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Supporting the development of lightweight design structures with simple methods in early stages

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Abstract
Mattheck [1] presents very simple methods for developing lightweight design structures based on bionic ideas. These methods can already be used to develop structures on a very low level of detail. This allows developing structures with a view on lightweight design already in the conceptual phase. In order to do this there is no need for computer aided methods. However, the methods of Mattheck [1] focus on static problems and do not support finding solutions for problems with a limited installation space. Thus, within this contribution the methods were combined with the Contact and Channel Model [2] which is a method for supporting designers in analysing products, their structures and functions and synthesising solutions for design problems. In addition, the methods of Mattheck [1] are further developed in order to support developing lightweight structures respecting also the problem of moved structures with different loadings over time and respecting the installation space limitation.

Keywords: Design method, lightweight design structure development, bionic lightweight design

1 Introduction

In lightweight design, computer aided methods are used in order to optimise the shape and the topology of parts of a product. These methods cause great efforts and costs and are not applicable in early development stages. In contrast, Mattheck [1] proposes some simple rules in order to support the development of lightweight design structures. He derives his approach, called the Thinking Tools after Nature, from studies of the structure and shape of trees. These Thinking Tools support developing structures adapted to the affecting forces. The method was evaluated by the comparison of the structures developed by means of the method and the structures developed by a topology optimisation method. Both methods led to very similar results, but the efforts of using the Thinking Tools are much lower.

2 Problem statement and goals

Nevertheless, the method of the Thinking Tools after Nature [1] is limited to the consideration of static problems. This means, only static and simplified bearings and loadings are considered. However, most structures in mechanical engineering include moving parts. The procedure must be further developed in order to support developing structures with such moved elements. Furthermore, the procedure does not support the analysis of existing structures or complex bearings. Especially in lightweight design, existing elements have to be analysed if they are necessary or if they can be left out. Moreover, only single parts and no assemblies or whole products are considered by the method. The Thinking Tools propose no visualisation elements which can support a fast description of structures for the analysis of existing and the synthesis of new structures. Easy and fast usable visualisation elements could support the development and discussion of structure solution variants. By using the Thinking Tools, the method often results in a very complex and large structure. Because in mechanical engineering these structures have to fit into the product, there is often a limitation of installation space. Currently, it is a sharp contrast between the large structures resulting of the Thinking Tools and the space limitation. Thus, the Thinking Tools with their great support in finding lightweight structure solutions are not yet easily and systematically applicable on mechanical engineering problems. Therefore, the research question to be answered in this contribution is: How should the approaches of the Thinking Tools after Nature [1] for the application on the development of lightweight design structures be utilised in mechanical engineering?

The Contact & Channel - Model as proposed by Albers et al. [2] supports the systematic analysis of existing structures and also of complex bearings. In addition, the method supports the analysis of dynamic systems by describing them in sequences. This allows the description of a dynamic problem by using several static views. The Contact & Channel - Model is already further developed and used in order to find lightweight solutions [3], but it cannot support the development of lightweight design structures as the Thinking Tools after Nature can. Hence, the aim of the contribution is to combine the approaches of the Thinking Tools [1] and the Contact & Channel - Model [2]. Thus, a method will be developed for supporting the development of lightweight structures with very low efforts and very simple methods. Therefore, this paper shows the further development of the methods of Mattheck [1] and contributes to their applicability and distribution.

3 Methods

The research is based on the Design Research Methodology (DRM) according to Blessing and Chakrabarti [4]. The DRM proposes four steps of research. The research presented in this contribution addresses three of these four steps. In the Research Clarification, which is step one of the DRM, the research question is clarified (see Sections 1 and 2). The results of step two, the Descriptive Study 1, are discussed in Section 4. The next step is the Prescriptive Study, in which the results and the developed support are presented, as shown in Section 5. The last step of the DRM is the Descriptive Study 2. In this step the evaluation of the contribution has to be realised. This is not content of this contribution and has to follow, as mentioned in the outlook. Only some exemplary calculations regarding the evaluation of the further development of the approaches according to Mattheck [1] are presented in Section 5.

4 State of the art

In this section the state of the art of lightweight design is summarised and the Thinking Tools after Nature as well as the Contact & Channel - Model are presented.

4.1 Lightweight design

The literature of lightweight design proposes several lightweight design strategies, as for example conditional, material, manufacturing, conceptual, bionic and shape lightweight design [5]. In order to put shape lightweight design into practice, there exist individual lightweight design principles which support designers in developing a lightweight design shape. For example, if there is a bending load, hollow cross-sections have to be preferred [6].

In addition, there is a lot of calculation in order to develop structures and shapes with a high lightweight design potential [6]. Because this calculation is very complex and time consuming many software products and computer support has been developed for this purpose. It also exists software which proposes a mass distribution within the structure adapted to the applied loadings. But, it is a lot of knowledge, time and money are needed in order to analyse and synthesise such structures even with software support [1]. Besides, there are some bionic lightweight design approaches which search for similar solutions for their technical problems in nature, as for example Mattheck proposes [1].

4.2 Thinking Tools after Nature according to Mattheck [1]

Mattheck [1] proposes simple methods in order to develop lightweight design structures. The two most comprehensive are discussed in the following.

4.2.1 Lightweight Structural Design based on Ropes [1]

Mattheck [1] proposes a simple formula in order to develop lightweight structural design. The main idea is to think in terms of ropes when developing a lightweight design structure. The first step (Step A) of the procedure is to define the load and support conditions, as Figure 1 shows. Next step (Step B) is to develop a structure which bears the load and applies the loading into the bearings by using ropes and compression struts. In the third step (Step C) the compression bars must be pre-bend in order to make them susceptible to buckling, i.e. produce compression arcs. In the last step (Step D) the compression bars which have a preferred direction for buckling, must be blocked by using a tension rope.

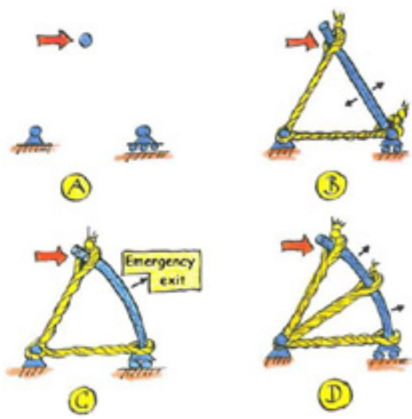


Figure 1 Formula for developing lightweight structural design based on ropes [1]

4.2.2 The Force Cone Approach

By the Force Cone Approach (FCA) Mattheck [1] proposes a method which is based on the assumption, that a single force pushes a 90 degrees compression cone in front of it and pulls a 90 degrees tension cone behind it. The greatest part of the power is transferred within these cones and respecting this, leads to lightweight design structures. In the first step of the FCA (Step A) the supports and forces are analysed, as shown in Figure 2. In Step B the force cones are attached to the loads. In the third step (Step C) the Force Cones are attached to the support forces. The points, which are called primary points, in which tension and compression intersect at right angles, are marked in Step D. Next, the supports, loads and primary points are connected in order to develop a lightweight design structure as shown in Steps E and F.

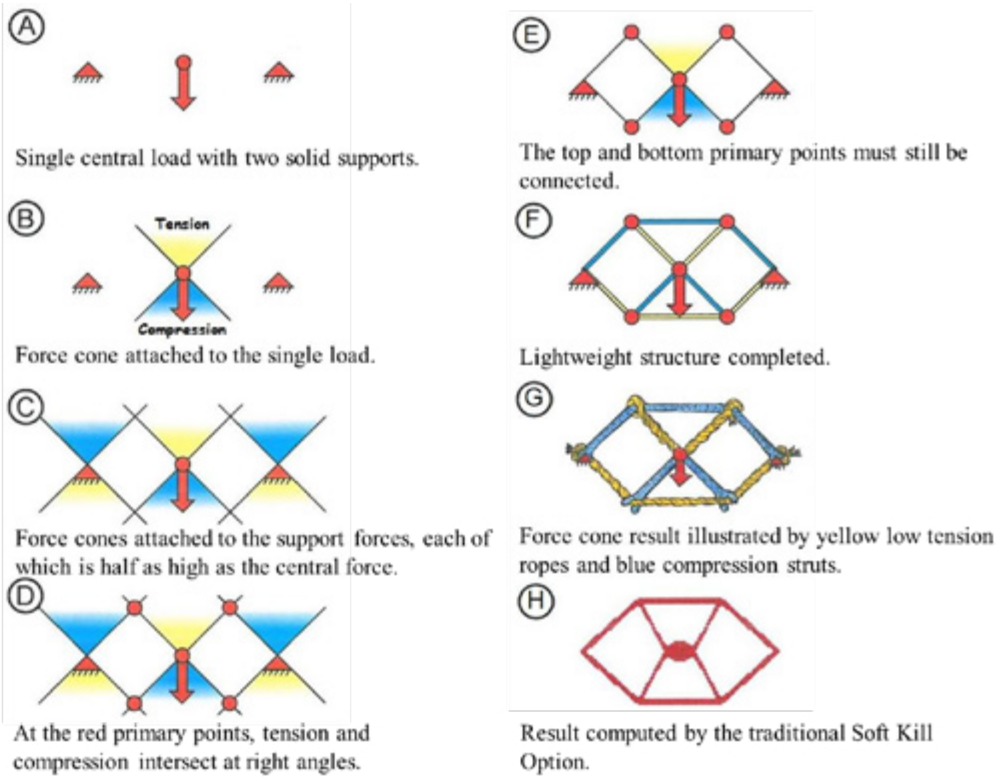


Figure 2 Force Cone Approach [1]

Furthermore, Mattheck [1] shows, that these simple methods lead to very similar structures as those developed by using computer support and topology optimisation methods. Figure 2 shows exemplarily in Step G a structure developed by the Force Cone Approach and in Step H a structure developed by using computer aided topology optimisation.
The support of the Thinking Tools of Mattheck [1] is limited to static problems. It does not allow considering dynamic problems and it does not support the analysis of existing structures. Furthermore, the method does not consider installation space limitations. But in literature there is another model and method which can support at least some of these aspects, this is the Contact & Channel - Model, as presented in the following.

4.3 Contact & Channel - Model

The Contact & Channel - Model (C&C-M) according to [2] is a model and a method which builds a connection between the function and the shape of parts, assemblies and products. With the model, technical systems are described by using the elements Working Surface Pairs (WSP) and Channel Support Structures (CSS). The Working Surface Pairs, which consist of two Working Surfaces (WS), are connected by the Channel Support Structures, which are volumes that channel energy in order to fulfil the function of the technical system, as shown in Figure 3. [2]
The method consists of an analysis phase, in which the technical system is described by the Working Surface Pairs and Channel Support Structures. The analysis phase is build up by four major steps. The first step is the definition of the part of the system and its boundaries which shall be investigated. The second step is the determination of the location where the considered functions are fulfilled. The third step is the use of the Comb Approach, which

means that those parts of the technical system will be detailed, where it is necessary in order to solve the problems. In the last step of the analysis phase, the Sequence Model is used in order to describe dynamic systems. The Sequence Model describes the dynamic system in the most relevant states. The decomposition of the dynamic system in a sequence of static states supports the reduction of the complexity of the problem [7]. Also, the method comprises a synthesis phase, in which solutions are systematically searched. This is supported by varying the elements using the following four meta-rules: Adding Working Surface Pairs and Channel Support Structures, removing Working Surface Pairs and Channel Support Structures and changing properties of Working Surface Pairs and Channel Support Structures [2].

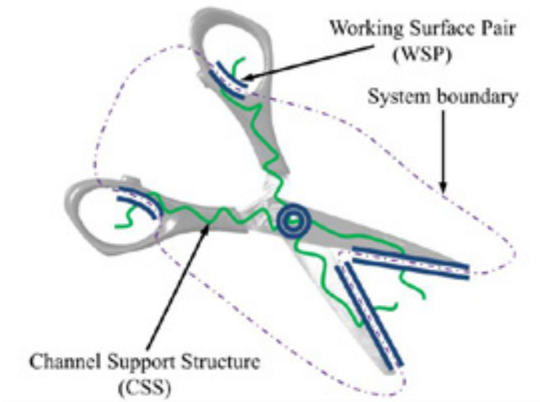


Figure 3 Elements of the Contact & Channel – Model [3]

5 Supporting the development of lightweight design structures

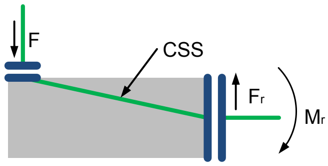
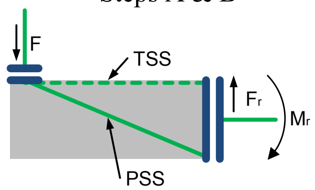
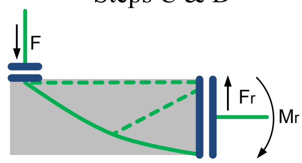
In this section, the Thinking Tools after Nature [1] and the Contact & Channel – Model [2] are combined and further developed in order to support designers developing lightweight design structures.

5.1 Tension Support Structures (TSS), Pressure Support Structures (PSS) and Working Surface Pairs (WSP)

In order to describe different kinds of Channel and Support Structures, Table 1 shows an easy way of visualising these Tension Support Structures (TSS) and Pressure Support Structures (PSS). The visualisation of these different structures is the basis for the designers discussing the synthesis of lightweight structures and of different solutions. Furthermore, it allows applying the approaches of Mattheck [1] on the structures analysed and synthesised by means of the Contact & Channel - Model. Thus, both methods can be applied simultaneously.

In the following a simple example of a bending beam, loaded with one or two forces on the left hand side and firmly clamped on the right hand side, are discussed in order to support understanding of the presented approach. Table 1 describes the formula for developing lightweight structural design based on ropes according to Figure 1 using the further developed Contact & Channel - Model, see Steps A & B and Steps C & D. In the Steps A & B a structure is built to support the applied force on the top of the bar. The structure is built up by one Tension Support Structure, which is visualised using a dashed line, and one Pressure Support Structure, which is visualised using a solid line. On the right side of the bar, there are the reaction force and reaction moment which represent the interaction of the system with the support. In the Steps C & D the Pressure Support Structure is bended and the resulting buckling direction is blocked by another Tension Support Structure, compare to Figure 1, Steps C and D.

Table 1 Describing Tension Support Structures (TSS) and Pressure Support Structures (PSS)

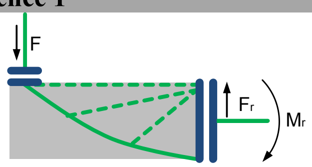
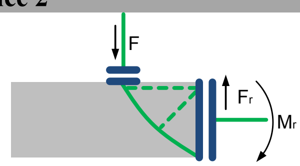
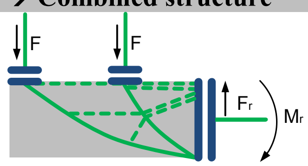
Description in the C&C-M	**Description combined with the Thinking Tools**	
Channel Support Structure	Tension Support Structures	Pressure Support Structures
	Steps A & B 	
	Steps C & D 	

5.2 Sequence Analysis

In the case of structures which have different loadings over time, the Contact & Channel - Model proposes the Sequence Analysis. In the Sequence Analysis different sequences are analysed and described as quasi static and modelled, as shown for the example in Table 2 in the upper line. Structures can be developed for each of these quasi static loadings by using the approaches of Mattheck [1].

In order to develop a structure which is suitable for all loadings over all sequences, the idea is to superpose all loadings and all structures developed for those loadings, as shown in Table 2 in line two. In order to do this, it is very important to identify the most important sequences and the acting forces, because the developed structures are highly specialised in bearing these considered loadings. Important sequences can result for example, if additional forces start to act onto the structure or if load maxima appear.

Table 2 Sequences and their combination

Sequence 1	**Sequence 2**
	
Combined Sequences 1 & 2 → Combined structure	
	

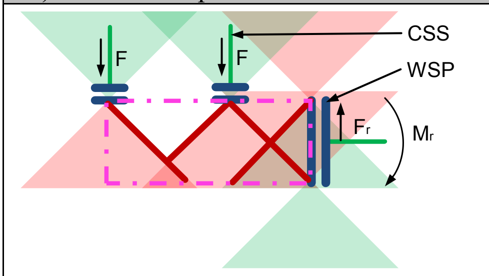
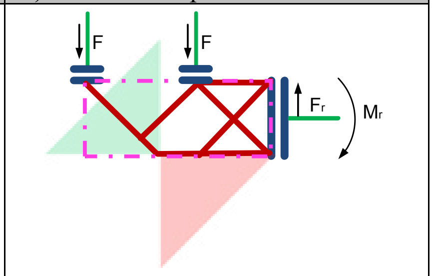
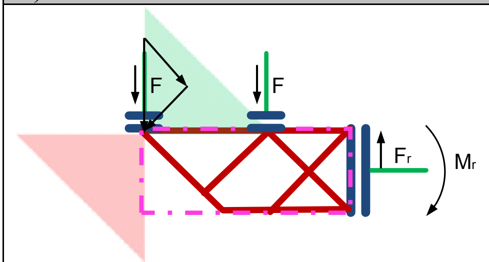
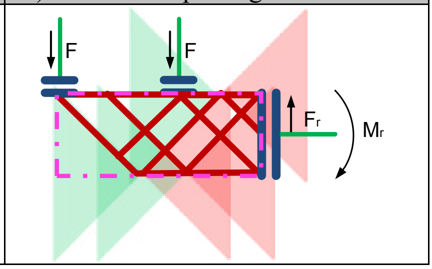
In the end, the proposed structure has to be analysed and adopted regarding its manufacturability. A consensus between the lightweight design structure and a variation of it has to be found which can be easily manufactured.

5.3 Tension and pressure cones and the installation space limitation

Table 3 shows in Section A an example with two forces applied on the top of the installation space and the support with the reacting forces and moments on the right side of the installation space. The force cones are visualised according to the Force Cone Approach, as presented in Figure 2. In order to exploit the support as far as possible, force cones are drawn at both ends of the Channel Support Structure of the support. Also in Section A, the structures within the cones are depicted. But these structures are limited to the installation space and are interrupted by the systems boundary. Thus, there results in this case no complete and connected structure. Because the structure elements are defined for transmitting either a compressive force or a tensile force, there is a tensile or compressive force at the end of the developed structure element. Therefore, another force cone can be drawn at the end of each element, as exemplarily shown in Section B of Table 3. The structures have to be developed into the direction of the support. The force on the left end of the structure is only supported by one pressure structure which would have to bear bending load, if the structure would be finished by this. Decomposing the force which is applied into the structure into one part along the pressure structure element and one force in right angle to that, results in a force which the pressure structure element cannot bear. For this structure another force cone is visualised in Section C of Table 3 in order to find another structure which can bear this component of the applied force. At the end of each structure element a force cone can be drawn and thus a path for the force transmission can be built from the application of force to the support. Furthermore, on each structure element, which seems to be long enough to get a problem with buckling, a force cone can be drawn in order to develop further supporting structure elements, as shown in Section D of Table 3. Hence, a lightweight structure is developed based on the ideas of Mattheck [1] but also respecting the installation space limitation. Furthermore, in the case of these structures the last step has to be the analysis regarding its manufacturability.

The developed structure was exemplarily calculated by using the Finite Element Method, as shown in Figure 5. The structure is compared to a structure which fills out the whole installation space, as visualised in Figure 4. Furthermore, the structures have a round area near to the support in order to reduce the effect of the support. The transition into the support is not focus of this example and has to be analysed in all cases of lightweight structures. Both structures have same height and length. Moreover, both are loaded according to the loads and supports as already assumed in the Tables 2 and 3. Of course, filling out the whole installation space with material is the case in which the structure can bear the most loadings, but in terms of lightweight design, this is not the best solution. Thus, the thickness of the developed structure was adapted in order to realise comparable loadings in both structures. Therefore, the mass of the structure using the method is more than 25 % lower. The structure developed by using the presented method is adapted to the applied forces and thus it has no special stress peaks in the areas where the loadings are applied. Furthermore, the material in the structure is stressed more regularly. This results in better exploited material which causes less needed material and leads to a lightweight design structure. Besides, the example shows, that it is very important to provide round transitions between the structure elements in order to avoid notch effects.

Table 3 Lightweight structure development under consideration of limitations

A) Tension and pressure cones	B) Installation space limitation
	
C) Structure based on the cones	D) Solution respecting the limitation
	

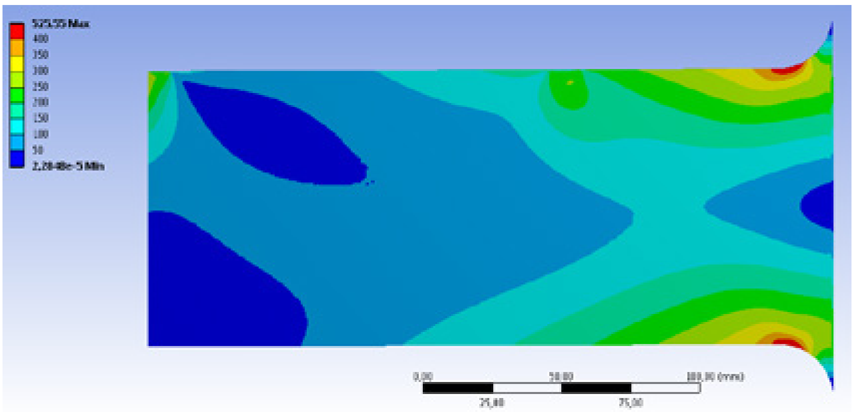


Figure 4 Solid material structure - von Mises stress in MPA

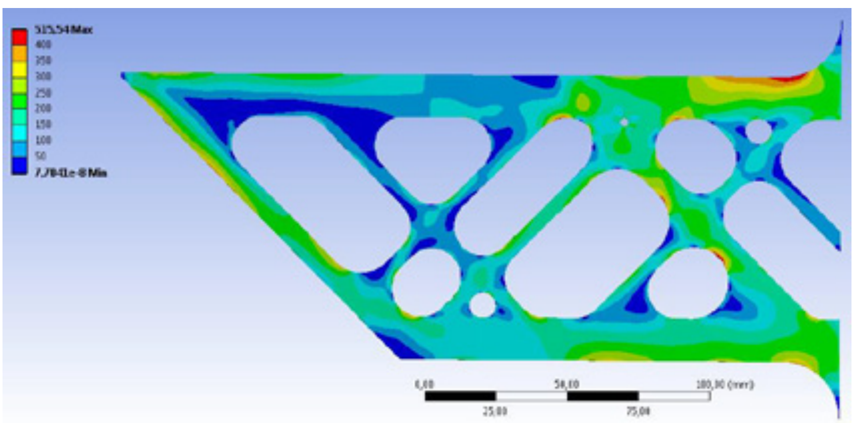


Figure 5 Developed structure - von Mises stress in MPA

5.4 Conclusion of the main rules

The presented further development of the Thinking Tools of Mattheck and the combination with the Contact & Channel - Model is here called Lightweight Design Thinking Tools (LDTT). In the last two sub-sections the further development of two methods of Mattheck [1] were discussed. Both are not contradictory but can be used complementarily. Comparing for example the structures resulting from the last two sub-sections (Table 2 and Section C in Table 3) shows, that they are very similar.

The main content of the methods is thinking in tensile and pressure structures. Also bending loads have to be transferred into such forces. Forces shall be applied within the 90 degree pressure and tensile cones or near to it. Pressure structure elements can be bent to give them a preferred buckling direction and this direction can be blocked by a tensile structure element. Forces have to be supported by at least two structure elements except for a force which can be supported by a single tensile structure element contrary to the direction of this force. In case of moved systems or systems with different loadings over the time, the Sequence Analysis can support the description and application of the method. If the installation space is limited, the not connected structure elements apply a force at their ends, at which the force cones can be used in order to find a structure supporting these forces with view on lightweight design. The structures can be detailed and refined nearly without a limit. The detailing has to be balanced to the problem of manufacturing these more and more complex structures. By using the Contact & Channel - Model also existing structures can be analysed and compared to a structure developed according to the Lightweight Design Thinking Tools. Balancing the advantages and the efforts of the new structures leads to the decision which structure will be followed up. Furthermore, the steps of the synthesis phase of the Contact & Channel - Model can be used for varying also boundary conditions of the structure and the considered system. Based on the further developed visualisation of the Tension and Pressure Support Structures, the designers are able to visualise the transmission of power within the system. Moreover, this builds the basis for the discussion of and the decision for different lightweight structure variants. Nevertheless, the presented method is based on the reduction of a three dimensional problem to a two dimensional problem. But, it is important to consider also the third dimension, as for example by analysing one or two more layers.

6 Discussion

The developed method supports a fast and easy development of lightweight design structures already in the early stages of the product development process as for example in the conceptual stage according to Pahl et al. [8], by making the ideas of the Thinking Tools after Nature [1] applicable on mechanical engineering problems. Also, more complex structures can be developed, visualised and discussed without the need for complex computer aided calculations.

The correctness, reliability and performance of the Thinking Tools after Nature and the Contact & Channel - Model are assumed as basis for this contribution and cannot be evaluated within this contribution.

The Lightweight Design Thinking Tools can be used in education for explaining the backgrounds of developing lightweight design structures using these simple methods and rules. Of course, the method does not substitute the topology optimisation software and the structure calculation methods. These must be used later on in the product development process. This rough way of developing first structures already with a view on lightweight design and the detailed calculation based on computer aided methods can complement each other. The Lightweight Design Thinking Tools can support designers in exploiting the great lightweight design potential caused by the great freedom in the early development steps.

The method is further developed by using the Sequence Analysis of the Contact & Channel - Model. It is very important to identify the most important sequences of the considered system and the acting forces, because the developed structures are specialised in bearing those. If the wrong or too few sequences are considered, it is possible that the structure cannot bear loadings of other important sequences. This can lead to an unsuitable solution. Besides, the presented approaches are focused on sequences which can be described as quasi statically. For highly dynamic systems, the reliability and performance of the method has to be investigated. Furthermore, the application of forces into structures which are not that oversized, as it is the case in lightweight design, has to be considered. If the area of the structure in which the forces are applied is for example weakened by drillings, the structures can fail at these weak points. The developed structures do not represent the perfect solutions, but the rules and methods presented shall support designers in finding good structure solutions with view on lightweight design and power transmission.

7 Conclusion and outlook

The presented Lightweight Design Thinking Tools are based on the further development and combination of the Thinking Tools after Nature and the Contact & Channel - Model. The Lightweight Design Thinking Tools support designers in developing lightweight design structures. The application of the method is shown by a simple example and only evaluated by calculations for this example. The presented approaches have to be evaluated and further developed in order to comply with scientific requirements.

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