EXTENSION OF THE LIGHTWEIGHT DESIGN THINKING TOOLS FOR THE APPLICATION ON MORE COMPLEX PROBLEMS

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Abstract

The Thinking Tools after Nature are a bionic approach based on simple rules in order to develop lightweight design structures without need for topology optimisation software. The Lightweight Design Thinking Tools are a further development of that approach in order to respect space limitations and more dynamic problems. Nevertheless, both tools are limited to two dimensional problems. The major aim of this research is to make the ideas of the Thinking Tools after Nature applicable in the field of mechanical engineering and product development. In order to reach this aim, the application of the method on three dimensional problems will be analysed and an approach for developing three dimensional lightweight structures using the Lightweight Design Thinking Tools will be presented.
Furthermore, in the existing approaches only very simple force application cases and bearings are considered. Since there are often more complex surfaces in the field of mechanical engineering on which forces are applied these more complex surfaces will also be discussed in the contribution.

Keywords: Design methods, Design for X (DfX), Conceptual design, Lightweight Design

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1 INTRODUCTION

The structure of a product determines a great part of the product's mass. Developing lightweight structures using topology optimisation software requires a great deal of effort. Furthermore, applying topology optimisation software presupposes a certain level of detail, thus it is not easily applicable or in some cases not applicable at all in the early phases of the product development process. In addition, using the software is limited to single parts or only to small assemblies in most cases due to the escalating calculation efforts.

Mattheck (2011) proposes a bionic approach called the Thinking Tools after Nature based on observations of the growth of trees. These simple rules support the development of lightweight structures without the need for software or computer support. The results of respecting these rules while developing structures is very similar compared to those structures developed using topology optimisation software. Nevertheless, the Thinking Tools after Nature do not respect space limitations which often occur while developing structures in mechanical engineering. Furthermore, the approach is limited to static problems. However, most products in mechanical engineering include moving parts.

Posner et al. (2014) presented a further development of the Thinking Tools after Nature, called the Lightweight Design Thinking Tools, which allow using these rules in the case of space limitation as well, and in the case of more dynamic problems.

2 PROBLEM STATEMENT AND GOALS

Since the approach of the Thinking Tools after Nature (Mattheck, 2011) and its further development called the Lightweight Design Thinking Tools are both limited to two dimensional problems, the major aim of this research is to make the ideas of the Thinking Tools after Nature more easily applicable in the field of mechanical engineering and product development. In order to achieve this aim, the application of the method to three dimensional problems will be analysed and an approach for developing three dimensional lightweight structures using the Lightweight Design Thinking Tools will be presented.

Furthermore, in the existing approaches only very simple force application cases and bearings are considered. Since there are often more complex surfaces in the field of mechanical engineering on which forces are applied, these more complex surfaces will also be discussed in the following. Besides, some further aspects, as for example the level of detail on which the method shall be applied, will be outlined.

3 METHODS

The presented research is based on the Design Research Methodology (DRM) according to Blessing and Chakrabarti (2009). The methodology concludes four major steps. Three of these four steps are addressed in this contribution. In the first step of the DRM, the Research Clarification, the research aims are clarified (compare Sections 1 and 2). In the Descriptive Study I, the state of the art is analysed, these results are presented in Section 4. The third step is the Prescriptive Study, in which the results of the research are developed. The last step is the Descriptive Study II. In this step, the results are evaluated in order to comply with scientific requirements. This evaluation is not content of this contribution and has to follow in the next research steps, as mentioned in the outlook.

4 STATE OF THE ART

In this section, first, the state of the art in lightweight design is analysed. Furthermore, the Thinking Tools after Nature according to Mattheck (2011) are presented. The Lightweight Design Thinking Tools are an extension of the methods of Mattheck and are discussed in addition.

4.1 Lightweight Design

In literature, several lightweight design strategies, as for example bionic (Zaho, 2010), material (Ashby, 2005), manufacturing (Bühring-Polaczek et al., 2011), system (Schmidt, 2003), conditional (Haldenwanger, 1997) and shape (Klein, 2013) lightweight design, are described. Beside those strategies, lightweight design principles are provided in order to put shape lightweight design into practice. One example for those lightweight design principles is, if there is a bending load, hollow cross sections must be preferred (Klein, 2013). Furthermore, a lot of calculation is used in order to develop lightweight design structures and shapes. Since this calculation is very complex, computer aid is used in order to reduce the efforts. Topology optimisation software calculates the mass distribution within a space limitation in order to bear the loadings and channel the forces into the bearings with as less mass as possible. Nevertheless, for developing lightweight design structures using topology optimisation software still a lot of knowledge, time and money is needed (Mattheck, 2011). In contrast to this complex software, literature presents a bionic approach which can support designers in developing lightweight design structures with very less efforts.

4.2 Thinking Tools

The Thinking Tools after Nature are a bionic approach developed by Mattheck (2011). The method is based on simple rules. The main idea is to develop structures only using pressure and tensile elements and to avoid bending load on the elements.

One method of the Thinking Tools after Nature is the so called Formula for developing lightweight structural design based on tension ropes and compression struts. This Formula comprises four steps, as shown in Figure 1 on the left hand-side. In the first step, the load and support conditions are defined (see Step A). In Step B, the structure to bear those loads is developed using only tension ropes and compression struts. Next, the compression struts are pre-bend in order to give them a preferred direction for buckling in Step C. This preferred buckling direction is blocked in Step D using a tension rope.

The Lightweight Design Thinking Tools developed by Posner et al. (2014) combine the Thinking Tools after Nature (Mattheck, 2011) with the Contact and Channel - Model (C&C-M) (Albers, 2003), which is a model and a method that supports analysing and varying existing structures and products. On the right hand-side of Figure 1, the steps of the Formula of the Thinking Tools after Nature are described using the Working and Surface Pairs (WSP) and Channel and Support Structures (CSS) according to the C&C-M (Posner et al. 2014). The CSS channel energy from one WSP to another and thus the abstract model describes how the system fulfils its function. In the Lightweight Design Thinking Tools, as Posner et al. (2014) call their further developed method, there are two different types of CSS, one called the Pressure and Support Structure (PSS), visualised as a solid line, only channeling compression loads and the other, called the Tension and Support Structure (TSS), visualised as a dotted line, channeling only tension loads. Using this description, the rules and procedures of the Thinking Tools after Nature and the Contact and Channel - Model are usable simultaneously within the Lightweight Design Thinking Tools.

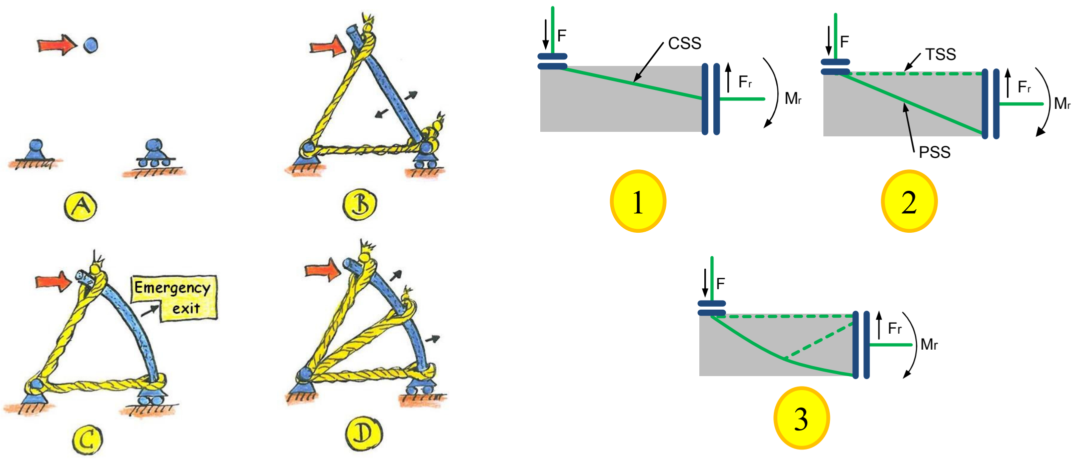


Figure 1. Formula for developing lightweight structural design based on ropes [on the left according to (Mattheck, 2011); on the right according to (Posner et al., 2014)]

Another approach of Mattheck (2011) is the Force Cone Approach (FCA). This approach is based on the assumption, that a single force causes a 90 degree compression cone in the direction of the force and pulls a 90 degrees tension cone opposed to the direction of the force. By developing structures along those cones, lightweight structure solutions can be developed easily. In Step A, the loading and support conditions are defined. Afterwards, the Force Cones are attached to the loads in Step B and to the supports in Step C. The intersection points where the Force Cones intersect at right angles are called primary points and marked in Step D. In Steps E and F, these primary points, supports and loadings are connected in order to develop a lightweight design structure. The structures developed using these rules, as exemplarily shown in Step G, lead to very similar structures compared to those structures developed using topology optimisation software (Soft Kill Option), as shown in Step H in Figure 2.

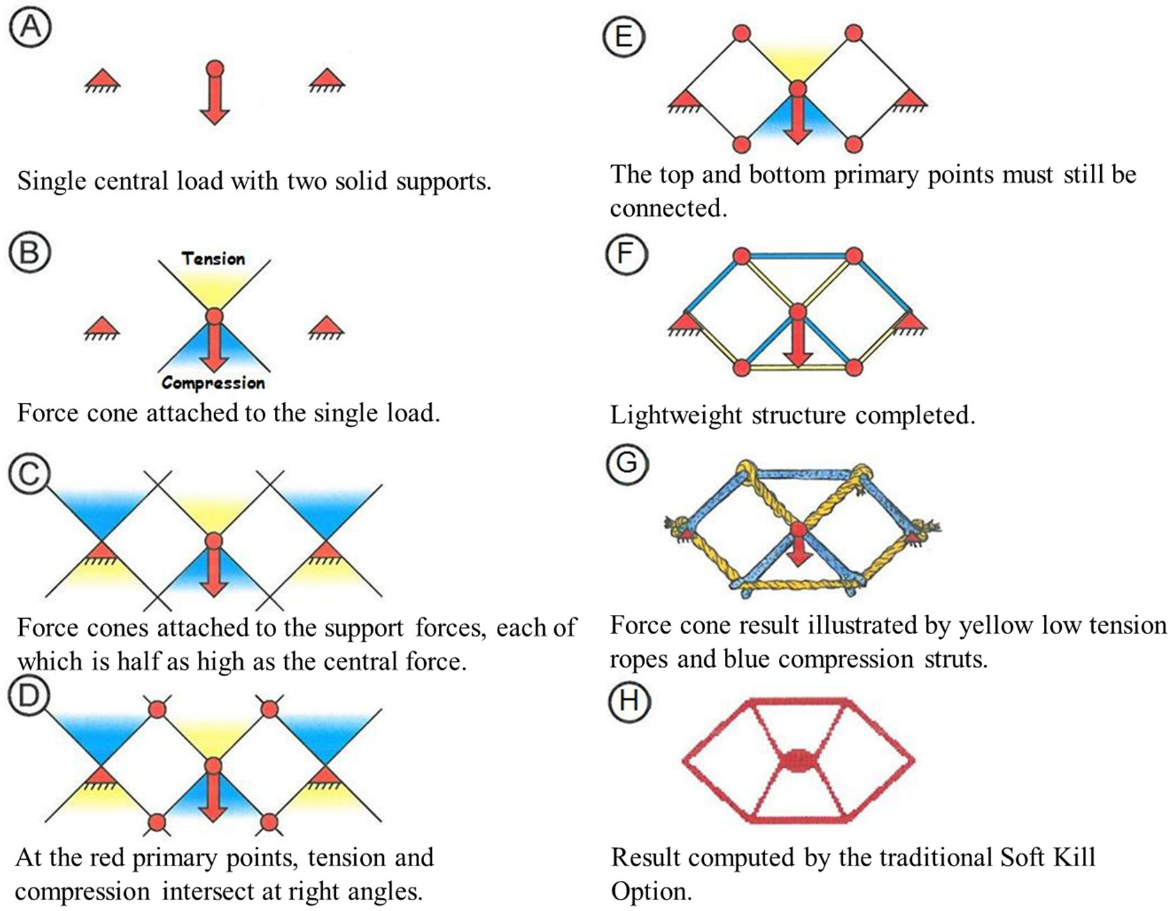


Figure 2. Force Cone Approach (Mattheck, 2011)

Due to the fact that the Thinking Tools after Nature are limited to only static problems, Posner et al. (2014) further developed the approach in order to make it applicable on more dynamic problems. Thus, the Lightweight Design Thinking Tools propose to use the Sequence Model of the C&C-M. The Sequence Model recommends describing the most important quasi static states for the whole sequence. Therefore, also motions can be described and the Lightweight Design Thinking Tools can again be applied, see Table 1.

Because the Thinking Tools after Nature do not support developing lightweight structures under consideration of space limitations, Posner et al. (2014) presented an approach to consider those limitations. In Table 2, the procedure of the Force Cone Approach (FCA) according to Mattheck (2011) is described using the Lightweight Design Thinking Tools based on the elements of the C&C-M. In addition, the structure elements are interrupted by the system boundary, as shown in Step A. The idea is that at the end of an element that is only loaded with compression or tension there is a force in the direction of the element or in the opposite direction of it. Thus, again the FCA can be used in order to further develop the structure and to close the gaps within the structure. In some cases, as shown in Step B, there is still a bending load on a structure element. In those cases, the component of the force orthogonal to the loaded structure element has to be supported using further elements. Hence, a support for this component of the force can be developed using the FCA again applied only on this component of the force (Step C). In addition, the FCA can be used in order to detail the structure, as shown in Step D. As for example if there is still an element which seems to be critical regarding buckling, again a Force Cone can be attached to the middle of the element and thus the structure can be detailed using the FCA in order to support this element against buckling.

However, in mechanical engineering the development of lightweight structures is in most cases a three dimensional problem. But, neither Thinking Tools after Nature nor the Lightweight Design Thinking Tools propose a support to develop three dimensional lightweight structures.

Table 1. Sequences and their combination according to the Lightweight Design Thinking Tools (Posner et al., 2014)

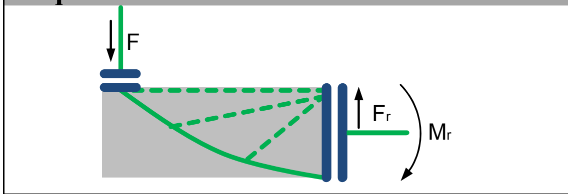
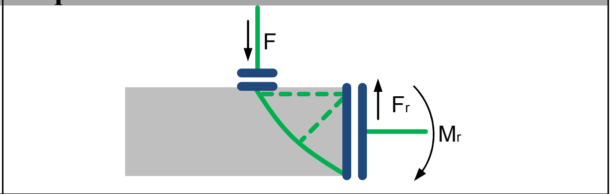
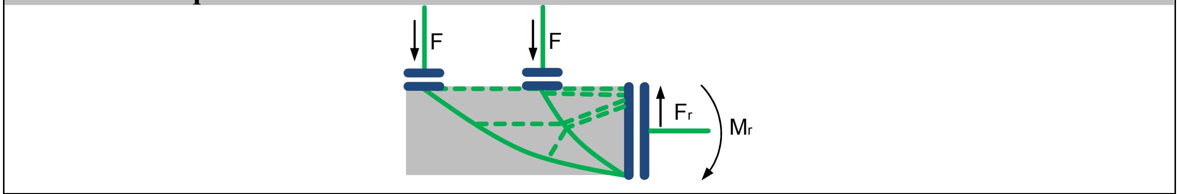
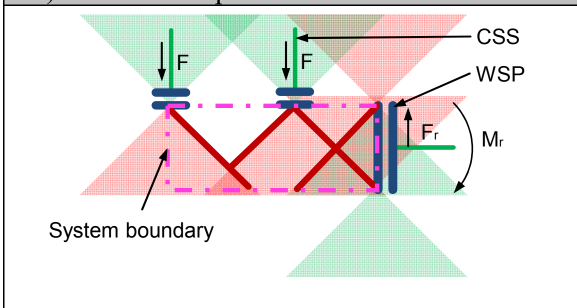
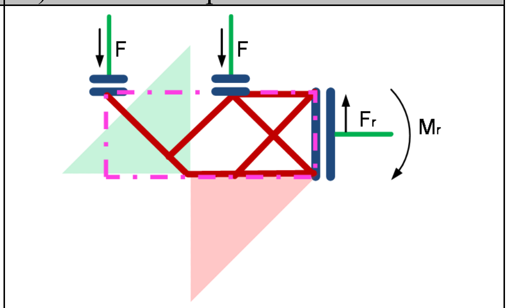
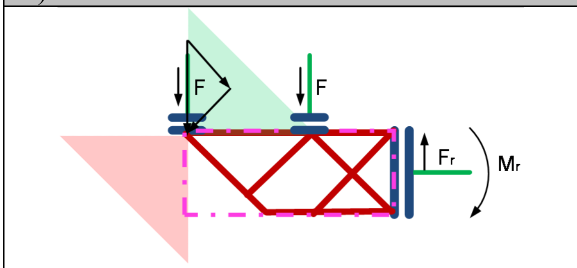
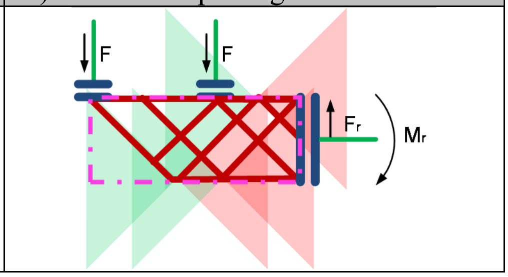
Sequence 1	**Sequence 2**
	
Combined Sequences 1 & 2 → Combined structure	
	

Table 2. Lightweight structure development under consideration of limitations according to the Lightweight Design Thinking Tools (Posner et al., 2014)

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

5 EXTENSION OF THE LIGHTWEIGHT DESIGN THINKING TOOLS

Due to the problem, that there is no support in developing three dimensional lightweight design structures based on simple rules, in the following the development of three dimensional lightweight structures using the Lightweight Design Thinking Tools is discussed. Further aspects as for example the consideration of more complex WSP based on more complex bearings or force applications are also considered.

5.1 Three dimensional view

Since Mattheck (2011) states that a force always causes a 90 degree pressure cone in the direction of the force and a 90 degree tensile cone behind the force in the opposite direction of the force, those cones are three dimensional. Hence, all structure development problems are also three dimensional. Figure 3 shows the pressure cone caused by a single force. This three dimensional view can be described using three orthogonal views. This way of describing three dimensional problems using two dimensional views is used also in engineering drawings. Thus, in order to develop a lightweight design structure, there must be considered at least three views to allow a holistic description of the three dimensional problem, apart the exception of rotationally symmetric products. Those three views do not have to be at right angles to each other in all cases but they must be at least at an angle greater than zero to each other. Further views and cross sections must be taken into account if necessary, similar to the engineering drawings, their views and sectional drawings.

Based on the ideas of Mattheck (2011), a lightweight structure can be developed as shown in the first two dimensional view in Figure 3. In order to describe a further important view, the second two dimensional view is needed. However, a third two dimensional view is needed in order to describe the whole three dimensional structure, as also shown in Figure 3. In the third view, the Thinking Tools after Nature according to Mattheck (2011) and the Lightweight Design Thinking Tools are not applicable because the force acts orthogonal to the considered layer. However, the decision whether a structure is realised as a sheet based construction, as shown in Figure 3 on the upper right hand-side, or a solution using a framework, as shown in Figure 3 on the lower right hand-side, depends on further criteria as for example the possibilities of manufacturing.

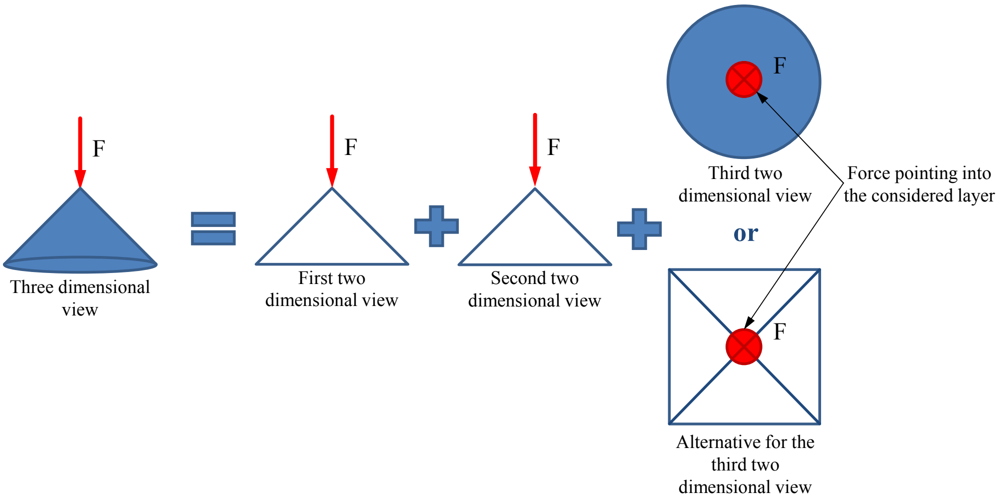


Figure 3. Force Cone and alternative derived structure

In mechanical engineering the installation space is often limited because of further parts and components of the product or due to functional reasons. The Lightweight Design Thinking Tools are approaches in order to support the development of lightweight structures in the case of space limitations, compare Table 2. Applied on the considered Force Cone a structure as shown in the second and third two dimensional views can be developed using the Lightweight Design Thinking Tools, as shown in Figure 4.

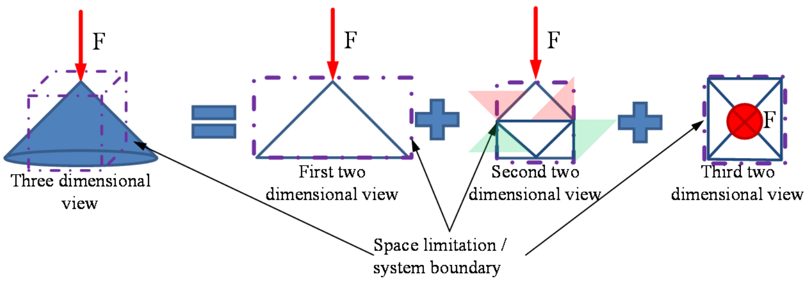


Figure 4. Force Cone and derived structure under consideration of space limitation

In the case of space limitations, sometimes single views are that limited that there is no optimisation potential using the Lightweight Design Thinking Tools. In those cases either the structure is realised using a full cross section, which means, that as for example the whole space within the space limitation is filled with material or further cross sections in order to increase the moments of inertia are used, e.g. using hollow cross sections or H-beams.

While developing lightweight structures, those views which have the greatest freedom also regarding their space limitations must be taken into account carefully. Those views have to be identified and optimised, because they offer a great optimisation potential using the Lightweight Design Thinking Tools.

The most important function of the structure is channelling energy from the applied forces to the bearings at which the reacting forces are applied. Thus, the views in which the applied forces and/or the bearings are located have to be considered for developing lightweight structures. Since the applied forces and bearings are not always in the same layer, in some cases more than one view must be taken into account, those in which the applied forces are located and those in which the bearings are located.

As the Lightweight Design Thinking Tools support considering more dynamic problems in which the structure includes moving elements or different loads over time by using several quasi static views, these sequences have to be taken into account while developing lightweight structures. The identification of the most important views, regarding different sequences as well as considering different views is important for developing lightweight structures holistically.

Based on these identified views, the Lightweight Design Thinking Tools can be applied in order to develop a lightweight structure solution for each single important view. In addition, for the views which are less important or strictly limited as for example regarding their space limitation, also the structures or cross sections of the structures have to be determined.

In the last step, the developed lightweight structures of the different views have to be combined in order to result in a lightweight structure solution for the whole considered part, assembly or product.

Based on these considerations, the procedure which supports identifying the most important views and cross sections for the development of lightweight structures using the Lightweight Design Thinking Tools is summarised in the following procedure:

1. Identifying the most important views and cross sections
   a. Identifying the views with the highest freedom (e.g. regarding the space limitations or the possibilities of manufacturing)
   b. Identifying the views in which the bearings and/or the applied forces are located
2. Identifying the most important sequences and furthermore the most important views and cross sections regarding those sequences
3. Applying the Lightweight Design Thinking Tools in order to develop lightweight structure solutions for the most important views and cross sections
4. Determining the structures and cross sections for the less important views
5. Combining the structure solutions in order to develop one resulting lightweight structure solution

In Figure 6, an example of a bending beam which is fixed on the left hand-side and loaded on its end on the right hand-side with a single force is shown, as an example which will be used to aid understanding of the procedure. The space limitation is shown as a three dimensional installation space. The applied force and the bearings are shown in View 2, see procedure Step 1. Thus, we identify that view as most important. The loading is assumed as static loading, thus, no further sequences and no further views are considered, see procedure Step 2. Therefore, a structure was developed using the Lightweight Design Thinking Tools (see procedure Step 3) and also the structure was calculated with a topology optimisation software which is shown on the right hand-side in Figure 6. View 1 is assumed as less important because the force is only orthogonal to that layer and View 3 is assumed as less important because of the stricter limited space in this view (compare Step 4). Step 5 of the procedure is not necessary for that simple example, because only one view is identified as important.

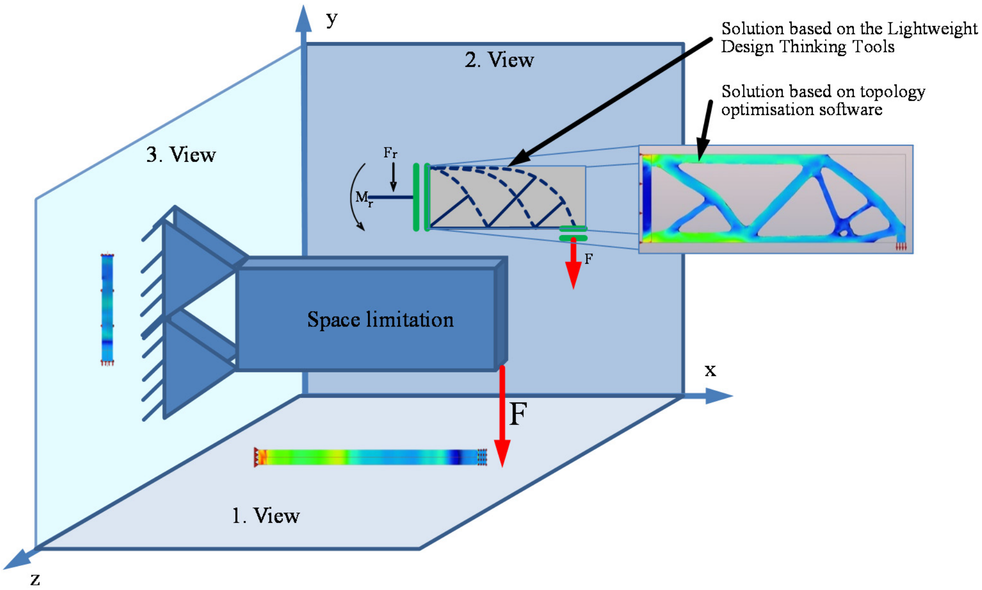


Figure 6. Applying the Lightweight Design Thinking Tools on three dimensional cases

5.2 More complex Working Surface Pairs

The most important aim in developing lightweight structures according to the ideas of Mattheck (2011) is to avoid bending load within the structure elements. Thus, it is necessary to avoid also the implementation of bending load into the Working Surface Pairs. This has to be taken into account especially in the case of more complex WSP. In simple cases the loadings can be reduced to one single resulting force in a single point, as shown in Figure 7. Based on that, a structure using the Thinking Tools can be developed.

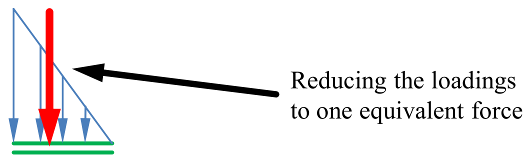


Figure 7. Reducing loadings to one equivalent force if possible

In the case of bigger WSP and especially in the case of bearings which should be exploited the best way, in terms of distributing the loadings the best way into the bearing surface, at least one force at each end of the WSP has to be considered, as shown in Figure 8. Thus, the support of the implemented forces or the channelling out of the forces in the case of bearings can be realised in the most stable way.

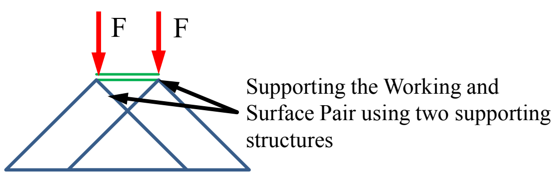


Figure 8. Supporting the Working Surface Pairs at its ends

Furthermore, complex curved or buckled WFP can be approximated and described using several simple WFP, as shown in Figure 9. This allows using the Lightweight Design Thinking Tools for developing structures which could bear the loadings of each single WFP and by combining those structures developing structures which could bear all loadings to be considered.

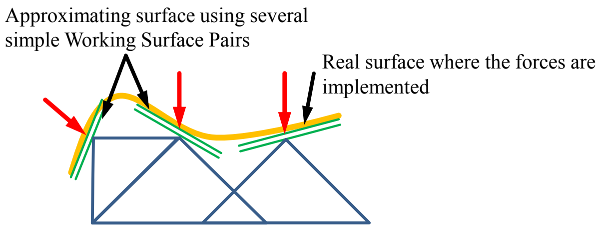


Figure 9. Approximating more complex surfaces using several simple Working Surface Pairs

If different forces act on the structure over time, as shown in Figure 10, the structure must not be developed aiming at only one sequence or on single forces of one sequence. In Figure 10 on the left hand-side the structure aims on bearing the loads at Time 1. Furthermore, at Time 2 another shifted force implements also a bending load into the WFP and thus into the developed structure. This bending load must be avoided. Again it is important to consider all loadings of all load cases and sequences in order to develop a structure including only elements which are loaded with pressure or tension loads only.

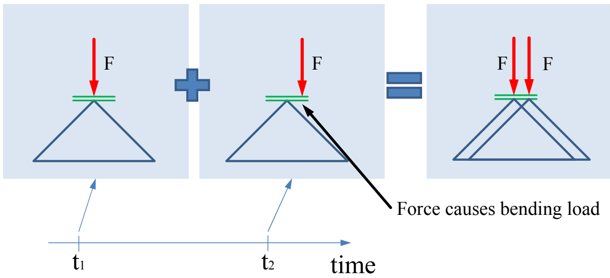


Figure 10. Considering different loadings in different sequences also within one Working Surface Pair

5.3 Further aspects to be considered while using the Lightweight Design Thinking Tools

Besides more complex WSP and three dimensional problems, there are some more aspects which must be taken into account while using the Lightweight Design Thinking Tools in the field of product development. One of these aspects is the level of detail which has to be considered. The Contact & Channel - Model according to Albers (2003) describes an approach called the Comb Approach which proposes to start the structure development with a low detailed level and afterwards to analyse in which parts of the system it is necessary to have a look at on a more detailed level. Therefore, still the level of detail for each part of the system is based on the estimation of the designers but they are guided in a stepwise procedure. The possibility of detailing a structure also depends on further aspects as for example the possibilities of manufacturing.

Furthermore, the thickness of each structure element has still to be calculated. If different structures must be combined, as for example in the case of different structures resulting from different sequences, those structure elements which are similar in different variants must have a thicker cross section. Moreover, dependent also on the material, tension structures can in many cases be downsized compared to the pressure structures, because pressure structures also have to be calculated against buckling.

6 DISCUSSION

The Lightweight Design Thinking Tools were applied in different industrial development projects by the authors. In those cooperations in the field of the automotive industry and machine-tool industry, the method was applied by designers of the companies under the moderation of the scientific designers. Within those application projects, the problems discussed in this contribution came up. The presented approach constitutes a stepwise procedure in order to support designers in managing those problems. This contribution focuses especially on the problem of managing three dimensional problems with the rules and procedures of the Lightweight Design Thinking Tools which are applicable on two dimensional problems. The procedure and its steps need still to be adapted and interpreted for the individual situation. In the contribution different aspects regarding the application

of the method on three dimensional problems are discussed. One aspect is the need for the consideration of different views while developing three dimensional structures. Which and how many views are needed depend for example on the applied forces, bearings, space limitations and possibilities of manufacturing.
The contribution does not present a total new method, rather it supports the application of the existing method of the Lightweight Design Thinking Tools in order to manage problems of applying it on complex development projects in practice. The presented extension of the Lightweight Design Thinking Tools could for several reasons, e.g. the high complexity of the industrial application projects, not be shown on the example of the industrial projects within this contribution. Thus, the presented contents were on the one hand discussed on the basic example of the Force Cone. Since this Force Cone is one of the major ideas of the Thinking Tools, it also shows that these ideas can be transferred as well as on more complex cases. On the other hand, the steps of the procedure are briefly discussed on the common example of a bending beam with the only aim to aid understanding. In addition, different cases of more complex WSP which occurred in industrial applications of the method are discussed in the contribution. This supports designers also in handling these challenges in spite of the fact that the designers must transfer those solutions onto their individual problem statements. Moreover, the aspects of the thickness of the element´s cross-sections and the different levels of detailing are discussed. However, the presented approaches are developed based on the application in industrial application projects, they have to be evaluated and further developed in order to comply with scientific requirements. This further development and evaluation has to be the next step.

7 CONCLUSION AND OUTLOOK

In this contribution, different approaches of managing problems of the application of the Lightweight Design Thinking Tools are discussed. Thus, the Lightweight Design Thinking Tools are further developed with a focus on applying them on three dimensional problems. These approaches must be further developed, evaluated and validated in order to comply with scientific requirements. Moreover, further aspects in order to make the methods easier applicable to industrial product development projects must be analysed.

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