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A VISUALIZATION CONCEPT FOR SUPPORTING MODULE LIGHTWEIGHT DESIGN

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ABSTRACT

In the aviation industry there is a current trend towards modular product design. As usual in aviation design, weight is a crucial factor. Hence, a modular product should not outweigh a former non modular product with an identical functionality. The modules themselves have to be very light to compensate the additional weight due to module interfaces in order to fulfill its demands. With the increasing need for a lighter design the complexity for finding weight optimization potential increases. An easily usable visualization approach for reducing the complexity of a Module Lightweight Design is presented. Adapted treemaps were identified as a suitable tool. In the following, basics of Modularization and Lightweight Design are explained and the adapted treemaps for Module Lightweight Design are discussed and applied in an example.

Keywords: Modularization, Treemaps, Lightweight Design

1 INTRODUCTION

Customers demand more and more individualized products today. Additionally there are different mechanical requirements like design for maintenance, assembly, upgradeability and sourcing. Modularization is a widely used concept for supporting these development aims [1]. However, Modularization per se induces additional interfaces, which potentially cause higher weight. This often interferes with Lightweight Design.

Module Lightweight Design, therefore, focuses on a weight reduction particularly inside of a module's structure and its interfaces. Using the principle of Integration of Function applied on the hierarchical level of single parts and inside of the module boundaries shows promising benefits.

Due to the rising complexity of products, an identification of singular parts with weight saving potentials becomes more and more challenging. The designer needs a support for the identification of those potentials. Treemaps offer an intuitive way for the visualization of a high number of hierarchical sorted items. They use 100% of a specified area for a separation into rectangular blocks according to a hierarchical structure. The size of the blocks can be set to correspond to the elements' weight. This paper describes an approach that uses treemaps to visualize the potential for Lightweight Design in modularized product architectures.

Further on, basics of Modularization and a suitable visualization support for modularized products are explained. In addition, the common approaches for Lightweight Design are introduced; typically they are a combination of the three categories of optimizations (material, structure and system) [2]. According to these explanations, Module Lightweight Design is derived. After explaining the requirements towards a Module Lightweight Design support, the visualization using adapted treemaps is introduced. It is shown how this visualization supports the designer by giving valuable information for improving the product's Lightweight Design. This theoretical approach by using adapted treemaps is practically applied in an example of a modularized aircraft galley.

2 MODULARIZATION

Over the last decades, customers have demanded an ever increasing variety of individualized products. Along with this comes aspects like maintenance, assembly, upgradeability, configurability and standardized interfaces for the supplier. Modularization is a widely used concept to tackle these problems [1]. By the development of several basic modules - which later on can be combined into different final products - a high variety of different products can be realized.

First, the term "Modularization" needs to be clarified. In literature there are many definitions for modularization; Salvador [3] identified two major characteristics for a modularized product:

- Separable physical component groups form the final product.
- The component groups can be set up differently to achieve product configurations.

In the following, we will consider a product, which fulfills these characteristics as modularized.

Pimmler/Eppinger and Erixon introduced some fundamental concepts to develop modularized product structures. Pimmler and Eppingers' approach is based on the Design Structure Matrix (DSM) and focuses on the functional product perspective [4]. For using the matrix two additional steps are necessary. First the product has to be decomposed into components with respect to the functionality. These components represent the functions of the product. In a second step, the interactions between these components have to be identified and documented. In the DSM the information of components and their interactions is correlated. Pimmler and Eppinger distinguish between four different interaction types, which are energy, material, information and spatial. Within the DSM the interaction types between the components are evaluated. Subsequently a permutation algorithm sorts the components into different chunks according to their interactions. The modules can be identified by these chunks. Erixon's "Modular Function Deployment" (MFD) defines its modules on a product strategic view [5]. A Module Indication Matrix (MIM) is used. The MIM correlates the product components to so-called module drivers. These module drivers represent reasons for combining components into modules. Since the method is based on product strategic aspects the module drivers are aspects from different phases of the product life cycle. Within the MIM the components are evaluated with respect to the module drivers. High scoring components are considered as modules themselves or as a base module, which then collects components with a similar scoring. The work of Pimmler/ Eppinger and Erixon has been used as a basis for many other different modularization methods.

Blees introduces a visualization to show proposed modularization concepts [6]. The so-called Module Interface Graph (MIG) arranges the simplified package dimension of the modules within the product layout. In addition, the interfaces between the different modules are shown (see Fig. 1). This gives an overview of the products module layout and important interfaces.

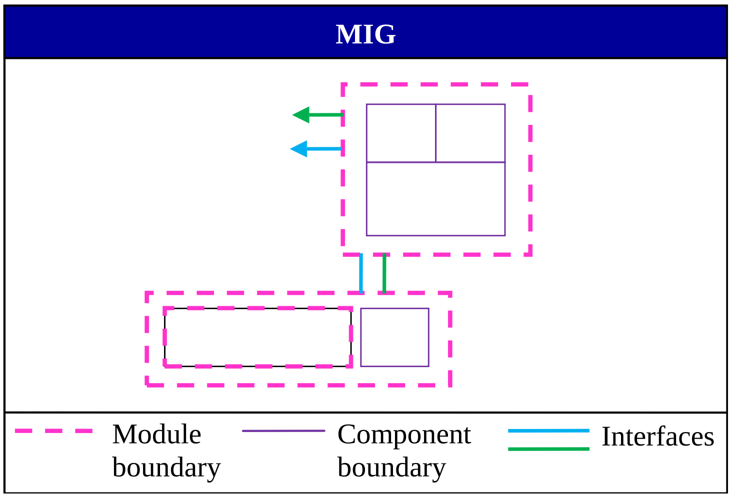

Figure 1. Module Interface Graph (MIG)

The reduction of the number of interfaces and a minimum of interdependencies between the modules are main goals for a successful modularization. However, the more differential product architecture causes additional weight, which is a major drawback for certain products. The next chapter introduces the basic categories of Lightweight Design as a basis for overcoming this problem.

3 LIGHWEIGHT DESIGN

Lightweight Design is typically a combination of the three categories of optimization: material, structure and system. These categories of Lightweight Design can be understood as follows, as described in Sobek (see also Fig. 2) [2]:

- Material Lightweight Design uses the optimal material for the product with respect to lightweight consideration. Material criterions such as stiffness by weight can be a measurement.
- Optimizing the realized load path of given load collectives in a structure under certain boundary

conditions with a minimum of weight is the principle goal of Structural Lightweight Design

- System Lightweight Design considers the whole system. The system itself supports Lightweight Design. For example, further functions can be assigned to the structure in addition to the pure function “carry loads”. Therefore multifunctional parts are created.

The manufacturing of the products sets constraints for Material-, Structural-, and System Lightweight Design Optimization. A typical question is: Can the specific material be shaped according to the designed structure? If this is the case, products still need to be producible within the target costs.

The designer almost intuitively uses a combination of these categories. Still it is helpful to consider the three perspectives separately for a redesign following a systematic approach. This reduces the complexity of the optimization. It also helps avoid the consideration of just one category of Lightweight Design. For example a change of the material without properly adapting the structure of the product can lead to suboptimal utilization of the material. A well-balanced Lightweight Design among the categories is best practice. However, System Lightweight Design is given less attention in literature compared to structural and material optimizations. The visualization concept proposed in this paper contributes in order to overcome this deficit. The focus is therefore on System Lightweight Design. For consistent economic Lightweight Design it is useful to consider all three perspectives closely together not neglecting to watch out for the incurred manufacturing costs .

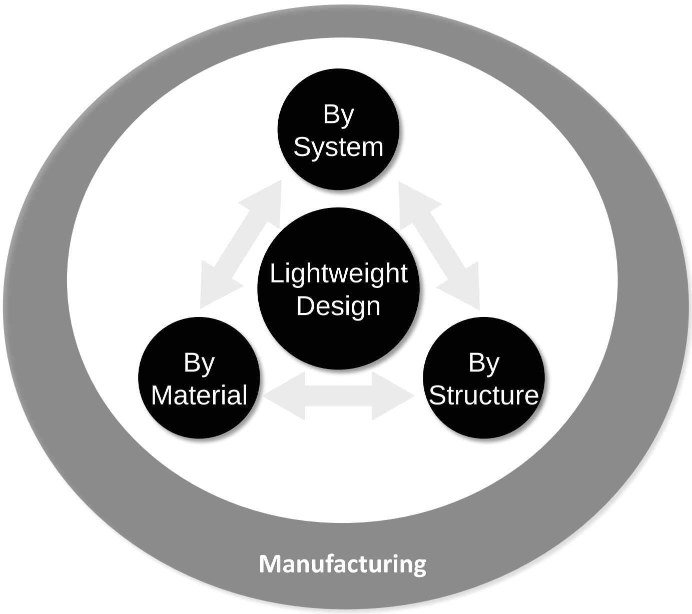

Figure 2 Lightweight Design Categories

Also one single highly optimized part can lead to high development and manufacturing costs. Such a top-level optimization can lead to less robustness of the final product too, since it is more likely to fail (due to reduced safety factors). A balanced optimization of more parts to reach the target weight is often the better choice.

3 MODULE LIGHTWEIGHT DESIGN

When additional interfaces are induced for a modularized product structure, Lightweight Design and Modularization show their contrary nature. Module Lightweight Design should, therefore, focus on reducing the weight significantly within each of the modules. Integration of Function on part level inside of the module boundaries is a suitable approach [5]. Several functions are combined within one part; this can reduce the weight due to less interfaces. The two parameters that can be influenced by the designer, in order to undertake an optimization using Integration of Functions, are form and material. They are linked to each other and cannot be modified without paying attention to arising needs for changes in the other. Both together will be designed accordingly to the desired function of the part. However, in the case of Integration of Function it is only possible to join parts together if a material is used that fulfills all related material requirements. Only then, an integral part made of a single material can be designed.

The term “Integration of Function” can be either defined by looking at single parts where more functions have been integrated into, or by looking at the working surfaces (on a lower level in hierarchy), that are necessary to fulfill the respective functions. Ehrlenspiel [6] describes the latter case where working surfaces have to be joined as “Aggregation of Functions”. In our case the first definition will suffice however, without prohibiting the use of the second. As long as more functions are integrated into a single, integral part, the weight saving may occur. Whether working surfaces have merged also is only of secondary importance in this particular case.

But when is Integration of Function generally possible? Boothroyd describes the theoretical minimum number of parts as a situation where several parts were joined together into a new part if none of the following aspect may be the case [7]:

1. During the normal operating mode of the product, the part moves relatively to all other parts already assembled. (Small motions do not qualify if they can be obtained using elastic hinges.)
2. The part must be of a different material than, or must be isolated from, all other parts assembled (for insulation, electrical isolation, vibration damping, etc.).
3. The part must be separate from all other assembled parts; otherwise, the assembly of parts meeting one of the preceding criteria would be prevented.

A theoretical minimum of parts may not be the most reasonable economical and constructive solution. However, in this state, the theoretical number of interfaces is minimized within the module and therefore a minimal weight may be achieved in theory. So it is justified to at least check every possibility for Integration of Function according to the rules above in respect to the overall weight of the product. The resulting possible integral solution will then have to be judged based on the weight change in order to clarify whether the step from differential to integral parts makes an overall success in weight reduction.

An advantage of Module Lightweight Design is economies of scale. Additional costs for higher design and production effort may be compensated due to the reusability of the modules.

One of the major problems within the optimization is to find the most parts with the highest potential for a successful approach in Lightweight Design. The complexity of products and high number of parts contribute significantly to this problem. A powerful visualization to support Module Lightweight Design is necessary to support analysis of potentials and the weight distribution, decision making and idea generation for solutions.

4 VISUALIZATION SUPPORT FOR LIGHTWEIGHT MODULAR DESIGN

For different phases of the Design process, various visualizations are supportive. The described MIG provides an overview of the module definition. It gives hierarchical and relational views for the modules. In Lightweight Design the display of different information is necessary. It is obvious that the weight itself is a good indicator. However, it is not sufficient for Module Lightweight Design. The hierarchy of the modules and components inside of the modules are also important. Additionally the part material is helpful information for using Integration of Functions where integral single parts need to be of the same material. All this information should be visualized in an intuitive way with a good usability, thus help reducing complexity instead of just visualizing a product’s complexity. The latter would just contribute to a designer’s reluctance to use the tool. This can be prevented by using clear arrangements of the structure. In summary, the requirements towards a support can be formulated:

- Visualization of the weight of single parts, modules, etc. in their hierarchical structure
- All parts with their characteristics displayed in one frame of view
- Clear arrangement, easy to understand

A visualization method used in product development, which complies with the stated requirements could not be found. E.g. an ABC analysis of product parts’ weight cannot represent a hierarchical structure. In the research conducted, it was found that adapted Treemaps are a suitable approach.

Treemaps: An introduction

Treemaps use 100% of a specified area to separate a hierarchical structure into rectangular blocks. Partitioning algorithms are used for achieving this. A quantifiable dimension of the system is represented by the size of the blocks. A qualitative dimension can be represented by a color coding of the blocks.

The main features of the treemaps are:

- Hierarchy of a structure displayed as sets through nested frames

- A quantifying and comparable dimension depicted by the size of the blocks
- A second dimension of relations and affiliations through color coding of the blocks
- Where applicable: information is overlaid for selected blocks through software interaction

The general development of a Treemap will be described with a simple and general example: the composition of the gas price in Germany (see Fig. 3). The gas price for the consumer consists of three major price factors - tax, the resource gas and expenses of the gas company. Tax is subdivided into petroleum tax and sales tax. The system used as an explanatory example here has a hierarchical depth of three levels. It starts with 100% of the available space of a block - this is 100% of the fuel price. In a second step, this block is vertically divided into sub-blocks according to the hierarchy of the system. There are three blocks for tax, gas and the company. In this case, the size shall correspond to the price value they represent. The tax is horizontally separated according to the value of sales tax and petroleum tax. Additionally the price factors can be color coded (tax = red; gas = green; company = blue). The final treemap shows a good overview of how the gas price is composed.

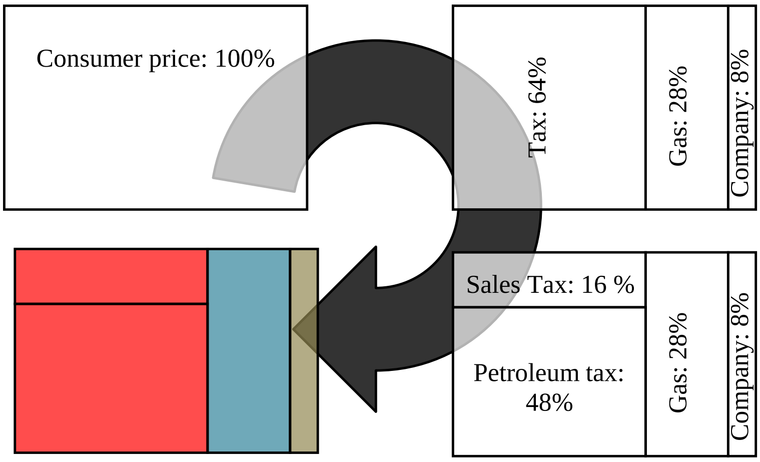

Figure 3 General example of a Treemap

Treemaps were invented in 1991 by Ben Shneiderman [8]. Shortly after their invention, Johnson and Shneiderman formulated the main objectives for treemaps: Efficient Space Utilization, Interactivity, Comprehension and Aesthetics. Those expressed aims were realized in the same publication. Following on, tools evolved and commercial products were created. Examples include the display of economic data on the 2008/2009 financial crisis, business economics, key factors of enterprises and parameters in technical control loops. So far the use of treemaps for analyzing the structure of a product could not be found in literature, as well as treemap tools for engineering design support. Since this is a new field of application for treemaps, it is required to adapt treemaps for this specific task.

Adapted treemaps for Module Lightweight Design

The quantifiable dimension specifies the size (area) of the blocks in accordance with its share in the whole structure. The maximum display area (e.g. by screen size and resolution specified) corresponds to 100% of the quantifiable dimension, reflecting the full dimension of the investigated structure. In our current application with the weight as a quantifiable dimension, the full display area accords to 100% of the products structural weight. The substructures show a surface size according to their contribution to the total weight. The allocation is done by partitioning algorithms. First algorithms were based on the "Slice and Dice" principle [8], where only width or height of a block where divided by the next hierarchical sublevel components. They produced often elongated rectangles. Such treemaps are less intuitive to use, since the resulting areas can be difficult to compare to each other. Later improved algorithms produce close to square boxes. This supports the human visual cognition.

However, the alphanumeric order of the simple "Slice and Dice" algorithm cannot be maintained. So the arrangement of the boxes within the same unit or group is only based on the size criteria. More information about partitioning algorithms can be found in [9].

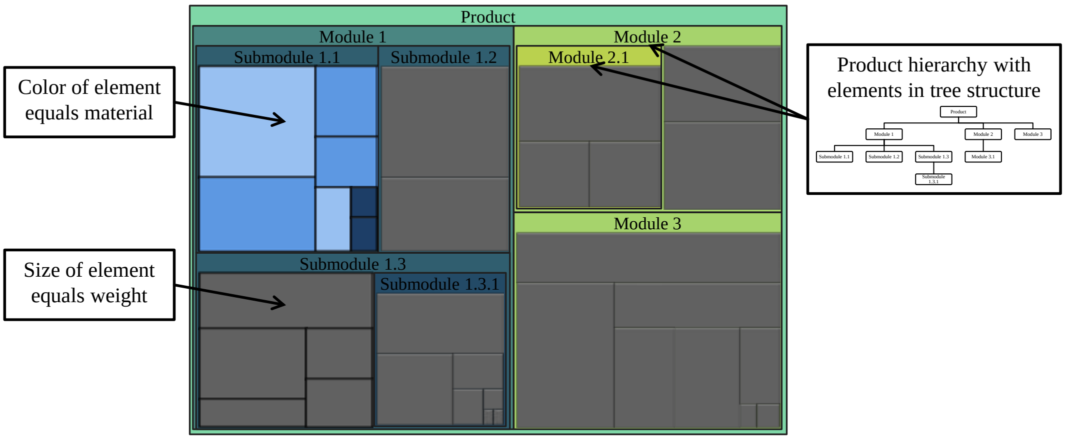

Figure 4 Adapted treemap for the use in Module Lightweight Design

In order to visualize the results of the last optimization loop, it would be helpful to be able to compare the situation before and after the optimization in the treemap. The 100% display area could be related to a fixed number, which originates i.e. from the "before"-situation. The later "after" situation does not use all of the display space visualizing the difference. An animated transition in the representation of the software contributes to a better understanding of the comparison of before and after.

The parts of an assembly or group can be arranged in frames to emphasise their affiliation. The visualization of the grouping can be done by using so called "nested tree maps", which have a border around a group or subgroup. This improves the recognition, which is considered as essential. The drawback is the reduction of useable space for the blocks since the borders take up space as well.

A software implementation generates the displayed information of a database. Complex and large structures implicate the use of special database formats such as MySQL. Small amounts of data can be stored in XML or text files, which do not require additional software. The integration into a CAD system is of interest. A transparent implementation in a CAD system could help to overcome possible inhibitions of the designer using different software with additional interfaces for each task. A manual processing of the data or external storage would then become unnecessary, which would be beneficial.

Available treemap software offers the important possibility of interaction of the user with the tool. Additional information can be made visible by specific interaction events. Examples are the zooming-in on particular groups or the animation between stationary states. In addition, "mouse over" effects enhance the interactive character of the software. In this case, extra properties of a part can be displayed.

Figure 4 shows an example of an adapted Treemap for modular product architecture. The Treemap gives an excellent visualization of the hierarchy of the structure and the weight of components in the structure. The weight of the modules or components can be easily compared, even over different hierarchical levels. This intuitively leads the designer to the hot spots for optimization. Additionally the designer sees the material of a component. There he can find inspirations for optimizations in the different categories of lightweight design. Since the designer sees both the weight and material of the parts, he can consider a material change of certain parts. For the optimization of the structure, further information (like stresses) can be included to the treemaps. Additionally, ideas for merging parts into integral structures can be identified leading to weight benefits by eliminating the corresponding interfaces. Due to their intuitive arrangement, treemaps can encourage the generation of new innovative ideas. They visualize the potential for weight reduction and give the designer an idea on which parts to improve. This approach therefore is not limited to a certain category of Lightweight Design.

5 EXAMPLE OF AN TREEMAP IN MODULE LIGHTWEIGHT DESIGN

For the demonstration of the support, an aircraft galley is chosen. Previously, the galley was analyzed and modularized based on different divisional perspectives by Jonas [10] according to a method by Blees [4]. The performed modularization leads to a concept with an upper- and lower platform module including three hat modules in between. Figure 5 shows a Module Interface Graph for the galley. As shown in the figure, most interactions between galley and aircraft are within the middle section of the galley. Accordingly, the Galley is divided into 3 sections. Besides a mechanical connection between the modules, there are only a few other media or information flows between the modules. This reduces the number of interfaces. The upper and lower sections are found to be predominantly invariant. Both are used as a platform. The middle section is designed to provide the variety demanded by the customer. It is crucial to reduce the interactions between the modules for reducing the weight. This is an important perspective for the modularization to achieve a successful Module Lightweight Design. An advantage of the developed modular approach is the use of standardized modules. Instead of a new design and manufacturing process for each new customer, the efforts can be limited to individual modules. This allows a cheaper standardized development and production.

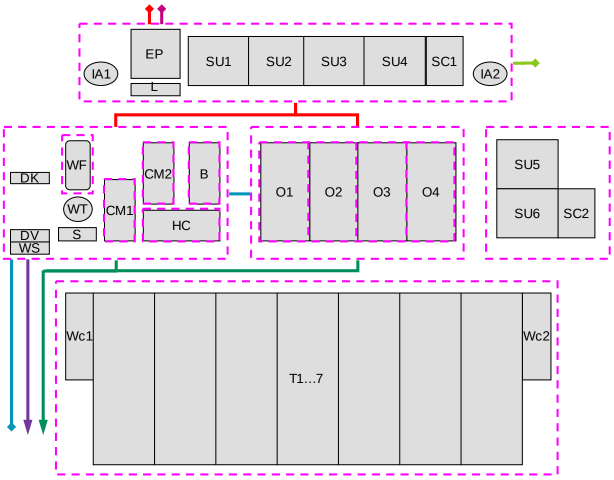

Figure 5 MIG of modularized aircraft galley [10]

The modularization additionally allows decoupled manufacturing processes of modules. Since only certain modules, if any, require a redesign, the production time can be reduced and a quicker response to customers' requests and orders can be achieved. This provides a competitive advantage. In addition, the lower and upper section can be manufactured in stock. This allows a better compensation of product demand variations. Furthermore, there is the possibility to exchange modules afterwards. If requirements for the galley change, it is possible to replace the individual modules. Exemplary situations can be summer/winter flight plan or aircraft sale. For this purpose, not the whole galley, but only a new hat module unit, for example, is required..

In Figure 6 the CAD model of the galley with three different middle sections is shown. The connection interfaces are designed to support the concept of "in field" interchangeability. This requirement aggravates the weight problem as it leads to even more restrictions for the modularization and the interfaces. The standardized interfaces need special attention in engineering design. The geometrical consistency among the different variants has to be assured. This also includes the assembly / disassembly process. An easy assembly of connectors is critical for providing the required flexibility for the airlines.

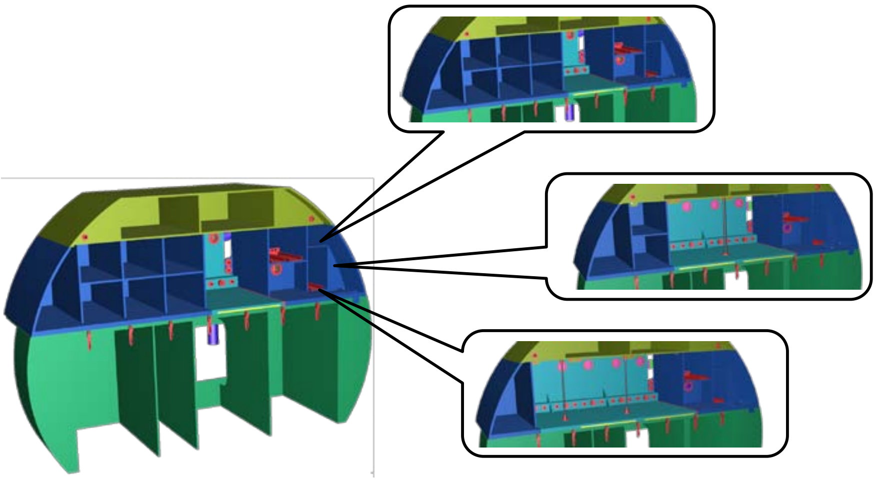

Figure 6 CAD of modularized aircraft galley [10]

For the treemap visualization, a basic export plug-in for a CAD system was created. The hierarchical structure as well as the material data and weight of the parts are directly imported from the CAD system into a treemap program. Thus, the usability was significantly increased. The designer needs to group the part models and assembly models according to the module definition. This is a result of the direct use of hierarchical part / assembly structure out of the CAD system. The structure is partially defined within the modularization. By defining boundaries of the modules, it is also easier for a team of designers to align the workloads.

The research was conducted under the research project “FlexGalley” with industrial cooperation Partner Mühlenberg Interiors, a manufacturer for cabin monuments like galleys. Since the weight distribution data of the real galley is confidential, a modified and simplified version is used to demonstrate the method in this paper. The adapted Treemap visualization is illustrated in Figure 7. According to the modularization, the treemap of the galley is divided into main modules. Using the treemap, some Lightweight Design considerations become obvious. The three modules of the middle section are heavier than the upper and lower section together. For example, the module storage 1 is as heavy as the lower section. Using only CAD-view, this would not become obvious. A standard ABC analysis on module level would give similar results. However, this would give no insights into the modules’ composition meaning their subassemblies and single parts accounting for the weight. In the Treemap, designers and decision makers can see the modules’ composition and the material of the parts. It shows that the lower section is almost completely made of low density sandwich panels. The storage 1 module has many parts made from aluminum alloy, which all weigh almost the same as a sandwich panel. Therefore, the huge number of small parts accumulates to a noticeable weight. Often these parts show many interfaces (differential structure). As a result, the necessity of these interfaces has to be checked for identifying weight reduction potentials. When the designer has become familiar with the visualized structure of his products, he will be better able to match the CAD drawing intuitively to parts and their weight contribution to the overall weight. On the PC workstation, a treemap software offers additional interactive features such as zoom in and out on the hierarchy level. Also additional information is shown (e.g. exact weight, volume, material) with a mouse-over effect when selecting a part.

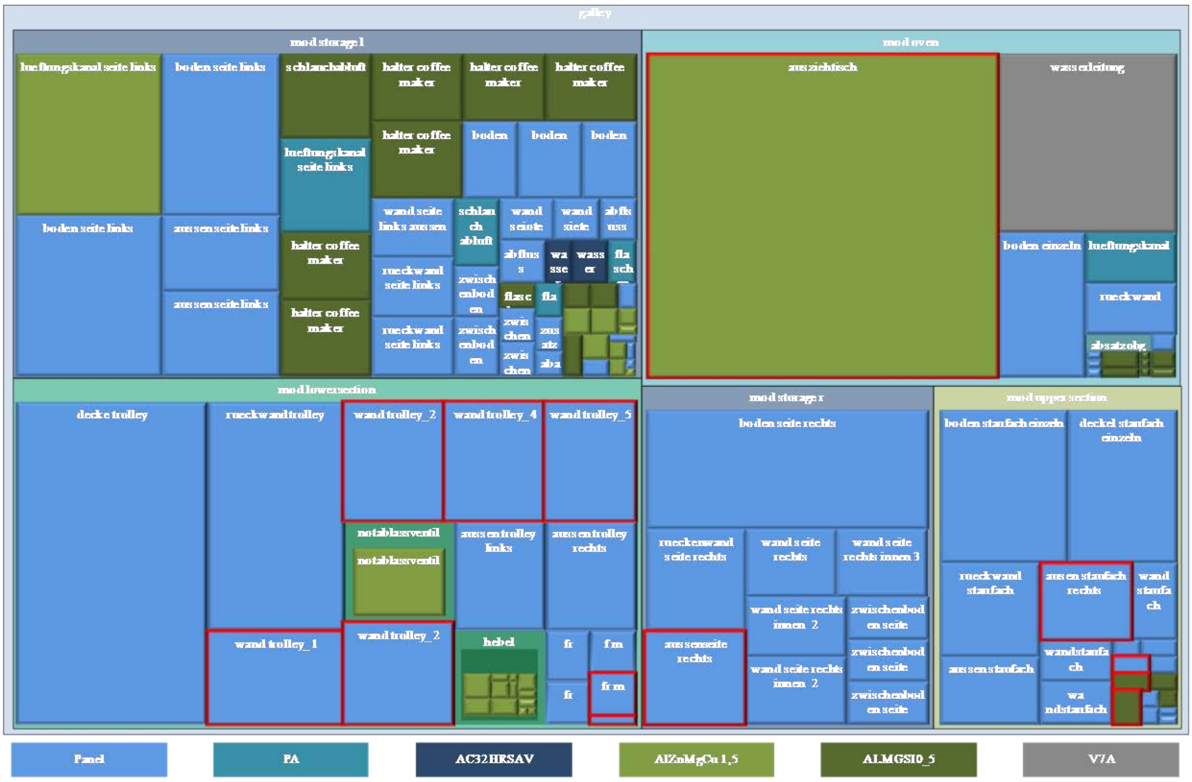

Figure 7 Treemap of the modularized aircraft galley taken from data of cabin monument manufacturer Mühlenberg Interiors.

By using the treemap, several potentials for Module Lightweight Design were identified. The concerned elements are marked with a red frame in the treemap. Figure 8 exemplarily shows optimizations.

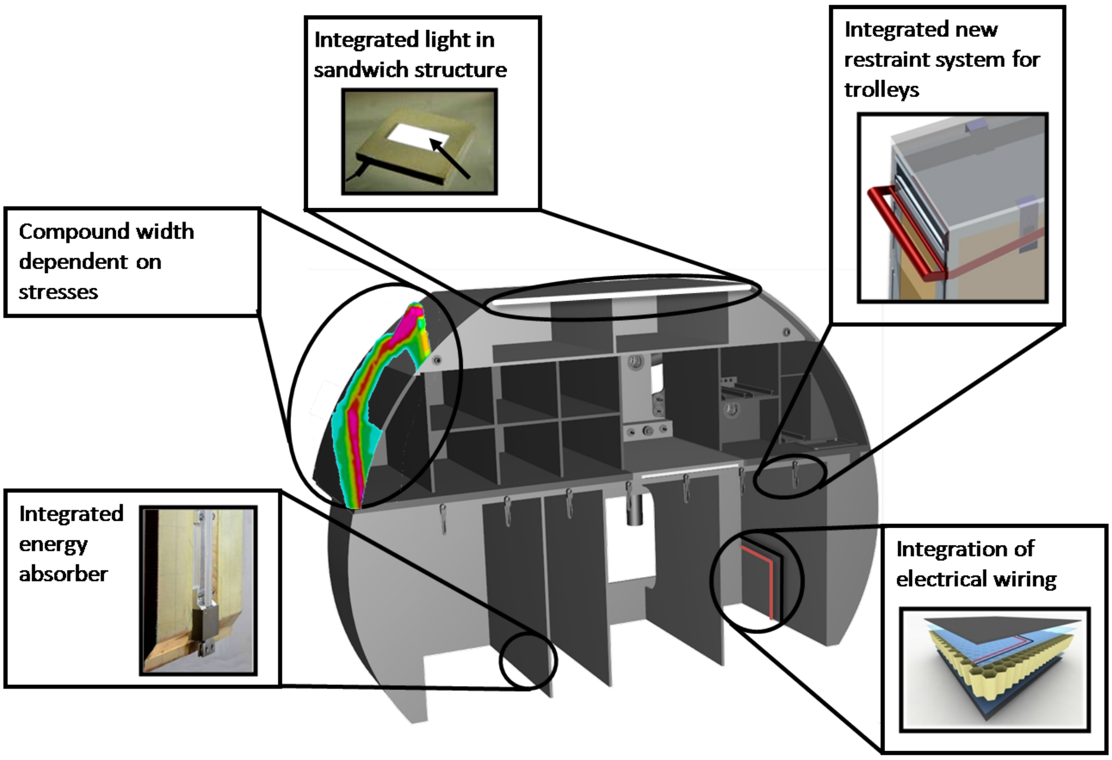

Figure 8 Lightweight Design optimizations of the galley

As an example, energy absorbing elements were integrated for reducing load collectives in case of emergency landings, which the structure needs to bear. After that, the structure of the sandwich compound was optimized according to the given stress. This resulted in optimized Glass Fiber Reinforced Plastic – Honeycomb sandwich panels. The compound width was optimized by locally strengthening the panel.

The components for providing the light function of the galley in the upper section were identified to be relatively heavy. As a solution, an integration of light into the sandwich panels is not only attractive due to weight reduction, but also for design reasons. By using a new combinatorial method [5] the integration of electro-luminescent (EL) film between the Glass Fiber Reinforced Plastic (GFRP) sheets was derived. This offered additional weight benefits, because formerly used isolating elements of the EL-structure were not needed any more. The GFRP sheets realize the isolating function.

The integrated new restraint system for the trolleys itself is heavier than the former system. However, it offers enhanced ergonomics for the cabin crew. Additionally, a better fixation of the trolleys and, therefore, noise and vibration benefits were achieved. The additional mechanical elements for noise reduction are now redundant and overall weight can be reduced.

In the aviation sector electronic cables have to be fixed to the structure by a holder. Therefore, inserts have to be put inside the sandwich panel. These small parts accumulate to a considerable weight. The first approach was to put the cable between two GFRP sheets of the sandwich panel. In a second approach, the wiring was printed onto the GFRP sheet with a conductive ink. The first sheet acts as substrate carrier for the ink. The second outer sheet isolates the electric path. This lowers the amount of attachment points significantly. A drawback lies in service and repair aspects. In case of a cable failure, the whole module or at least the sandwich panel needs to be exchanged.

Overall, the treemaps gave a good guide to find potentials for Module Lightweight Design. Of course, the designer has to use this information and still look for a solution using his knowledge and creativity. The visualization helps to support this process by decreasing the complexity.

6 CONCLUSION

Modularization is a promising approach to providing the variety demanded by the customer. The increasing of weight due to interfaces has to be tackled with a consequent implementation of the Module Lightweight Design concept.

Treemaps offer an easy and intuitive way to visualize weight distribution and the resulting potential for Lightweight Design in respect to a product's hierarchical architecture. This visualization can easily display several thousand parts to visualize, as proven in IT applications [8]. The Modularity, even on subsystem level, is easily visible.

The proposed visualization by adapted treemaps fulfills the task to support Module Lightweight Design in a very intuitive way. However, the designer is still the source of a good solution.

ACKNOWLEDGMENTS

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