HOLISTIC LIGHTWEIGHT DESIGN FOR FUNCTION AND MASS: A FRAMEWORK FOR THE FUNCTION MASS ANALYSIS

B. Posner, A. Keller, H. Binz and D. Roth

Keywords: design method, design for x, design for function, design for mass, lightweight design

1. Introduction

Lightweight design or design for function and mass is becoming increasingly important. There are a number of different causes for this. Reducing the mass of a product can reduce energy consumption and CO_2 emissions. This can lead to the improved economic and ecological performance of the product, for example, in the case of vehicles. Also, by reducing mass, acceleration times can be shortened, for example, in the case of industrial robots. In addition to the reduction of mass, optimisation of the distribution of mass can reduce the physical forces and moments resulting from the mass of the product and thus the physical impact on the user can be reduced. Optimisation of the distribution of mass can also result in better dynamic properties of the product, such as for example higher possible cornering speeds in the case of vehicles [Ponn 2011]. As a result of the distribution of mass, the mass moment of inertia of the product can also be influenced. Optimisation of the mass moment of inertia again has an influence on the acceleration time, which can be reduced by optimising this moment [Feyerabend 1991]. The reverse shows that holistic designing for function and mass means respecting mass as an optimisation criterion as well as respecting the distribution of mass and the resulting mass moment of inertia.

There is a great deal of literature dealing with lightweight design [cf. Henning 2011 for an exhaustive review]. This presents a number of lightweight approaches in detail, such as condition, system, material, conceptional, shape, calculation and manufacturing lightweight design. In addition, it also asserts that the methodical procedures of lightweight design correnspond to a certain extent to the procedures of general design methodology [Henning 2011]. Beyond that, Ponn et. al. [Ponn 2011] stated that it is important to set targets for the mass of the product to pool all efforts to reach these targets. These targets should be broken down to mass aims for each part of the product and also for the fulfilment of each function. To operationalise this Feyerabend [Feyerabend 1991] transferred the method of the Value Analysis (VA) from its application to reduce cost to the application to reduce mass. However, he did not specify a procedure to take account of the mass distribution and the resulting mass moment of inertia. This means, that there is no method for holistic design for function and mass. To close this gap a new method, called the Function Mass Analysis, will be developed.

For developing a method for holistic design for function and mass, first the requirements which the method must fulfill must be clarified. Reducing the mass of a random selected component of a technical system or product can negatively affect the mass distribution of the product. As a result of this problem, a method for optimising the mass should also address optimisation of the distribution of mass, e.g. the arrangement of components and assemblies and their individual mass. Rotating these components around an axis defines the moment of inertia resulting from these components and their arrangement. Holistic optimisation of the mass means also respecting this moment of inertia resulting from the distance between each component and the rotation axis and its individual mass. So the method to be developed should support the holistic design for function and mass respecting the mass, the distribution of mass and the mass moment of inertia resulting from the distribution of mass within the product.

In addition to setting targets and the holistic consideration of mass optimisation, the method should support the designer in searching for the appropriate lightweight approach. This means that this paper do not set out to expand or advance one of the existing lightweight approaches. The method should offer a way to systematically derive the compatible lightweight approaches and should help to generate a bandwidth of lightweight solutions. This bandwidth of solutions should be methodically assessed under consideration of other previously not considered aspects such as the vibration characteristics, the costs, the stiffness and other aspects which can be derived from the list of requirements. Respecting these characteristics, as for example the vibration characteristics, which represent a crucial point in the lightweight design, represents a potential for later expansion of the method.

For realising these aims, the method should take into account existing methods of the state of the art of design methodology as well as the existing lightweight approaches of the lightweight design, and should also contribute to the state of the art of the design methodology and of the lightweight design.

The application of the method should be limited to products where mass optimisation is a stated goal. Products which have advantages out of a larger mass, such as the perception by customers that a pen appears of higher value if it has a certain mass, will be excluded from consideration. No further limitation of the application of the method should be necessary. Mechatronic systems should also be optimised in a similar way to purely mechanical systems.

A method for design for function and mass can be classified according to the "Design for X" (DfX) systematisation by [Clarkson 2005]. Because the optimised function and mass of the product increase functionality, reduce burden on the user, improve dynamic characteristics, implement lower energy or fuel consumption and impact and thus lower cost, the method is settled up in the field of Design for Use, but also in Design for Cost. Even more assignments at other DfX criteria, such as the design for low resources are conceivable, because there is a reduction in mass thus resulting in materials savings. However, also the state of the art of the DfX includes no method for a holistic design for function and mass.

2. Problem statement and goals

There is a gap in lightweight design methodology in holistically regarding the mass, the distribution of mass and the mass moment of inertia resulting from the distribution of mass for holistic optimisation of the mass and by that, of the lightweight design. The weight and the mass of products are rather descriptive characteristics of products that are not formulated in terms of objectives, which are broken down to component level [Ponn 2011]. More specifically, the designer optimises the product with more or less unsystematically selected lightweight approaches once the product design is nearing creation. The superior aim is to develop a method to support the holistic design for function and mass. This method has to support the designer in the effective and efficient development of lightweight products. To achieve this superior goal, the objective of this paper is to answer the following main research question: *How can a designer be supported in designing for lightweight?* To answer this research question a hypothesis can be formulated: *The designer can be supported in designing for lightweight by a method for holistic design for function and mass.*

From the main research question and the hypothesis, several research questions have been derived, which are presented in Table 1. To answer these research questions, Section 3 presents the state of the art of the methods for design for function and mass. In Section 4 the requirements on such a method are worked out. Assessment criteria are derived for each requirement. With the help of these assessment criteria, assessment of the methods of the state of the art is presented in Section 5. Section 6 discusses the results of this assessment and presents the pros and cons of the methods. A framework for a method for holistic design for function and mass, which is based on the results of the assessment of the state of the art for design for function and mass, is presented in Section 7 and discussed in Section 8.

Table 1. Overview about the research questions of the article

Research Question	Section							
	1	2	3	4	5	6	7	8
Why is design for lightweight important for engineering design?	■	■						
What are the methods for design for function and mass?			■					
What are the requirements on a method for design for function and mass?				■				
What are the possible assessment criteria for each requirement?				■				
Which of the developed assessment criteria are fulfilled by the methods of the state of the art?					■			
Which method could be the basis for a further development of a method for design for function and mass?						■		
How can a framework for a method for design for function and mass look?							■	
What is the innovation potential of the developed framework?								■
What are the limitations of the use of this framework?								■
What are the following steps of the further development of this framework?								■

3. State-of-the-art of the design methodology and preselection of methods

As a subdiscipline of mechanical engineering, aeronautics and space technology, the mass of a structure is at the centre of considerations when it comes to constructive lightweight design. The literature of lightweight design provides for a methodical product development process, as also in the general design methodology according to [Pahl et. al. 2007] or others. Moreover, in lightweight design the driver mass is accommodated by different lightweight design approaches, such as the material, shape, bionic, constraint driven, conceptional, system or manufacture lightweight approaches [Henning 2011]. In addition, dimensioning and calculation is the basis reducing the mass of oversized parts. For this there is a lot of software to support the designer in calculating and in optimising the structure of such parts.

Furthermore, in lightweight design there are design rules complementary to the methodical design process, for example, according to Pahl et al. [Pahl 2007] as methodical support for the designer in designing for mass. One of these rules is, for example, to design direct power transmission as a preference. Ashby [Ashby 2005] created a method to choose the best fitting material for each design problem. In addition, there are two approaches in lightweight design for creating a method for design for function and mass by transferring the VA from its application to costs to an application to mass. The VA is originally a method of the methodology of the Value Management to design to cost [DIN 12973]. VA is defined as a method for function-oriented and economical design process with the aim of increasing the value of the object in question. For this, value is defined by the VA as fulfilment of needs, e.g. the fulfillment of functions, divided by the resources used, e.g. the costs which were generated [VDI 2800]. Firstly, the functions and costs which must be fulfilled were investigated by the VA. After that, target costs were defined which are broken down to each function and each part of the product. For the attainment of these targets, the VA supports the identification of solutions. The core of the method is collaboration in an interdisciplinary team which includes all involved sections of the enterprise [Kermode 2000]. Broderick extended the definition of value by adding a trade-off factor as an incentive to reduce component mass. This factor is defined as cost per kilogram and it must be multiplied by the weight of the product. These calculated costs must be added to the costs in the definition of the value [Broderick 1992]. A further development of the VA to the Value Analysis

Weight (VAW) defines value as the ratio of function and weight. The VAW is the result of a transfer from the VA by the application to optimising the costs to the application to optimising weight.

4. Requirements and assessment criteria

In order to perform an assessment of the investigated methods, first the requirements which are important for a method for design for function and mass must be established. For that purpose the case of designing for function and mass must be investigated for the important aspects to be respected. To make these requirements measurable assessment criteria will be derived from each requirement. With the help of these criteria a yes or no decision will be made regarding wether the method to be assessed fulfils each criterion or not. By means of these assessment criteria the methods of the state of the art will be assessed. An overview of the developed requirements is given in Table 2. The requirements will be established in detail in the following subchapters.

Table 2. Requirements for a method for design for function and mass

Section	Requirement
4.1	Consideration of functions
4.2	Consideration of mass
4.3	Consideration of mass distribution
4.4	Consideration of mass moment of inertia
4.5	Consideration of mass-dependent working principle
4.6	Consideration of further product properties
4.7	Support of the conceptional and embodiment design phases
4.8	Validity

4.1 Consideration of functions

The superior objective of every product is to fulfil its functions. With regard to design for mass the importance of functions and the amount of mass required to implement these functions must be balanced and functions not required by the user must be omitted. By appreciating the importance of the function and by calculating the mass required to implement this function for exsiting products, the designer is supported in deciding, as wether or not the function must be implemented. To realise this, the method must determine the importance of each function. After that, the preceding or competitive product must be analysed for the amount of mass required to implement this function. By that the following four cases can occur, as shown in Figure 1. As shown in the figure, important functions that are realised by big mass can be optimised, but if the function is not especially important to the user, the function can be omitted or if the designer wishes to realise it, the function must be realised in a mass-optimised way. If important functions are realised by small mass, the need for action is not particularly significant. Furthermore, unimportant functions which are realised by small mass can be held or omitted.

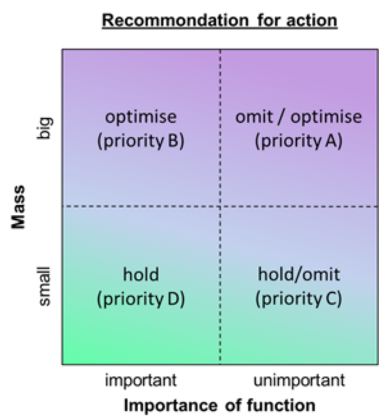


Figure 1. Recommondation for action within the importance of function vs. mass - portfolio

The conclusion from this consideration is that different cases with regard to the functions and the mass which is caused by the implementation of these functions must be considered. For this, purpose the requirement on the method is to respect the functions with its different importance and the mass they cause. The assessment criterion on this requirement is that the method must analyse and structure the functions of the product. The different importance of the functions must be considered by ranking each function.

4.2 Consideration of mass

The mass of a product, its parts and its assemblies must be respected by the method. The assessment criterion is that the method must support engineers in systematically reducing the mass of the product. The method should include a method to establish a ranking for the parts and assemblies with respect to the potential to reduce the mass of the whole product.

4.3 Consideration of mass distribution

The mass distribution must also be respected in addition to the mass. The exclusive reduction of randomly chosen parts of the product can implicate a change for the worse for the distribution of mass. To avoid this, the method must consider the mass distribution in the early phases of product design. To fulfil this, the method must take account for the position of the parts and their individual masses.

4.4 Consideration of mass moment of inertia

The distribution of mass, i.e. means each individual mass and its distance with respect to an axis of rotation determines a mass moment of inertia. Changing the arrangement of the parts of the product in order to optimise the distribution and the balance of mass can lead to a larger mass moment of inertia. A larger mass moment of inertia can increase energy consumption, such as the fuel consumption of a car or it can lengthen acceleration time, such as that of an industrial robot. To avoid this, the mass moment of inertia must also be considered in the design process. For the method, this means that it must also fulfil the assessment criterion which stipulates that the method must demonstrate the influence of changing the arrangement of the parts of the product on the mass moment of inertia. In addition, the method must support the designer in designing a product with a desired mass moment of inertia.

4.5 Consideration of mass dependent working principle

Mass cannot be reduced arbitrarily. A certain amount of mass is required to fulfil the functions. Looking at the first phases of the engineering design process according to Pahl [Pahl 2007], the first point in which mass is appointed is at the working principle. Before development of the working principle, only functions of the product are fixed. However, mass cannot be assigned to a function. Some working principles, like using the mass of a flywheel to store energy, are dependent on the mass of the flywheel. This means that the greater the mass of the flywheel, the more energy can be stored. This calls for extra consideration of mass-dependent working principles. The assessment criterion is to consider the mass dependencies of the relevant working principles.

4.6 Consideration of further product properties

Each product must fulfil several requirements. In this assessment only products for which mass is an important success factor are regarded. However, keeping all other product properties out of consideration is not target-oriented. To obtain a product with good properties regarding its mass, the method should help to generate a bandwidth of solutions for this. But in the selecting of one of these solutions all other requirements on the product must be taken into consideration. The assessment criterion on the method for this is that it must respect different requirements in addition to the mass properties in the selection of one of the solutions which were previously generated.

4.7 Support of the concept and embodiment design phases

The biggest influence on the products properties has the designer in the first phases of the product development process [Pahl 2007]. Therefore it is important to consider the design for function and mass as early as the first phases of the product development process, e.g. in the conceptional and embodiment design phases. The derived assessment criterion is that the method must address these conceptional and embodiment design phases.

4.8 Validity

Methods of the engineering design are theoretical constructions. To prove the applicability of the method, it must be validated. To fulfil the assessment criterion, it is adequate if the method is tested on some practical examples.

5. Assessment

In this section the assessment criteria of Section 4 are used to assess the methods discussed in Section 3. Therefore, for each method and each criterion a decision was made, whether the method fulfils the criterion or not. In Table 3, the results of the assessment are presented in the form of a yes or no decision as to whether or not the method fulfils the criterion.

Table 3. Results of the assessment of the methods of the state of the art

("X" stands for fulfilled criterion, "O" stands for unfulfilled criterion)

Number	Assessment criterion / **Method**	Value Analysis	Function Analysis	Target Costing	Quality Function Deployment	Design Rules	Value Analysis Weight	Value Analysis with Consideration of Weight	Number of complying methods
I	Consideration of functions	X	X	O	X	O	X	X	5
II	Consideration of mass	O	O	O	O	O	X	O	1
III	Consideration of mass distribution	O	O	O	O	O	O	O	0
IV	Consideration of mass moment of inertia	O	O	O	O	O	O	O	0
V	Consideration of mass-dependent working principle	O	O	O	O	O	O	O	0
VI	Consideration of further product properties	X	X	O	X	O	X	X	5
VII	Support of the conceptional and embodiment design phases	X	O	O	O	O	X	X	3
VIII	Validity	X	X	X	X	X	O	O	5
Number of fulfilled criteria		4	3	1	3	1	4	3	

6. Discussion of the assessment

The assessment results are firstly summarised from the point of view of the methods. The assessment shows, that the VA comprising the Function Analysis, the Quality Function Deployment and the Target Costing, is an interesting method to be transferred to the optimisation of function and mass. This is documented by the most fulfilled criteria in the assessment for the VA and the transferred VAW. The assessment result also shows that the VAW is the most promising method generated by this transfer. Besides that, the assessment demonstrates some methods which can be deployed for some special applications, that can be part of the method for design for function and weight. Furthermore the assessment shows, that the Design Rules cannot support the designer in considering functions, mass, mass distribution, mass moment of inertia, mass-dependent working principle, or all further product properties. This demonstrates that this method cannot support the designer in holistic designing for function and mass. These Design Rules can only be deployed as a methodical component for a method for design for function and mass.

From the point of view of the assessment criteria the assessment delivers the result that a number of criteria are not fulfilled at all. It also shows that the criterion on respecting the mass as an optimisation criterion is only fulfilled by the transferred VAW. This fact indicates that this method is the most appropriate basis on which to develop a method for holistic design for function and mass. However, as is the case with the other assessed methods, this method does not fulfil the assessment criterion considering the mass as a holistic optimisation criterion. This appears in the fact that no method fulfilled the criterion on the consideration of the distribution of mass, the mass moment of inertia and mass-dependent working principles. This indicates the demand for the further development of the method and documents the gap in the state of the art of lightweight design methodology.

The performed assessment has no claim to be exhaustive. It should only confirm the gap in the state of the art of the design methodology to design for lightweight. In addition, the assessment should confirm the advantages of the VA used as a basis to develop a method for designing for function and mass. An exhaustive assessment of the methods has to respect further requirements which are stated on design methods. Hence, a lot more assessment criteria have to be derived from these requirements. These assessment criteria have to be formulated in a very strict way to allow a definite decision whether the criterion is fulfilled or not.

However, for the following further development of a framework for a method for design for function and mass, the VA and the transferred VAW are chosen as the basis, as they fulfil the most assessment criteria and by that, the most requirements.

7. Developing a framework for a "Function Mass Analysis"

The VA emerged as a matched method for the further development of a method to support designers in the holistic design for function and mass. Thus in this section, a framework for such a method will be developed using the VA as a basis. This method will be called "Function Mass Analysis" (FMA) owning to its origin in the VA and its target of optimising the function and the mass of products.

By developing the requirements for the assessment in Section 5, it proved important to address the function, the mass, the distribution of mass as well as the mass moment of inertia by the method to holistically respect the mass as an optimisation criterion. This is so important because these criteria influence one another, as shown in Figure 2.

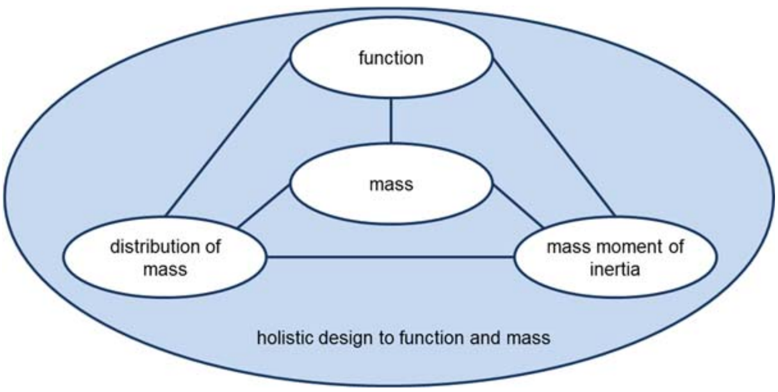


Figure 2. Holistic design for function and mass

The VA must be transferred from the application to mass as an optimisation to the application to cost to develop a framework to realise these targets according to the VAW. Not only the mass, but the distribution of mass and the mass moment of inertia must also be respected. Figure 3 shows the steps of the procedure of the VA on the left-hand side and the transferred and adapted procedure of the

VAW on the right-hand side. The optimisation criterion cost of the VA has to be replaced by the optimisation criterion mass. The course of the VAW already implemented this fact but it does not implement holistically the methodical and systematic consideration of mass with respect to mass distribution and mass moment of inertia. Therefore, Figure 3 shows in which steps the VA must respect the mass as an optimisation criterion and how both methods must be complemented by considering the mass distribution and the mass moment of inertia as an optimisation criterion.
Figure 3 also shows that the VAW was generated specifically from steps 3 to 7 of the VA. Before these steps were implemented in the VAW, Feyerabend [Feyerabend 1991]only scheduled a step to seek for the problem which should be solved by deploying the method. The steps 0 to 3 shall be retained and integrated in the FMA. In these steps the project, the team and the superior targets of the application of the method must be planned. Further steps 3 to 7 build the core of the method. These steps will be considered in detail later on. Steps 8 and 9 of the VA in which the worked out proposals which are presented and realised can also be adopted to the FMA. Thus steps 3 to 7 are the basic difference between the VA, the VAW and the Function Mass Analysis. This difference will be worked out in detail in the following blocks.

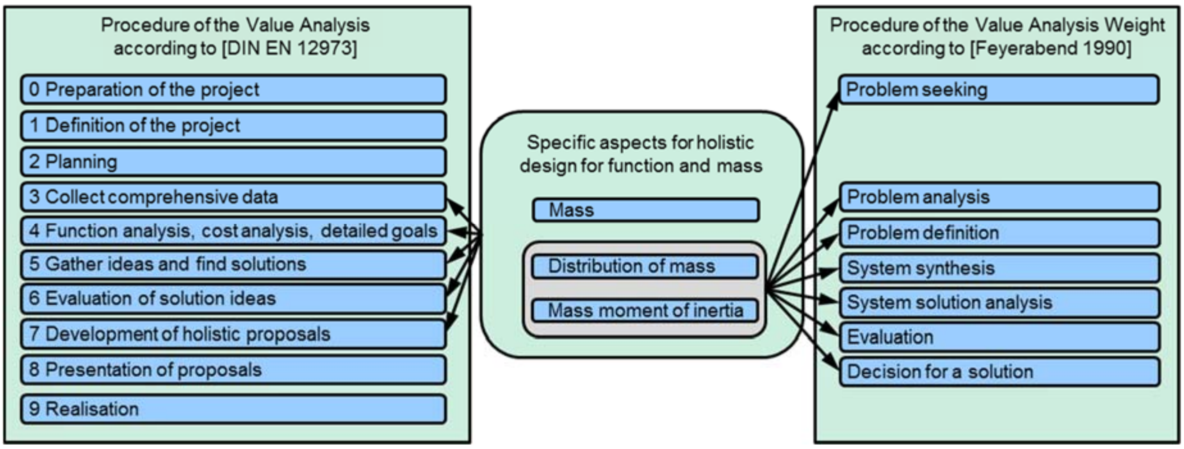
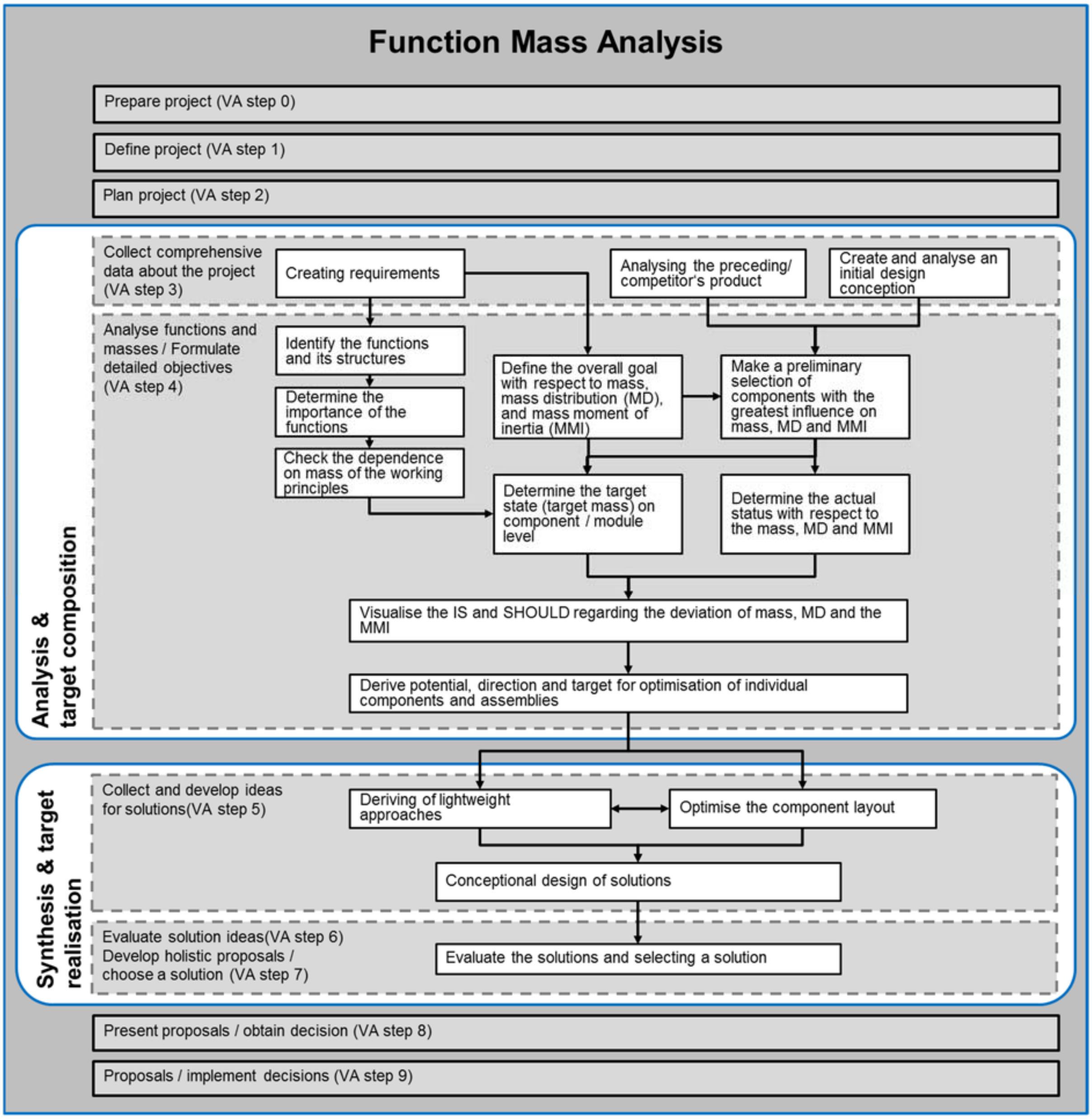


Figure 3. Comparison of the value analysis and the value analysis weight

Figure 4 shows the approach of the FMA. Steps 0 to 2 and 8 to 9 are assumed from the VA as already discussed. In step 3, first, the requirement must be deployed. The VA is set aside for the optimisation of an existing product, e.g. a competitive product or a preceding product. The FMA will also be based on these existing products, but one approach is to take first crude concepts as a basis for its application. In step 4, the demanded functions and their structure must be worked out, e.g. by using a "FAST-Diagram" [DIN EN 12973]. By using the method of the "Comparison of Pairs "[Ponn 2011] the importance of each function for the customer is approximated. Furthermore, for each function the working principle by which the function is to be implemented must be investigated to determine whether or not the working principle is dependent on the mass of its parts, as it is in the case of a fly wheel, for example. For developing mass targets for each function and part, firstly targets for the mass, the mass distribution and the mass moment of inertia must be developed. A benchmark may be useful in this. These superior targets must be broken down by multiplying the superior target with the percentual importance of the functions to obtain a target mass for each function. By percentually relating each part or assembly to the fulfilment of one or more functions be mass targets can be developed similar to the costs at the VA. By describing a demanded center of gravity of the product, the intended mass distribution can be defined. Targets for the mass moment of inertia must also be developed. To work out the current state, the preceding product or concept must be investigated. Thus the demanded and the current situation are described and the differences can be visualised. From the visualisation of these differences optimisation directions and targets can be developed. In the fifth step a bandwidth of solutions for reaching the optimisation targets must be developed. The sixth step implements an assessment of each solution to choose the best solution under respecting all assessment criteria which are imposed on this product. In the seventh step the solutions for each part or assembly of the product must be combined to obtain the best holistic solution for the product.

8. Discussion of the framework

In Section 7, a framework for a method for design for function and mass was presented. The innovation potential of this framework is that it respects holistically the mass, the mass distribution and the mass moment of inertia. The framework, is based on concepts of the VA as, for example, the idea to implement an interdisciplinary team to respect all domains of a company in the product development. Beside that, the method transferred the target implementation of the VA to set up targets for the mass. The framework is the basis for a further, detailed development. By this a holistic procedure will be developed to support the designer in designing for mass and function. After that, the procedure has to be properly validated in order to comply with scientific requirements. This validation is the prerequisite for the application of the method in practice. The superior objective of the application of the validated method is to make a contribution to a faster and more efficient development of lightweight products.



VA Value Analysis
MD mass distribution
MMI mass moment of inertia

Figure 4. Framework of the Function Mass Analysis

9. Conclusion

The research question of this article concerned which method could support the design for function and mass. By analysing and assessing the methods of the state of the art of the design methodology using pre-defined requirements, the VA was found which could be taken as the basis for further development of a method for design for function and mass. As this method does not fulfil all requirements, it was further developed to form a framework for a method for design for function and mass. This framework is called the "Function Mass Analysis" (FMA) and respects the state of the art, the function, the mass, the mass distribution, and the mass moment of inertia for holistically designing for function and mass. The FMA also supports the designer in setting up targets for the mass of the product and breaking them down to function and component level. Developing the framework will continue in subsequent studies to finally provide a holistic method for design for function and mass.

References

Ashby, M., "Material selection in mechanical design", Elsevier Butterworth-Heinemann, Amsterdam, 2005.

Broderick, R. W., "The application of value analysis to some Ariane 5 launcher sub-systems", Proceedings of the Institution of Mechanical Engineers, Part G, Journal of Aerospace Engineering, Vol. 206, pp 63-70, 1992.

Clarkson, J., Eckert, C., "Design process improvement: A review of current practice", Springer-Verlag, London, UK, 2005.

DIN EN 12973, "Value Management", Deutsches Institut für Normung e.V., Beuth-Verlag Berlin, 2002.

Feyerabend, F., "Wertanalyse Gewicht" [engl. "Value Analysis Weight"], VDI Fortschrittberichte, VDI-Verlag, Düsseldorf, 1991.

Henning, F., Moeller, E., "Handbuch Leichtbau" [engl. "Handbook of lightweight design"], Carl Hanser Verlag, München, 2011.

Kermode, G. R., Sivaloganathan, S., Shahin, T. M. M., "Value analysis – the technique: state of the art and future directions" Proceedings of the Institution of Mechanical Engineers: Part B, Journal of Engineering Manufacture, Vol. 214, pp 41-47, 1998.

Pahl, G., Beitz, W., Feldhusen, J., Grote, K.-H., "Engineering Design: a systematic approach", third edition, Springer-Verlag, London, UK, 2007.

Ponn, J., Lindemann, U., "Konzeptentwicklung und Gestaltung technischer Produkte" [engl. "Concept development and design of technical products"], 2. Auflage, Springer-Verlag, Heidelberg, 2011.

VDI 2800, "Wertanalyse" [engl. "Value Analysis"], VDI-Richtlinie, Verband Deutscher Ingenieure e.V., Beuth-Verlag, Berlin, 2010.

Dipl.-Ing. Benedikt Posner
Academic assistant
University of Stuttgart, Institute of Engineering Design and Industrial Design (IKTD)
Pfaffenwaldring 9, 70569 Stuttgart, Germany
Telephone: +49 (0)711 685 66039
Telefax: +49 (0)711 685 66219
Email: benedikt.posner@iktd.uni-stuttgart.de
URL: http://www.iktd.uni-stuttgart.de