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DEVELOPMENT OF WORKING STRUCTURES WITH A FOCUS ON LIGHTWEIGHT DESIGN

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ABSTRACT

This paper presents a method for developing a variety of solutions for working principles and working structures with a focus on their lightweight design potential. Furthermore, an existing procedure and criteria are transferred, implemented and complemented in order to reduce the developed variety of solutions to focus on the selection of solutions with greater lightweight design potential. The procedure is demonstrated using the development of a vacuum shredder as an example, to assist understanding the method's application.

Index Terms - Lightweight design, working principle, working structure

1. INTRODUCTION

In the early phases of the product development process, the designers have great influence on the properties of the product [7]. One of these phases is the conceptual phase, in which the function structure and the working structure are developed and the principal solutions are assessed and selected [9]. In the lightweight design literature, different lightweight design strategies are proposed, such as material, conditional, shape or manufacturing lightweight design, for example [2]. However, there is no strategy and no method which supports the exploitation of the lightweight design potential of the whole conceptual stage. The only exception is a method for the development of function structures with regard to their lightweight design potential [12]. However, the development of the working structure also has considerable influence on the mass of the product, because different working structures need different mass for their realisation. Thus, finding the working structures, choosing and combining the working principles and selecting the working structures all greatly influence the mass that is required in order to fulfil the functions of the product. For example, a magnetic levitation train has about half of the mass per seat compared to a train with the working principle of the wheel-rail drive [10]. The aim of the contribution is to support the development of working structures with a focus on exploiting the lightweight design potential.

2. PROBLEMSTATEMENT AND GOALS

Actually, there is no method that supports the development of working structures with regard to exploiting lightweight design potential. Thus, the research question of this contribution is the following: "How can designers be supported in exploiting the lightweight design potential of working structures?" In order to answer this question the information content and the possible variations of the working principles and working structures are analysed. Furthermore, support for the systematic variation of working principles and structures is developed. By developing a variety of solutions, those with the highest lightweight design potential can be selected to be followed up. Furthermore, the number of solutions is reduced with focus on their lightweight design potential, in order to obtain a manageable number of working structures. Thus, the probability of finding working principles and developing working structures with a higher lightweight design potential is increased.

3. METHOD

This contribution is based on Design Research Methodology (DRM) [3]. The first three of the four steps of DRM are addressed. Firstly, in the Research Clarification the tasks are clarified and the research question is developed (Sections 1 and 2). In the second step, called the Descriptive Study 1, the state of the art is presented (Section 4). The third step, the Prescriptive Study, in which the main results of the contribution are developed, is presented in Sections 5, 6, 7 and 8. In the last step of the DRM, Descriptive Study 2, an extensive evaluation of the results has to be carried out in order to comply with scientific and business practice requirements. This step is not included in this contribution and must be performed afterwards. In Sections 6, 7 and 8, an example is provided to aid the understanding of the developed support. The example is just a scientific application of the method, not an industrial project. Thus, it is only a support evaluation according to Blessing and Chakrabarti [3]. It assists with understanding and demonstrates the applicability of the method. The extensive evaluation of the contents of this contribution must be carried out subsequently.

4. STATE OF THE ART

Firstly, the state of the art of the working principles and working structures and their development are presented. Afterwards, the Contact & Channel - Model, which is a model and method based on the description of working principles according to Roth [13] and which supports the systematic variation of such structures, is described. At the end of this section, the state of the lightweight design and its influence on the working structures are depicted.

4.1 Working principles and working structures

Pahl et al. [9] propose that the development of working principles and working structures is one of the major steps in the conceptual design phase. However, also in other development processes, as according to VDI 2221 [14], Roth [13], Ponn and Lindemann [10], the development of working structures is focused. The further investigations are mainly based on the product development process according to Pahl et al. [9], although there are also other product development processes and descriptions of working structures - or organ structures, as they are referred to by Hubka [5]. Furthermore, the developed results can also be implemented in other processes.

In the conceptual design phase according to Pahl et al. [9], first of all the essential problems are identified. On this basis, the function structures are established. Next, working principles are sought in order to fulfil the sub-functions. For assistance in this task, Pahl et al. [9] propose the Morphological Matrix in which sub-functions are represented in lines and working principles are listed in columns. Accordingly, the working principles are combined to form working structures. Afterwards, suitable working structures are selected, which are detailed and firmed up into principal solution variants in the next step. This detailing is necessary in order to evaluate the variants on the basis of technical and economic criteria in the last step of the conceptual design phase.

The working principle includes the physical effect, and the material and geometric characteristics. It is possible that more than one physical effect is needed in order to fulfil one function. The material characteristics comprise a general idea of the type of material. This

means the main material properties have to be determined, for example, whether the material is solid, liquid or gaseous, rigid or flexible, elastic or plastic [9].
The geometric characteristics are defined by the working location, the working geometry and the working motions. The working geometry is described by the arrangement of working surfaces or working spaces, for example, which can be varied with respect to and determined by their type, shape, position, size and number. The working motions are determined by the characteristics type, nature, direction, magnitude and number. Furthermore, by variation regarding these characteristics the working principle can be varied. The combination of all working principles required in order to fulfil all functions of the product is called the working structure. Thus, the working structure describes the interaction of the working principles. The working structure can be visualised by means of a circuit diagram, a flow chart or, in the case of mechanical artefacts, an abstract engineering drawing [9].

4.2 Contact & Channel - Model

The Contact & Channel - Model (C&C-M) according to Albers et al. [1] describes technical systems by using Working Surface Pairs (WSP) and Channel and Support Structures (CSS), as shown in Figure 1. The WSP consist of two Working Surfaces (WS), which are in contact. The CSS build the connection between the WSP. Furthermore, the CSS channel energy between the WSP in order to fulfil the function of the technical system. Additional characteristics of the WSP and CSS are described by symbols, such as for the direction of acting forces, for example [1]. The WSP and CSS that do not contribute to the function of the technical system form the Remaining Structure (RS). The method consists of an analysis phase, in which the technical system is modelled and the problem is analysed, and a synthesis phase, in which solutions are developed for the problem under consideration. The synthesis phase comprises four Meta-Rules (MR), which are “Add WSP and CSS” (MR1), “Remove WSP and CSS” (MR2), “Change properties of WSP” (MR3) and “Change properties of CSS (MR4) [1]. Albers and Burkardt propose that the analysis phase of the C&C-M is useful for lightweight design, because it supports designers in gaining an in-depth understanding of the technical system, which is very important in lightweight design [2]. Also, Ottnad defines the reduction of the RS as an aim of lightweight design [8]. Posner et al. [11] combine the C&C-M with the lightweight design principles and strategies. Thus, they have developed the Contact & Channel - Model - for Design for Lightweight (C&C-M-DfL), which is a method for supporting designers in developing lightweight design solutions. This method uses the C&C-M to form the connection between the specific product and the lightweight design principles and strategies. However, this approach is not used to exploit the lightweight design potential of working principles or structures.

4.3 Design for Lightweight

In literature, there are several lightweight design strategies, such as material, manufacturing, shape, system, conceptual or conditional lightweight design, for example [2]. Furthermore, there are lightweight design principles that assist designers in developing the product shape with a focus on lightweight design, such as a preference for hollow cross-sections if there is a bending load, for example [6]. In addition, there is a focus on function integration in order to reduce the mass of the product [4]. Ponn and Lindemann [10] recommend a focus on lightweight design at an early stage, i.e. during the search for working principles and the development of working structures. However, there is no methodical support for the systematic development of working structures in order to exploit the lightweight design potential.

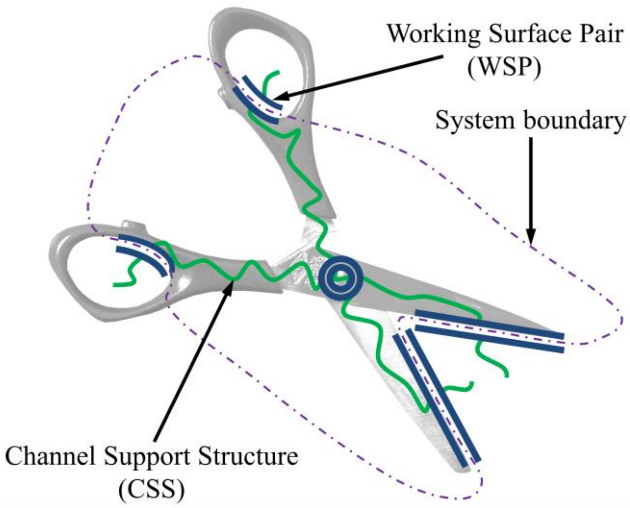


Figure 1: Elements of the Contact & Channel – Model [11]

5. REPRESENTATION AND VARIATION OF WORKING STRUCTURES

The intention of this section is to adapt the Contact & Channel - Model in order to describe all information content of the working principles and working structures. On this basis, the systematic variation of the synthesis phase of the Contact & Channel - Model is adapted in order to vary the working principles. The aim is to develop a variety of solutions to enable the selection of a solution with a higher lightweight design potential. Thus, the probability of finding solutions with a higher lightweight design potential is increased.

Table 1 shows the elements of working structures and working principles (columns 1 and 2), as discussed in Section 3.1. With the visualisation elements of the C&C-M, the WSP and the CSS, all geometric characteristics of a working principle can be described. In addition, the material characteristics of the working principles can be described using the symbols of the C&C-M, for visualising the state of aggregation of the material, for example. The physical effect is described by the combination of all elements of the working principle, the geometric and material characteristics according to [9]. Moreover, complete working structures, which are formed by the combination of working principles and their arrangement, can be described by means of the C&C-M.

Thus, only the working motions are not described by the WSP and CSS of the C&C-M. Of course, due to the WSP and their shape and number, only a few possible motions remain for the elements of the working principles. Furthermore, by using the Sequence Product Model, dynamic systems can be described in a sequence of states [1]. However, the introduction of a further element and implementation in the C&C-M allow a definite description of working motions and a systematic variation of working principles and their elements.

According to Pahl et al. [9], the working motion is defined by the type, nature, direction, magnitude and number. These characteristics will be qualitatively described in the following with the aid of an arrow. Table 2 shows the characteristics of working motions, their sub-characteristics and a possible visualisation of these.

This means that the working principles can be systematically and comprehensively varied by removing, adding or changing characteristics of the WSP, CSS and WM. Hence, these steps enable the working structures to be comprehensively varied under consideration of all characteristics, as demonstrated in column 5 of Table 1. This procedure, referred to here as the Contact, Channel & Motions – Model (CC&M-M), supports designers in developing a variety of solutions.

Table 1: Variation of working principles and working structures

1	2	3	4	5		
Elements of working structures (WS)	**Characteristics of working principles (WP)**	**Visualisation elements of WP**	**Characteristics of visualisation elements of WP**	**Possibilities of variation**		
				Add	**Remove**	**Change**
Arrangement of working principles						X
Working principles	Physical effect	All elements		X	X	X
	Geometric characteristics	Working Surface Pairs (WSP)	Type			X
			Shape			X
			Position			X
			Size			X
			Number	X	X	
		Channel and Support Structures (CSS)	Type			X
			Shape			X
			Position			X
			Size			X
			Number	X	X	
		Working motions (WM)	Type			X
			Nature			X
			Direction			X
			Magnitude			X
			Number	X	X	
	Material characteristics	Pictograms that describe characteristics of WSP/CSS	Rigid, flexible; elastic, plastic; stiff, hard, tough…	X	X	X

Table 2: Description of working motions (WM)

1	2	3	4
	Characteristics of working motions	**Sub-characteristics of working motions**	
Working motions (WM)	Type	Translation	Rotation
	Nature	Regular	Irregular
	Direction	Clockwise	Anti-clockwise
	Magnitude	Low velocity	High velocity
	Number	One	Two

6. APPROACH FOR THE DEVELOPMENT AND VARIATION OF WORKING STRUCTURES

On the left-hand side, Figure 2 shows the procedure for developing working structures according to [14]. On the right-hand side, the adapted procedure for the systematic development of working structures with a focus on increased lightweight design potential is presented. These steps are detailed and discussed in the following section. Using the development of a working structure of a vacuum shredder as an example, the contribution aims to aid better understanding of the procedure.

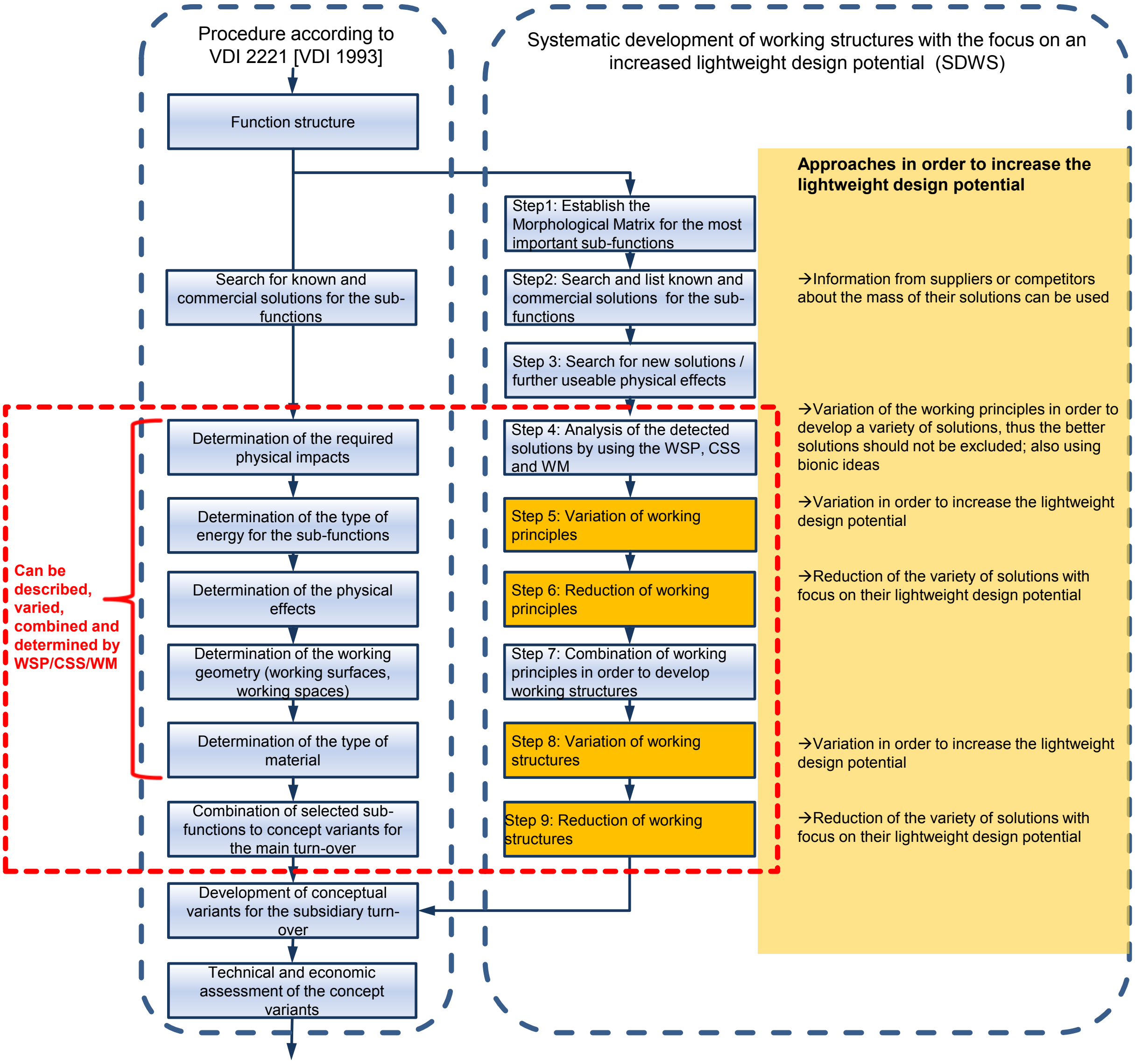


Figure 2: Procedure for the development of working structures with the focus on an increased lightweight design potential

The further developed procedure is based on the function structure. In the first step, the Morphological Matrix for the most important sub-functions has to be established according to [9]. In the second step, the designers search for existing solutions and solutions, which can be bought from suppliers. In the third step, new solutions are found. Intuitive methods such as Brainstorming, Method 635 or the Gallery Method, for example, can assist with finding and discovering solutions. The solutions can be visualised by a simple sketch [9]. The first three steps specify the procedure according to VDI 2221 [14]. In the next steps according to VDI 2221, all aspects of the working principles, for example the physical effects, working geometry or the type of material, are determined. As shown in Section 4, these aspects can be described by the elements WSP, CSS and WM. The advantages of these elements are that they support a further analysis of the detected solutions, and they can be varied systematically. Thus, step four in the new procedure proposes the analysis of the detected

solutions, enabling them to be better understood and forming the basis for the variation of the solutions in the fifth step. Due to limited resources, it is often not possible to follow up all solutions and possible combinations of working principles. Hence, the sixth step recommends reducing the working principles with regard to the lightweight design potential of the solutions. Therefore, the variety of solutions can be used in order to select the principles that offer an increased lightweight design potential. In step seven, the working principles are combined and thus working structures are developed. Again, like the working principles, the working structures can be varied in the eighth step and based on that the variety of developed working structures can be reduced on this basis in order to select those with the highest lightweight design potential. Steps 5, 6, 7 and 8 are detailed in the following sub-sections.
For the example of the vacuum shredder, the results of the first steps of the procedure are shown in Table 4. On the left-hand side, the most important sub-functions of the vacuum shredder are listed, as proposed in the first step of the procedure. Afterwards, initial solutions for the sub-functions of steps 2 and 3 are registered. In addition, the detected solutions are analysed with the elements WSP, CSS and WM, as also shown in Table 4. Steps 5 to 9 and their application on the example are discussed in the following sections.

7. VARIATION OF WORKING PRINCIPLES AND WORKING STRUCTURES

This section discusses steps 5 and 8 of the procedure for the development of working structures with the focus on an increased lightweight design potential using the example of a vacuum shredder. Figure 3 shows the sub-steps of the variation (steps of variation v.1 – v.7). The variation is based on the three meta-rules of the C&C-M, which suggest removing, adding or changing characteristics of the elements. In addition to the WSP and CSS, it also proposes varying the working motions (WM) and the systems boundary. These steps support the development of a variety of solutions in order to be able to choose a suitable solution with a focus on their lightweight design potential, for example. Thus, the probability of finding a suitable solution with a high lightweight design potential is increased.

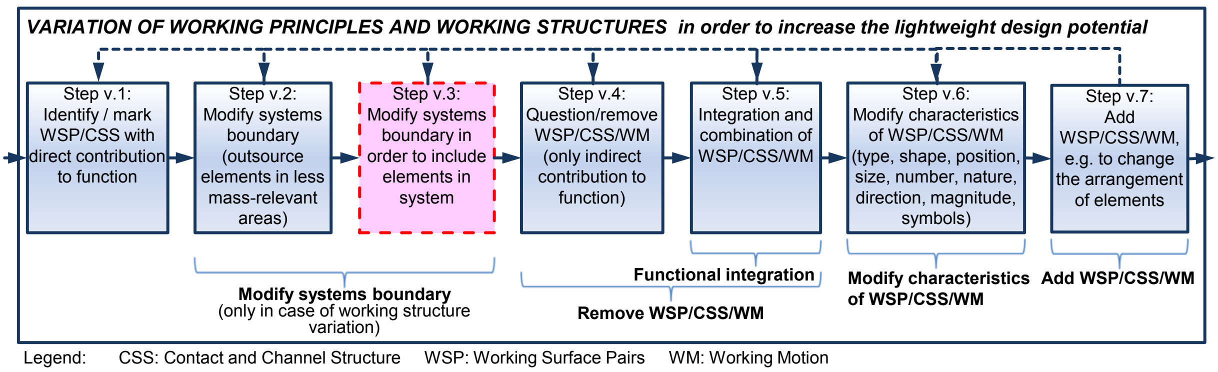
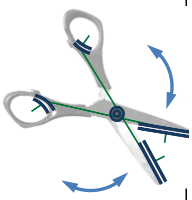
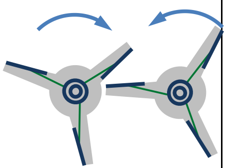
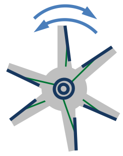
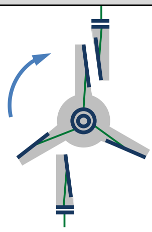
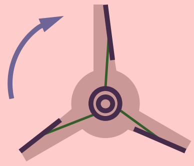


Figure 3: Variation of working principles and working structures (sub-steps of steps 5 and 8)

In order to show how the procedure supports the finding of solutions, it is discussed in relation to a working principle that fulfils one of the most important sub-functions of the vacuum shredder, the sub-function “chop solids”. Column 2 of Table 3 shows an initial first solution (working principle) that is cutting like a pair of scissors and was found by brainstorming.

Table 3: Variation of an initial working principle

Sub-function	Solution 1	Solution 2	Solution 3	Solution 4	Solution 5
Chop solids	 Shears	 2 rotating knives	 2 coaxial rotating knives	 1 rotating, 1 fixed knife	**Prioritise**  1 rotating knife
Steps of variation	-	v.4 (remove direction of WM); v.6 (modify WM)	v.5 (aggregation of WSP); v.7 (change WSP arrangement)	v.4 (remove WM); v.7 (change arrangement)	v.4 (remove WSP and CSS of fixed knives)

As Figure 3 shows, the sequence of the variation is very flexible and iterative. Thus, designers can progress from the first to the second solution in Table 3 by using the fourth or sixth step of variation. Additionally, in order to progress from Solution 3 to 4, the idea is that the second knife must not move relative to the other knife. The idea for this step can be supported by the variation steps four and seven. The only important fact in using this variation is that the designers achieve several possible solutions, so that they can select the most suitable and not be compelled to accept the first solution that they devise. The developed solutions have to be listed in the Morphological Matrix, in order that suitable ones can be selected for combining to form a working structure variant.

The variation is shown as a working principle, but as the working structure is just a combination of working principles, the procedure can similarly be applied to the variation of working structures. Of course, this has to be evaluated later on.

8. REDUCTION OF WORKING PRINCIPLES AND WORKING STRUCTURES

After developing a variety of solutions, there has to be a selection, firstly, of which solutions to use in order to combine the working principles to form a working structure (Step 6 in Figure 2) and, secondly, which working structures to follow up (Step 9 in Figure 2). Ponn et al. [10] propose a method with six steps of reduction as shown in the upper half of Figure 4. The steps (steps of reduction r.1 – r.6) recommend the prioritisation of single working principles in the Morphological Matrix. In order to prioritise the solutions according to their lightweight design potential, criteria have to be found to enable this prioritisation. Criteria already exist for the prioritisation of function structures according to their lightweight design potential [12]. These are transferred, implemented and complemented, as shown in Figure 4. Also, the method of Binary Comparison [9] can be used to support the comparison of two solutions with a focus on one of the criteria.

These criteria are used for the example of the vacuum shredder, which is discussed below for the sub-function “chop solids”. Due to the preference for solutions with fewer WSP/CSS/WM, the fifth solution of Table 3 is chosen. In order to give preference to solutions in which more than one sub-function is fulfilled by one working principle, the solution “rotating knife” (sub-function “chop solids”) is combined with the solution “turbine wheel” (sub-function “create vacuum”) to form one working principle in order to fulfil both sub-functions. The description using the WSP/CSS/WM looks very similar and their working motions are already the same. Thus, for designers it is very obvious that these two can be combined. This means that in addition to the criteria of the reduction procedure, the visualisation supports this function integration. The reduction procedure and the criteria can be applied to individual or all sub-functions in order to prioritise working principles so that they can be combined. Furthermore, the developed criteria can also be used to prioritise working structures. Thus, the variety of working structures can be reduced to obtain a number of working structures, which can be investigated further with due consideration of designers' limited resources.

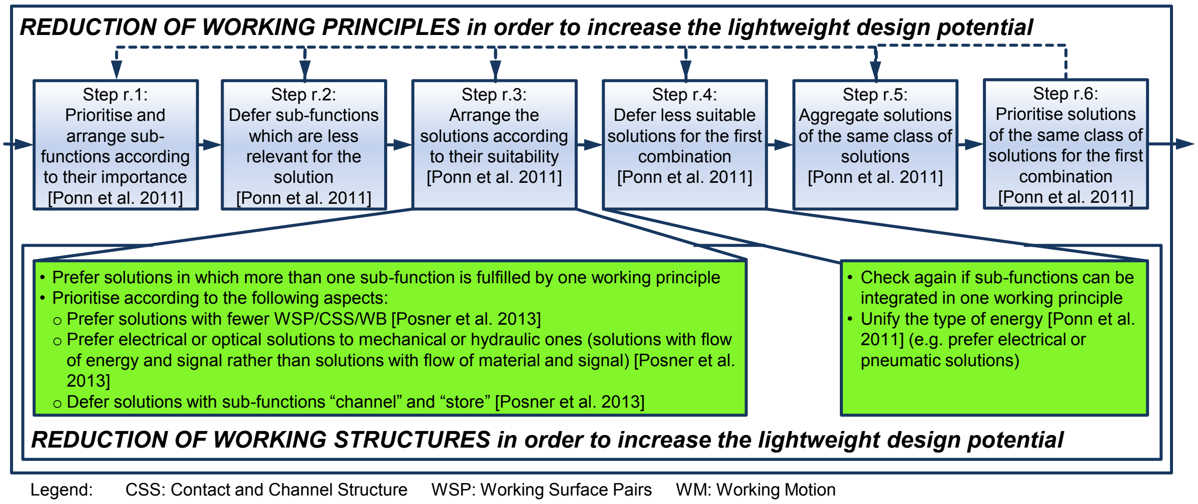
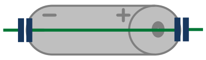
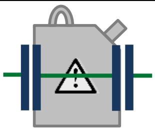
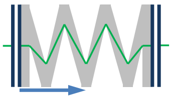
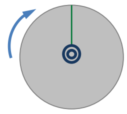
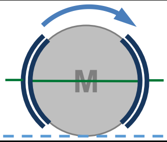
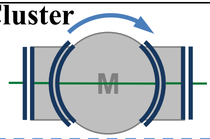
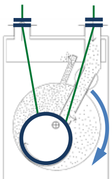
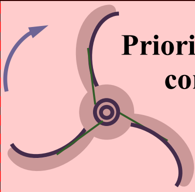
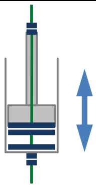
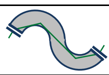
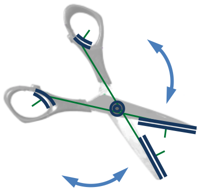
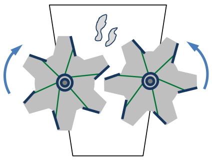
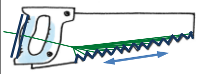
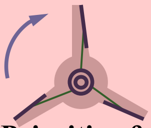
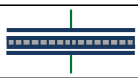
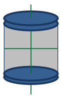


Figure 4: Steps and criteria for the reduction of working principles and working structure variants (compare to [10])

9. DISCUSSION

Basically, there are two possibilities for developing a working structure with considerable lightweight design potential. Firstly, designers could develop a working structure with great lightweight design potential based on their experience. But this is hard to do, even supposing a great experience of the designers. And the designers have to come up with the idea of considering the lightweight design potential while developing the working structure. Secondly, designers could develop a variety of solutions and then try to choose suitable solutions with a focus on their lightweight design potential, for example. This contribution presents a systematic procedure for developing a variety of working principle and working structure solutions. It also sets out a procedure for reducing this variety to a number of solutions that can be followed up. The criteria for the reduction of solutions are based on existing criteria for the reduction of function structures according to their lightweight design potential [12]. Of course, these criteria do not allow assessing the lightest solution. The mass of solutions is not defined until the detailed shape and material of all parts of the solutions have been defined. The working structure that results in the lightest product cannot be identified. However, the procedure presented here gives a hint of the solutions' potential for developing a solution that can be lighter than another. Furthermore, the procedure raises awareness of the fact that decisions taken by designers while developing working structures have considerable influence on the mass that is required to create the product. Additionally, lightweight design approaches, as the integration of functions, can be supported by the procedure even in this early development phase. The procedure is highly iterative and not each step has to be strictly executed in sequence. Rather, the method must be used in a suitable manner to encourage finding new ideas and solutions. The procedure has to be applied to industrial development problems and evaluated in order to comply with scientific and industrial requirements.

Table 4: Morphological Matrix of a vacuum shredder

Sub-solutions / **Sub-functions**	**Sub-solution 1**	**Sub-solution 2**	**Sub-solution 3**	**Sub-solution 4**
Store energy	WP 1: Battery  **Cluster**	WP 2: Fuel 	WP 3: Spring 	WP 4: Flywheel 
Change energy	WP 5: Electrical motor 	WP 6: Combustion engine **Cluster** 		
Create vacuum	WP 7: Vacuum pump 	WP 8: Turbine wheel **Prioritise & combine** 	WP 9: Cylinder 	
Absorb solids and air	WP 10: Flexible pipe 	WP 11: Rigid pipe 		
Chop solids	WP 12: Cutting 	WP 13: Ground 	WP 14: Sawing 	WP 15: Rotating knife  **Prioritise & combine**
Separate solids from air	WP 16: Screen 			
Store solids	WP 17: Flexible container  **Cluster**	WP 18: Rigid container 		

10. CONCLUSION AND OUTLOOK

This paper presents a method for developing a variety of solutions for working principles and working structures with a focus on their lightweight design potential. Furthermore, an existing procedure and criteria are transferred, implemented and complemented in order to reduce the developed variety of solutions to focus on the selection of solutions with greater lightweight design potential. The procedure is demonstrated using the development of a vacuum shredder as an example, to assist with understanding the method's application. The method requires further evaluation and development in order to comply with scientific requirements. This constitutes an initial approach for applying Design for X to the development of working structures using the example of Design for Lightweight. Further Design for X criteria can be investigated, so that they can be considered for working structure development.

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REFERENCES

[1] Albers, A., Burkardt, N., and Ohmer, M., "Approaches for the synthesis of technical systems within the Contact & Channel Model", International Conference on Engineering Design, Melbourne, pp. 1-11, 2005.
[2] Albers, A., and Burkardt, N., "Systemleichtbau - ganzheitliche Gewichtsreduzierung", Handbuch-Leichtbau, Henning, F., Moeller, E., Carl Hanser, München, 2011.
[3] Blessing, L., Chakrabarti, A., DRM, a Design Research Methodology, Springer, Dordrecht, 2009.
[4] Gumpinger, T., Jonas, H., and Krause, D., "New approach for lightweight design: From differential design to integration of function", Proceedings of the International Conference on Engineering Design 2009, Volume 2, Design Theory and Research Methodology, Norell Bergendahl, M. et al. (ed.), Design Society Glasgow, pp. 201-210, 2009.
[5] Hubka, V., Theorie Technischer Systeme, Springer, Berlin, 1984.
[6] Klein, B., Leichtbau-Konstruktion, Vieweg+Teubner, Wiesbaden, 2013.
[7] Krause, F.-L., Franke, H.-J., and Gausemeier, J., Innovationspotenziale in der Produktentwicklung, Carl Hanser, München, 2007.
[8] Ottnad, J., Topologieoptimierung von Bauteilen in dynamischen und geregelten Systemen, Dissertation, Technische Universität Karlsruhe, 2009.
[9] Pahl, G., Beitz, W., Feldhusen, J., and Grote, K.-H., Engineering Design – A systematic Approach, Springer, London, 2007.
[10] Ponn, J., and Lindemann, U., Konzeptentwicklung und Gestaltung technischer Produkte, Springer, Heidelberg, 2011.
[11] Posner, B., Binz, H., and Roth, D., "Using the Contact & Channel - Model for the methodical development of lightweight solutions", Norddesign 2012 Proceedings, Kyvsgaard Hansen, P., Rasmussen, J., Jörgensen, K., Tollestrup, C., Aalborg, pp. 512-519, 2012.
[12] Posner, B., Binz, H., and Roth, D., "Grundlagen zur Berücksichtigung von Design for X bei Funktionsstrukturen am Beispiel des Design for Lightweight", Stuttgarter Symposium für Produktentwicklung 2013, Spath, D., Bertsche, B., Binz, H., Stuttgart, 2013.
[13] Roth, K., Konstruieren mit Konstruktionskatalogen, Band 1, Springer, Berlin, 1994.
[14] Verein Deutscher Ingenieure, VDI 2221: Systematic approach to the development and design of technical systems and products, Beuth, Berlin, 1993.

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