis, the method is based on the analysis of existing similar products. This idea of comparing sub-solutions (sub-functions, working principles) of the product to be developed with existing products will be used in the following sections in order to support the assessment and selection of these sub-solutions with regard to their lightweight design potential. This approach makes it possible to achieve frontloading of the conceptual phase with the mass information about the sub-solutions and to use that information for the assessment and selection. The overall research question that needs to be answered in order to do this is the following: *How can the lightweight design potential of different solutions and sub-solutions in the conceptual design phase with its high level of abstraction systematically be estimated and assessed?*

3. Method

The results of the contribution are developed using the Design Research Methodology (DRM) according to Blessing and Chakrabarti [2009]. In the first step of the DRM, the Research Clarification, the tasks are clarified and the research questions and hypotheses are developed (see Sections 1 and 2). In Section 4, the state of the art, the results of the second step, Descriptive Study 1, are presented. The results of the third step, the Prescriptive Study, are the developed support and are presented in Sections 5, 6 and 7. The fourth step of the DRM, Descriptive Study 2, the extensive evaluation of the content of this paper, is mentioned in the outlook and represents the next step to be carried out based on this contribution.

In Section 7 a simple example is given in order to aid understanding of the method. The example was worked through in a team of three mechanical engineers. These engineers have a scientific background. The example is not based on an industrial project so it is only a supporting evaluation [Blessing and Chakrabarti 2009] that helps to understand and demonstrate the applicability of the method. The next step must be a detailed and extensive evaluation of the method.

4. State of the art

In the state of the art, the conceptual design phase, its assessment and selection steps and the Function Mass Analysis which will be used as a basis for the following development of a support are presented.

4.1 Conceptual design phase

Pahl et al. [2007] propose one of the most common procedures for the conceptual phase, as shown on the left side of Figure 1. The conceptual phase is based on the requirements list which is developed in the previous phase, called the planning phase. The first step of the conceptual phase is the abstraction of the problem in order to identify the essential problems. Next, the function structure which starts from the overall function of the product and ends in breaking down this overall function into its sub-functions is developed. Because there are different combinations of sub-functions that can fulfil the overall function, there is often more than one function structure to be developed for the product. The third step searches for working principles that fulfil the sub-functions. Once again, there is usually more than one working principle that fulfils one sub-function. Then in the fourth step the working principles are combined into working structures in order to fulfil all sub-functions and in doing so fulfil the overall function of the product. In this step as well, there is more than one possible combination of the working principles and thus of the working structures. In the fifth step, suitable combinations are selected. Next, the principle solution variants are firmed up in order to be able to asses them in the last step of the conceptual phase [Pahl et al. 2007]. The following consideration is based on this procedure of Pahl et al. [2007], although there are other procedures for the conceptual phase, such as [VDI 1993], [VDI 2004] or [Ponn and Lindemann 2011].

4.2 Assessment and selection in the conceptual design phase

The procedure of the conceptual phase according to Pahl et al. [2007] comprises different levels of abstraction of solutions in which more than one solution is possible. As discussed in the last sub-

section, it is possible that a number of different solutions are developed in steps 2, 3 and 4, as shown in Figure 1. Hence, there can be an explosion of the number of possible solutions which cannot be handled or followed up [Heller 2013]. This means there must be an assessment and a selection at the end of these steps if there are too many solutions to follow up [Pahl et al. 2007].
In literature, there are different methods for the assessment and selection of solutions. For example Pahl et al. [2007] propose the systematic selection chart or the technical and economical assessment. However, regardless of which method is chosen for the assessment, in order to assess the solutions with regard to their lightweight design potential, there must be information about how much mass is needed in order to fulfil the different solutions. There is no methodical support for gathering this information and thus preparing the selection.

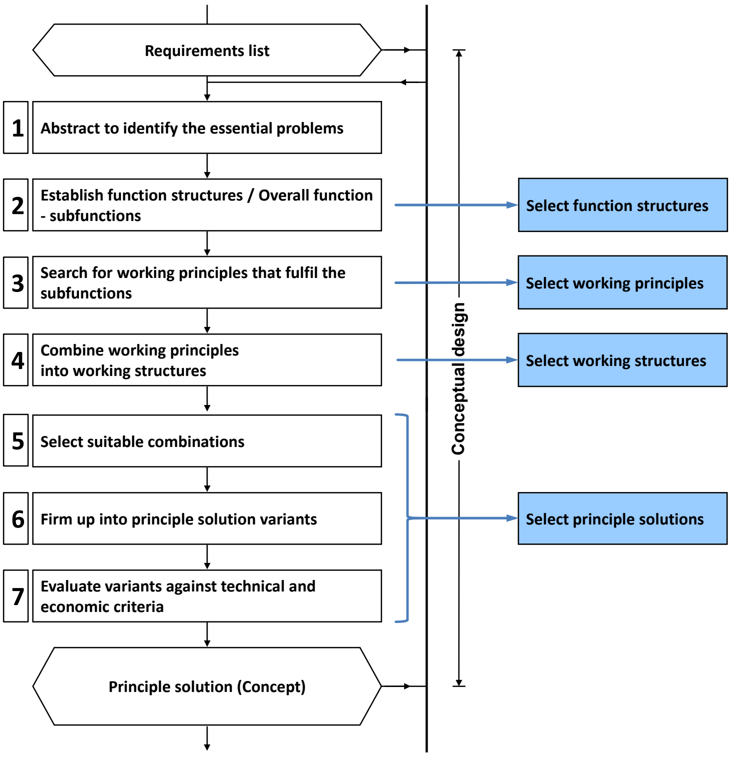

Figure 1. Steps of conceptual design [Pahl et al. 2007]

4.3 Approach of the Function Mass Analysis

The Function Mass Analysis (FMA) is based on the transfer of the Value Analysis to the application on mass instead of costs. The FMA supports an interdisciplinary team in developing or optimising products with regard to lightweight design [Posner et al. 2013].
In the first steps (0-2) the FMA-project is prepared, defined and planned. In the third step comprehensive data about the project is collected. The fourth step is the most important step of the method. During this step, the importance of functions, the mass required in existing products in order to fulfil these functions and the overall mass aims for the product and each function and component are developed. The fifth step supports the idea collection process and the finding of new solutions. These solutions have to be evaluated and selected in the sixth and seventh step. At the end of the process (step 8 and 9), the developed proposals are presented to the decision makers in order to obtain a decision and then the further implementation of the proposals is planned.
The basic idea of the FMA is to connect the function structure and its sub-functions, which have to be fulfilled and which are important for the customer, with existing solutions of similar products. Thus, the designers are able to analyse how important the functions are for the customer and which mass is needed for their fulfilment. Based on this information, they can decide which function should be fulfilled and which has a major discrepancy between its importance and its mass and thus has a high optimisation potential.

5. Assessment of solutions with different levels of abstraction in the conceptual phase

As previously discussed in Section 4.2 and shown in Figure 1, there are four possible steps in which a selection of solutions is possibly necessary. Whether it is necessary or not, depends on how many competitive solution results exist in the respective step. If there are more solutions than can be followed up, because of the limited resources, there has to be an assessment and selection. In order to perform these with regard to the lightweight design potential of the solutions, the information content of the different levels of abstraction of the solutions in the conceptual phase first have to be analysed. Function structures include no geometric or material information. Thus, there is no information about the volume or density and therefore no information about the mass required in order to fulfil the sub-functions. At the level of working principles, there is information about the physical effect as well as some geometrical and material attributes. However, the geometrical information is limited to a rough structure of the working principles. The material information does not include the detailed material that is used in order to achieve the working principle. Hence, there is also no information about the volume or the density of the material of the solution at the level of working principles. There is only information about the working surface pairs and their linking. Combining the working principles and thus combining the function structure with the working principles, results in the working structure. The working structure only includes additional information about the arrangement and interaction of the working principles. However, even at the step involving the development of working structures there is no information about the material, its density or the volume to be applied in order to achieve the working structures. Therefore, there is no information about the mass that will be required in order to implement the working structure in the product. To enable the assessment of the different solutions, Pahl et al. [2007] propose detailing the working structure. They call this more detailed state of the solution the 'principal solution', but they do not define it in detail. The level of abstraction of the principal solution can include rough information about the volume of the components, the materials and the density of the materials. This information can be used for an estimation of the mass of the different solutions.

This means that especially on the level of abstraction of the function structure, working principle and working structure there must be information gathered about the lightweight design potential in order to enable a selection to be made with regard to lightweight design aspects. In the following section a way of solving this problem and gathering this information will be shown.

6. Implementation of the Function Mass Analysis in the product development process

The Function Mass Analysis supports the frontloading of the function structure with information about the mass required in existing products in order to fulfil these functions. This idea will be used in the following section to gain information about the mass required for the realisation of different function structures, sub-functions, working principles and working structures.

Figure 2 shows the steps of the FMA assigned to the phases of the product development process according to Pahl et al. [2007]. It also shows the steps at which a decision is necessary as to whether or not there has to be an assessment and selection of the solutions. If there are too many solutions to follow them all up, a selection must be made. In order to consider the lightweight aspects in this selection, some preparation must be carried out for the assessment to gather more information about the lightweight design potential of the solutions. After this step, the actual assessment and selection can be executed. Then, the next step of the product development process can follow. This process has to be adapted to the situation in which it is applied, the number of solutions and the designers' existing resources in order to follow up more than one solution. The three possible use cases in which an assessment and selection are necessary and the idea of the FMA is to be implemented for preparing this assessment are shown in Figure 2.

The procedure allows the idea of the FMA to be respected in different situations of the conceptual phase of the product development process. It also implements different iterations in steps 4, 5 and 6 of the process of the FMA. The assessment preparation step, referred to here as the Function Mass

Estimation (FME), supports the assessment of the lightweight design potential right from the abstraction level of solutions in the conceptual phase. How to use the idea of the FMA in detail in order to perform the FME will be shown in the following section.

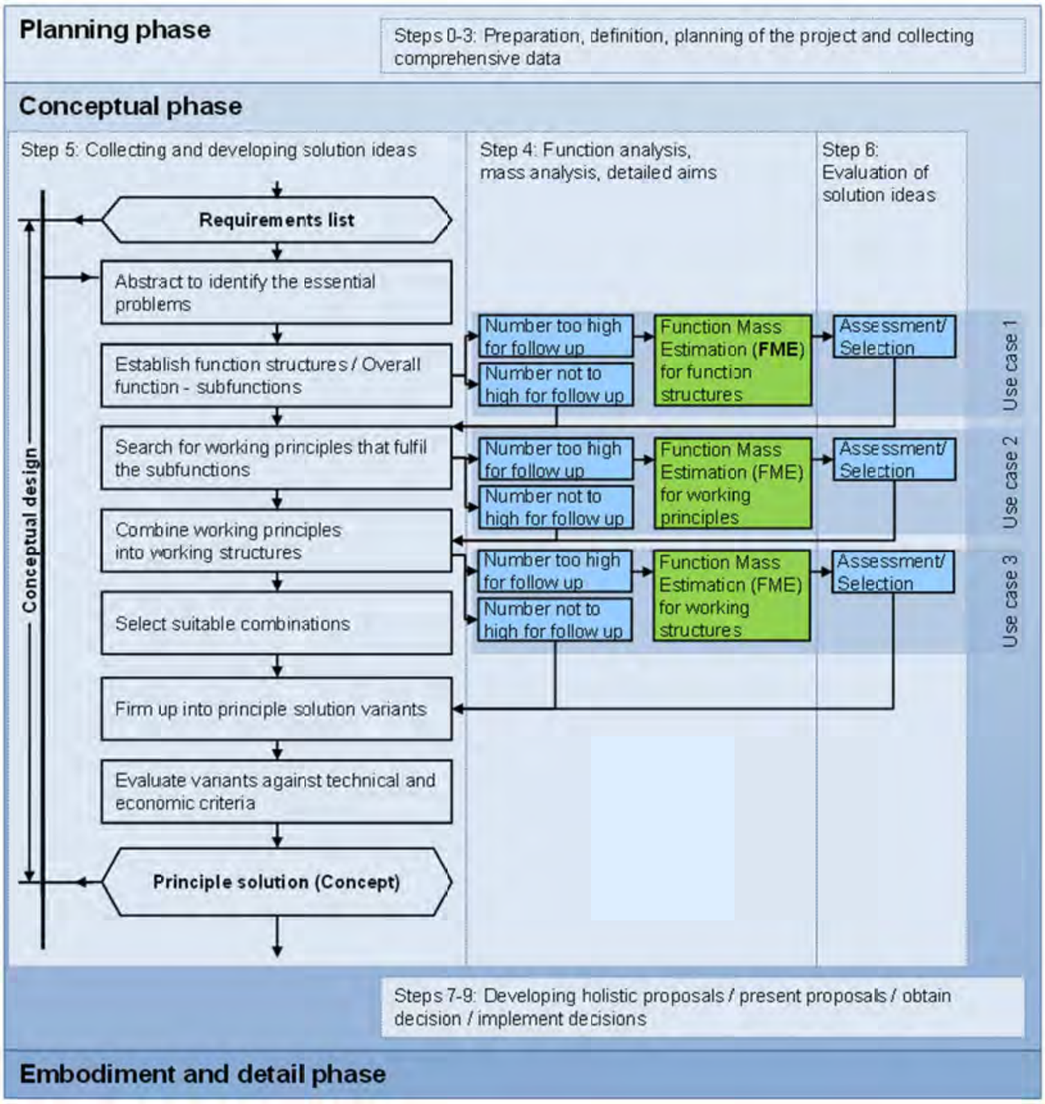

Figure 2. The Function Mass Estimation matched with the product development process and the Function Mass Analysis

7. Function Mass Estimation - systematic support of the lightweight design potential assessment in the conceptual phase

In order to use the idea of the Function Mass Analysis to support the decision as to whether and how single sub-functions, single working principles or working structures have to be realised, in the following section a procedure called the Function Mass Estimation (FME) is presented, as shown in Figure 3.

7.1 FME Step 0: Decision as to whether or not an assessment and selection is needed

If there are more solutions than can be followed up in one of the three aforementioned steps in the conceptual phase, the FME can be used to prepare the assessment and selection of the solutions with regard to the lightweight design potential. This has to be decided in Step 0 of the FME.
In the following section, the presented procedure will be applied to a simple example in order to provide a better understanding. A hedge trimmer is used as an example. It is assumed, that the

company already sells a combustion hedge trimmer and the function structure of it is available. While searching for different working principles for the sub-functions, the designers come up with the idea of developing an electric or cordless version of the hedge trimmer. The designers also assume that the mass of the product is a very important success factor for their product, because less mass means less physical strain for the user. In the conceptual phase after developing these ideas for the different working principles, the designers have to decide which working principles and thus which variant of the hedge trimmer they want to follow up, because the assumption is, that they can only follow up one solution due to the limited resources. In order to decide this, the FME will be applied to support the decision with regard to lightweight design. This application of the FME corresponds to the second use case in Figure 2.

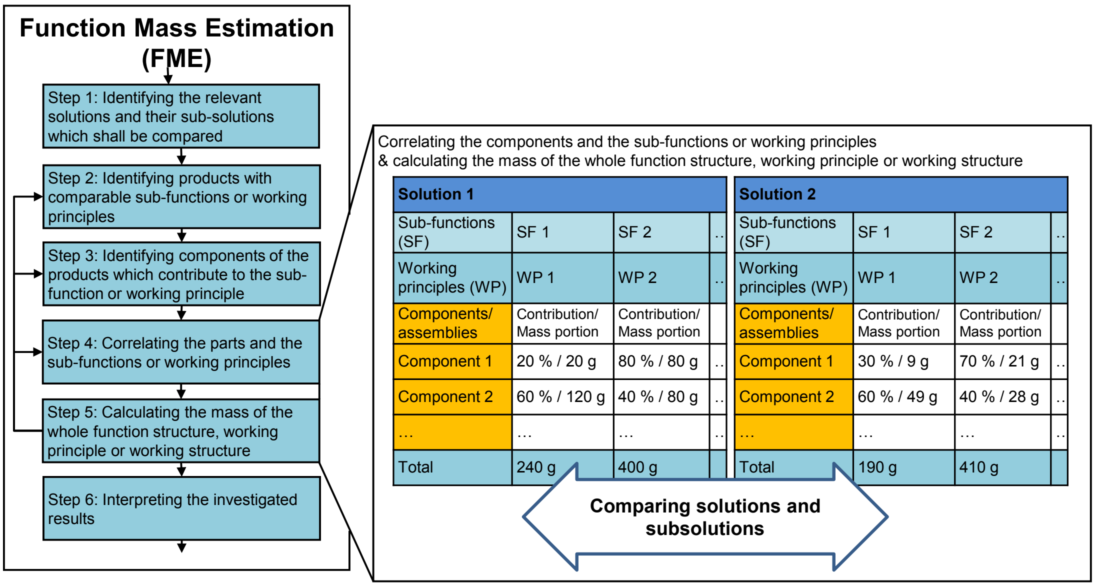

Figure 3. The procedure of the Function Mass Estimation (FME)

7.2 FME Step 1: Identifying the relevant solutions and their sub-solutions that are to be compared

First of all, the solution variants, such as the function structures, sub-functions, working principles and working structures that are to be compared must be identified.

The focus of the following section will be on the sub-functions “store energy”, “change energy” and “damp vibration”. The corresponding working principles (WP) of the analysed solutions (“WP fuel tank”, “WP combustion engine”, “WP springing” as shown in Table 1 and also “WP electric motor” and “WP battery”) are also examined, due to the considered alternatives of an electric or cordless hedge trimmer.

7.3 FME Step 2: Identifying products with comparable sub-functions or working principles

For these solution variants, products with at least similar single sub-functions or working principles have to be found. The advantage of the FME compared to the FMA is that a similar whole product does not have to be found, only a similar realisation of the individual sub-functions or working principles.

In the example of the hedge trimmer, the designers analyse an electric vacuum shredder that is already available on the market. By analysing it with the support of the FME, they try to estimate the lightweight potential of a possible electric and cordless hedge trimmer, as shown in Figure 4. The combustion and electric vacuum shredder are analysed due to their working principles for the sub-functions “WP change energy” and “WP springing”. However, because there is no working principle for the sub-function “store energy” in the electric vacuum shredder, a product has to be found that has this working principle in a comparable manner. In order to achieve this, a cordless hammer drill is also analysed.

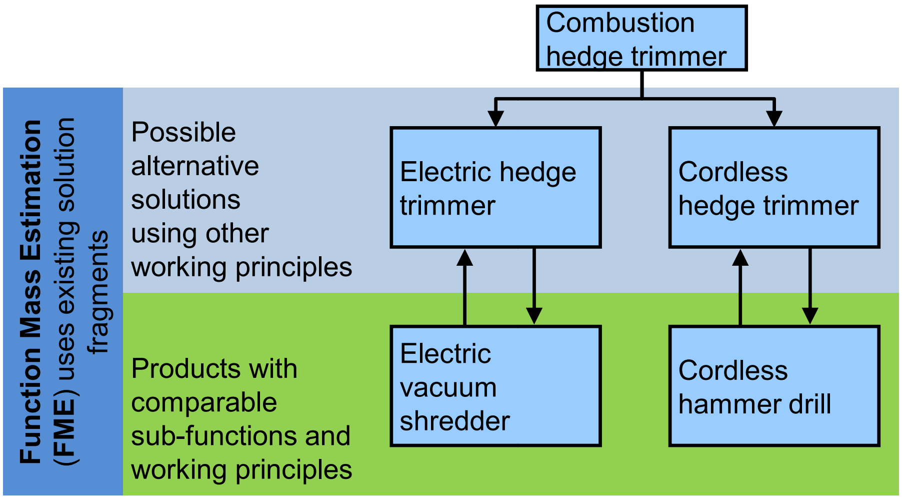

Figure 4. How to use the FME in order to estimate alternative hedge trimmer concepts

7.4 FME Step 3: Identifying product components which contribute to the sub-function or working principle

In the third step, the product components which contribute to the fulfilment of the considered sub-function or working principle have to be identified. As shown in the example in Table 1 for the combustion hedge trimmer, in this step the components which contribute to the considered sub-functions or working principles are listed on the left side of the table. This procedure must also be carried out for the other products and their components which have to be analysed.

7.5 FME Step 4: Correlating the components and the sub-functions or working principles

The contribution of each component to the fulfilment of the working principle or sub-function has to be quantified in the next step, by correlating the components with the sub-function or working principle. In the end, the amount of mass required in order to fulfil the considered sub-function or working principle has to be calculated. This process has to be performed for each possible solution and sub-function or working principle which the designers want to investigate.
In the fourth step, a table like Table 1 has to be developed for each analysed product. In these tables the designers have to estimate the percentage that a component contributes to the fulfilment of the different working principles or sub-functions. By multiplying this percentage by the mass of the component and totalling these masses for each component, the mass required for the fulfilment of one sub-function or working principle can be calculated, as also shown in the example in Table 1.

Table 1. Extract from FME for combustion hedge trimmer

Sub-function (SF)			Store energy		Change energy		…
Working principle (WP)			**WP fuel tank**		**WP combustion engine**		…
Component	Number	Total Mass	Contribution	Mass proportion	Contribution	Mass proportion	…
Fuel tank part 1	1	226 g	100 %	226 g			…
Screws for tank	4	20 g	100 %	20 g			
Fuel	1	380 g	100 %	380 g			…
Combustion engine	1	1423 g			100 %	1423 g	…
Spring	4	14 g					…
…	…	…	…		…	…	…
Total mass		5932 g		626 g		2881 g	…

7.6 FME Step 5: Calculating the mass of the whole function structure, working principle or working structure

If function structures or working structures have to be investigated, the results for the different sub-functions and working structures have to be combined in order to get a result for the structure. The results for different solutions can be used as a systematic estimation in order to support the decision regarding the solutions which the designers want to follow up.

In the case of the hedge trimmer development, the results of the single working principles of the different analysed products have to be summed up in order to get results for the solution alternatives of the electric and cordless hedge trimmer, as shown in Table 2. The mass of the sub-functions and working principles of the combustion hedge trimmer not considered in detail will be assumed as similar to those of the electric and cordless hedge trimmer variants. This helps to formulate a statement about the total mass of the solution variants.

Table 2. Overview of the results of the FME for example working principles

Product type	Sub-function				Mass from WP 1.-3.	Total mass	Light-weight potential compared to CHT
	Store energy	Change energy	Damping vibrations	Remaining sub-functions			
Combustion hedge trimmer (CHT)	1. WP: Fuel tank	2. WP: Combustion engine	3. WP: Springing	Remaining WP			
	626g	2881g	259g	2166g	**3766g**	**5932g**	
Combustion vacuum shredder	1. WP: Fuel tank	2. WP: Combustion engine	3. WP: Springing	Remaining WP			
	733g	2733g	196g	2639g	**3662g**	**6301g**	
Electric vacuum shredder	-	2. WP: Electric motor	-	Remaining WP			
	-	2029g	-	2549g	**2029g**	**4578g**	
Cordless hammer drill	1. WP: Battery	-	-	-			
	1427g	-	-	-	**-**	**-**	
Function Mass Estimation							
Cordless hedge trimmer	1. WP: Battery	2. WP: Electric motor	3. WP: -	Remaining WP			
	1427g	2029g	-	2166g	**3456g**	**5622g**	**More than 310g**
Electric hedge trimmer	1. WP: -	2. WP: Electric motor	3. WP: -	Remaining WP			
	-	2029g	-	2166g	**2029g**	**4195g**	**Approx. 1740g**

7.7 FME Step 6: Interpreting the investigated results

The interpretation of the investigated results forms the basis for the assessment and selection. The results of the FME are shown in Table 2 and the amount of mass for the three considered solution variants is also visualised in Figure 5. It can be seen, that the mass of the combustion engines for the hedge trimmer and the vacuum shredder are almost identical in spite of the fact that their designs are very different and that different attachment components have to be added to their mass because they contribute to the engine's working principle. The analysis of the combustion vacuum shredder would not be necessary in the case of the company which wants to analyse an alternative to their combustion hedge trimmer. It is only made to give an indication of the comparability of the results, even for different products. The working principle "battery", for example, should not be equated with the component battery, there are also further components which belong to and enable this working principle, such as the components of the component fixing equipment. It is also shown that the

cordless hedge trimmer has greater lightweight design potential than the combustion hedge trimmer, as shown by the mass reduction potential of more than 310 grams. One reason for this is that if an electric motor is used, the sub-function damp vibrations of the combustion engine can be omitted. In this case, the 230 volt version of the engine of the electric vacuum shredder is too large for the 36 volt battery which is chosen. This could lead to further mass reduction potential. The next step would be the investigation of different 36 volt motors which can fulfil the requirements. It is clear that the electric version of a hedge trimmer has a great lightweight design potential (1740g). That is because the sub-function “store energy” does not have to be implemented in the product. Of course, this is not a solution in all cases, as a professional user cannot use a cable connection throughout whole public gardens, for example. However, in the case of a hobby gardener with a small area of land, this can be a suitable solution with great advantages regarding the mass and thus the physical strain reduction.
Based on these results, the further assessment and selection can be carried out according to the tools proposed for example by Pahl et al. [2007], such as using the systematic selection chart or the technical and economical assessment. Therefore, all requirements which can be assessed at that high level of abstraction of the solutions have to be considered in the assessment and selection.

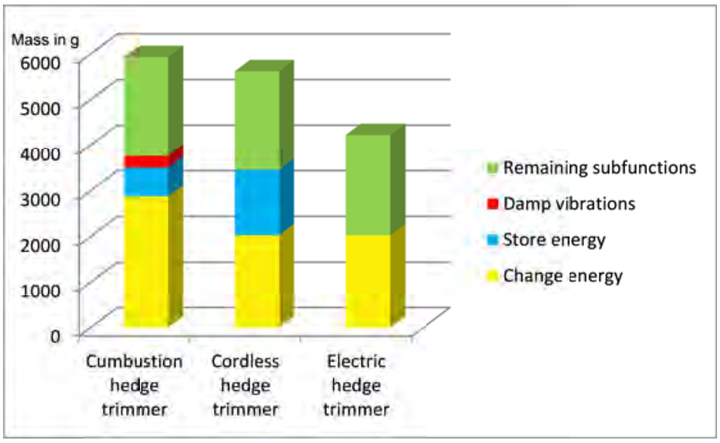

Figure 5. Amount of mass for the different solutions

8. Discussion

In many cases there are already existing solutions for the realisation of single working principles or sub-functions. The Function Mass Estimation (FME) supports the analysis of sub-solutions, such as sub-functions or working principles, by analysing existing products regarding the mass required to realise the sub-solutions. Using the results of the analysis of these sub-solutions and composing the sub-solutions to build up the considered function or working structures allows estimation with regard to the mass and thus with a focus on the lightweight design potential of different solutions.
One of the advantages of the method is that only sub-solutions of the solutions must already be implemented in other products, and even if not all sub-solutions are already implemented in other products, the estimation for the other sub-solutions supports the designers in their decision. The method is easy to use without the need for complex and expensive software, which is often the case in lightweight design. By using this method, the designers develop a deep understanding of the context of the product regarding the sub-functions, working principles and their implementation variants. The method also supports the detection of sub-functions or working principles which can be omitted in the case of some working principles. Of course, the idea of analysing similar products with similar solutions is not new, needs time and especially for the function modelling the designers need experience in doing it, but the FME supports designers in performing this analysis systematically. Thus, the results are well structured and can be compared with each other. It is extremely important for achieving reliable results that the characteristics of the analysed similar products are compared and matched precisely. In some cases it is hard to find similar solutions or even to find similar sub-solutions if the solutions are very new. However, for the application of the FME, even small sub-solutions of the solutions that are similar to other products are enough to benefit from the support of

the method. Furthermore, the results of this approach are only qualitative, which means that in the example of the hedge trimmer, the mass is not reduced by exactly 310 g simply by choosing the cordless solution. The mass of a product will not be determined until the detailed material with its density and the detailed shape and volume of the components are defined. However, the conceptual design phase has great lightweight design potential, because the designers have enormous freedom and determine most of the characteristics of the product in this phase. The FME helps designers to use this great potential in order to achieve a lightweight design.
This approach was developed based on the similar aims of the Design for Costs and the Design for Leightweight. In future work, it has to be investigated how this approach can be used for other Design for X criteria in order to exploit their potential during the conceptual stage.

9. Conclusion and outlook

The research question is answered by using the concept of the Function Mass Analysis in order to systematically analyse the amount of mass required for the sub-solutions of new solution variants in existing products. Thus, the method supports designers in systematically analysing existing components of solutions and uses these results to estimate which working principle, sub-function and thus working structure or function structure has the greater lightweight design potential. The developed method, the Function Mass Estimation, can be used at different levels of abstraction in the conceptual design phase and thus prepares the assessment and selection of solutions with regard to lightweight design aspects.
The approach of the FME has to be evaluated in order to comply with scientific requirements. It is also possible to transfer the approach in order to assess the concepts on their abstract levels with a focus on further criteria, such as the costs, for example.

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