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DEVELOPMENT OF MODULAR PRODUCTS UNDER CONSIDERATION OF LIGHTWEIGHT DESIGN

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ABSTRACT
Whether it is reduction of complexity during development or individual configuration for the consumer, modular products have many benefits throughout their product lifecycle. It is not surprising that many products are based on this principle. Along with modularisation, the tendency toward lighter, more efficient products is growing. Lightweight design of moving masses is crucial, particularly in the transportation sector. However, design conflicts between the two principles are hard to resolve. Modularised products tend to be heavier than non-modular products. Overcoming this conflict is an important step in serving the individual consumer and meeting environmental responsibilities.
The effects of modularisation on lightweight design are outlined. A strategy to handle the identified impacts is then presented.

Keywords: Modularisation, Lightweight Design, DSM

1 INTRODUCTION
In 2008 a modularisation approach for an aircraft galley was designed to reduce the inner variability while maintaining outer variability [1]. The results were promising but with one major drawback: weight. Several lightweight design optimizations [2] where made to reduce galley weight. Some weight drawbacks in the modularisation concept could not be assigned to specific parts nor actioned. In a small comparison with a few similar modularised and non-modularised galleys of competitors, the modularised concepts always fell short in the weight category. In the aviation industry, this extra weight is unfavourable in the purchase decision of the airline. This is obvious when the impact of additional weight in the aircraft is examined. Because an aircraft is designed to withstand high acceleration in an emergency, weight increase of a component always has secondary effects on the structure. The additional weight increases the load, which has to be absorbed by the structure. The structure may need to be reinforced to sustain this, creating more weight gain. The propagation of weight in aircrafts is typically around a factor of 4 [3], for example, if an aircraft has to carry 100kg additional weight, this leads to a weight increase of 400kg in total.
A modularisation has to be at least weight neutral or the costumer will not accept it. However, to capitalise on the modularisation concept, the additional effort required for the necessary weight optimisation in engineering and production has to be kept at a minimum. The question of how modularised products can be efficiently developed using lightweight design therefore arises.
Based on a literature review, the interdependencies between modularisation and the lightweight design concept are outlined and the main conflicts between them are identified. A supporting system model is then presented as the basis for modular lightweight design optimization. The strategy is trialled on the aircraft galley and then discussed.

2 MODULARITY AND LIGHTWEIGHT DESIGN
The section begins with a critical reflection of the similarities and differences between modularisation and lightweight design. Based on a literature review by Salvador [4], the characteristics of the modular concept and its transformation into the product are compared to lightweight design principles. There are multiple definitions of modularity as a result of the many perspectives on the term. Salvador summarises them and divides the perspectives into component commonality, component combinability, function binding, interface standardization and loose coupling [4].
The effects on lightweight design of the different perspectives may be similar; the main drivers for weight increase and the positive effects of modularisation are outlined.

2.1 Component commonality and lightweight design

Commonality of components in modularity is most often seen as the reuse of standardized components in different parts of the product and/or different product variants. This commonality view of modules may define them as an independent functional entity rather than just reused parts. The use of components in different applications (even if they are only slightly different) causes over-sizing of these parts [5] because they have different requirements in each configuration. This is in clear contrast to lightweight design, where over-sizing should be kept at a minimum [6]. Within a product, the over-sizing of a reused component may be traceable. However, the consequences in additional weight across a product family are hardly tangible. Over-sizing of modular products is often inevitable and, due to the complex interaction of modules in different product variants, it is often not quantifiable and hard to optimize.

To illustrate this effect, Figure 1 shows the variants of a cantilever. The variants consist of the same set of modules. Accordingly, the modules have to fit all the requirements across the variants. Variant V 1 is the initial state of the cantilever. All modules are designed with a minimum of over-sizing. In Variant V 2, the load F increases so the modules have to be adapted to withstand the additional load. With the load increase in module M 4, the weight propagation due to structural reinforcement occurs throughout all modules. It ends up with significantly more weight than the module set. In variant V 3, the position of module M 4 and M 3 is changed; due to this different position the load induced by M 3 has to be conveyed through to M 4 in the remaining modules. Therefore, M 4 in particular has to be reinforced and so gets heavier. This is just the first round of adaptation. The cycle repeats until a stable state is reached. In many variants, it ends with an undesirable over-sizing of modules.

Figure 1 shows a fractional weight propagation tree for module 4. The cycle begins in Step 2 of the propagation because M 4 indirectly influences itself. With an increasing number of variants and modules, such trees branch out rapidly, visualising the complexity.

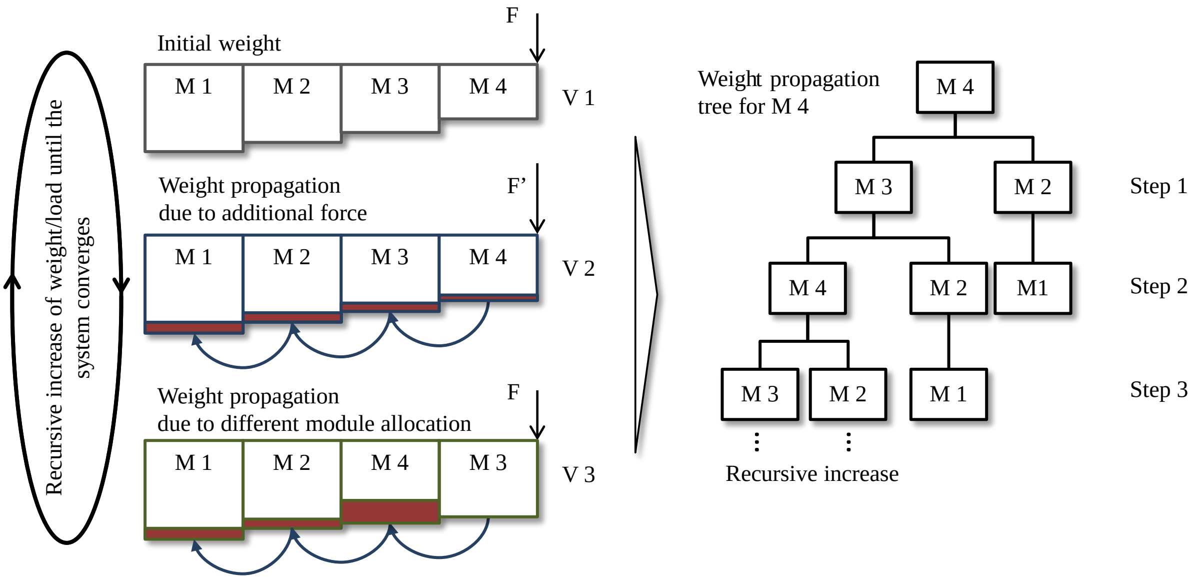

Figure 1 Weight propagation throughout the variants in modularised designs

2.2 Component combinability and lightweight design

Component combinability is building product variants out of the combination of a given set of modules. This combinability of components to maximize the variety of created products to fulfil customer needs is a widely understood meaning of modularity. This combinatorial freedom has to be reflected within the components. Thus, the universal application of modules leads to higher requirements, which result in functional and structural over-sizing. Variant 3 of Figure 1 shows the combinability of a module set. Module 3 and module 4 are both combined with module 2. This leads to higher requirements for module 4, which results in more weight.

2.3 Function binding and lightweight design

The concept of function binding is a specific functionality linked to one module, enabling the costumer to combine functions for their desired use. This is the opposite to integration of functions, which is a key concept of system lightweight design. Rather than separating functions into different modules, functions should be integrally combined in the product. With integration of function, the load-carrying structure has additional functionality, consequently, components and weight can be reduced.

For example, a set of modules should be able to build a motorized aircraft and a glider. The plane would need a module for fuselage, wings, engine and tank. For the glider, the engine and tank module could be spared. This has the disadvantage that the wing and tank must be split into separate modules. Modern aircrafts store fuel in the wing, thus wing and tank are combined to reduce weight. A modularised product family could not benefit from this lightweight design principle.

Independent functions may lead to redundant sub-functions within the modules [7], causing additional weight.

2.4 Interface standardisation and lightweight design

According to this view, interfaces should be standardised so that variants can be combined via a universal interface. This leads to even more design restrictions: over-sizing of the interface is the result. These interfaces may be designed for easy reversibility, e.g. for maintenance reasons or re-configurability in product system modularity. This reversibility requirement prohibits the use of lightweight interface connections, such as adhesive bonding, soldering and welding, because they are non-reversible.

Standardised interfaces are often restricted in their dimensions, because they have to fit in multiple designs. The size restriction, in combination with possible high loads of a variant, results in a high stress peak. This stress peak should be avoided in lightweight designs; instead, an evenly distributed load application should be favoured [6].

2.5 Loose coupling and lightweight design

In this concept, the cohesiveness of interactions within the module is stronger than external ones. Due to a reduction in interactions between modules, a specific module may have to fulfil certain functions itself. Another module may need this functionality, but each module has to provide this function individually due the loose coupling. This redundancy leads to functional over-sizing.

Göpfert mentions that a strong focus on the modules runs the risk of losing track of the overall product [7]. In lightweight design, interaction of the whole system to reduce the weight is a significant factor [8]. Loose coupling also allows building a multitude of variants, which leads to a complexity and requirement increase.

2.6 Summary

In the literature review, no specific advantage to modularisation for lightweight design could be found. However, lightweight design could benefit from the overall positive effects of modularisation. Dividing the product into small, hierarchically-structured parts leads to better understanding of the system, so the concept and design phases profit. System interrelation can be more easily identified due to clear separation. The integration of function approach can be applied at a module level [2]. The modularisation leads to multiple reuse of a part, thus effort for development and production enhancements per module can be increased. These scale factors can be used to reduce the module's weight.

As different perspectives of modularity are compared against lightweight design, the same conflicts occur. The major drawbacks of modularisation arise in three categories: weight increase due to interfaces, over-sizing, and complex design interactions.

Göpfert describes a way to set weight targets for functions or corresponding modules in his tool METUS. This reduces the weight, but does not include the effect on the system. It becomes clear that modularity and lightweight design are in some ways opponents. Thus, a strategy to overcome the conflicts and benefit from both is needed. A strategy for efficient reduction is presented in the next section.

3 OPTIMIZATION STRATEGY FOR MODULARISED LIGHWEIGHT DESIGN PRODUCTS

Figure 2 shows the consecutive steps of the approach for modularised products using lightweight design. Starting from the Module Interface Graph (MIG) visualisation of the variants of a modularised product family, the data is converted into a node-link representation. In the next step, these node-link diagrams are transferred into Design Structure Matrices (DSMs). All modules are globally defined to address all variants simultaneously, hence the DSMs are interlinked. With this system model, the optimization can address the previously stated conflicts. The optimization includes 3 steps to meet the weight target. First the interfaces of the modules are evaluated. Secondly, the over-sizing of the modules is reduced by matching module requirements across the variants. Last, for efficient lightweight design, weight-sensitive modules are traced and weight optimized. The three weight reduction steps have an increasing level of effort and costs. The degree of modularisation and the robustness against new variants or changes are reduced. Therefore, as soon as the target weight is reached optimization can be stopped to ensure a cost efficient and robust design.

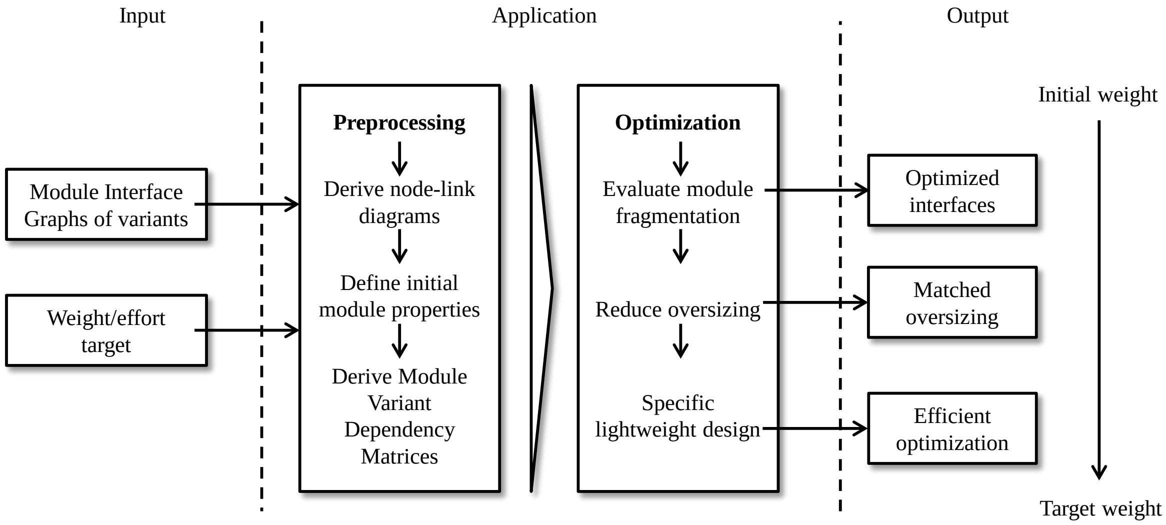

Figure 2 Overview of steps

3.1 A system model to support modular lightweight design

The aim of the system model is to provide the basis for the optimization of the modularised product family. It consists of an abstracted model of the product variants and their interrelations. It only contains information needed for the optimization to reduce complexity. The three steps are as follows:

Derive node-link diagrams

The output of the previous modularisation defines the modules, their interactions and, if applicable, the variants. The Module Interface Graph visualises this output and shows the modularisation in a transparent and intuitive way. This is used as input for the system model. The MIG 2D shapes of the modules are transferred to nodes in the node-link diagram. For this optimization, unnecessary complexity drivers are removed, hence the interactions between the modules, such as electrical power flow and media flow, are taken out, leaving only the relevant interface load interactions.
Therefore, interface loads link the nodes (modules) together. Figure 3 shows the MIG and the corresponding node-link diagram representation of a modularised product.

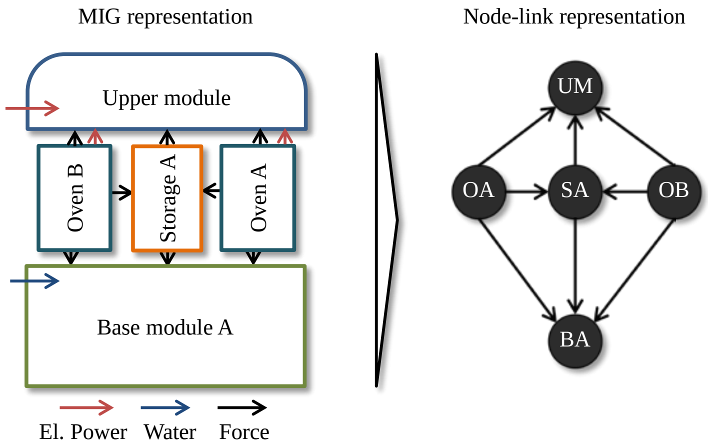

Figure 3 Derive node-link diagram from MIG

The load exchanged between modules represents interactions between the nodes. Depending on the level of detail of the product development phase, this information can be estimated, calculated, simulated or measured from a prototype test. To include weight propagation, a first estimation of a modules interface load consists of the forces of the accelerated module mass and the enforced load on the acting module. For modules with multiple outputs, the forces are split up, represented by a factor α. In the example of Figure 4, the interface conveys load from module 2 to module 1. The load increases with an increase in the mass or the interface load of module 2.

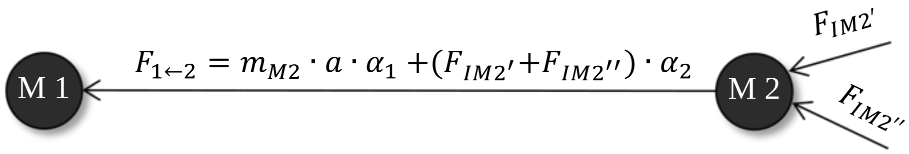

Figure 4 Interrelation of modules through distributed load

For a modularised product family, all variants of interest need to be converted into node-link diagrams. Figure 5 shows three different product variants and the corresponding node-link diagrams in different views. It is possible to stack these diagrams on each other. With a collapsed view of the node-link diagrams, the multitude of relations is visible. The variants consist of the same set modules. Therefore, the requirements of a module are defined by the variant in which the module occurs. This forms a connection between the node-link diagrams. If the collapsed view is rotated, the network of relations expands and the module connections are visible. The result is a multi-layered network that represents the modularisation of the product family.

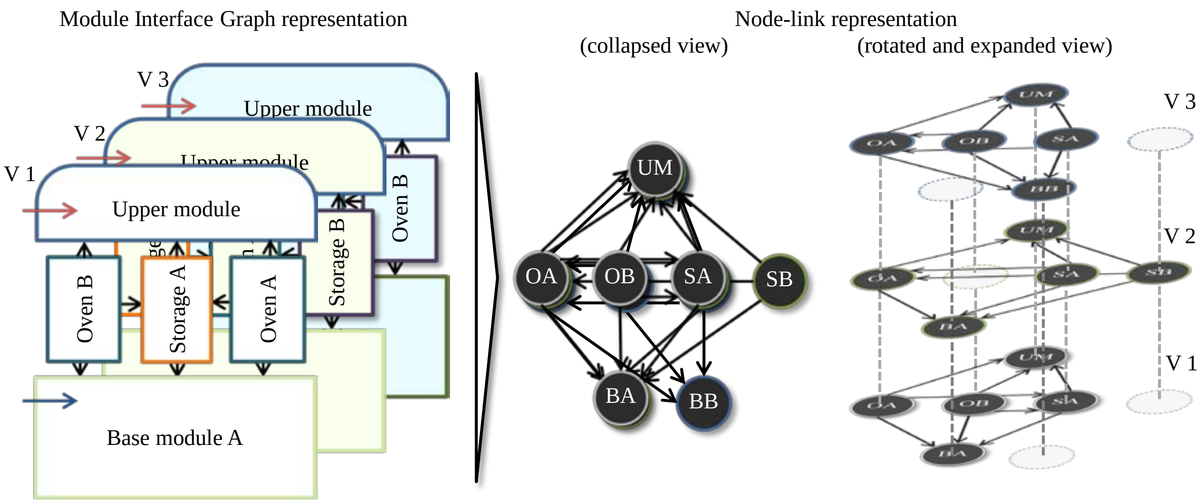

Figure 5 MIGs and multi-layered node-link representation of three product variants

Define initial module properties

The different modules are derived from the MIG and the essential data for the optimization process is added. To simulate the behaviour of the network, the following properties of the modules are needed:

- Payload: Not structure supporting masses.
- Weight of the structure: Weight of the load-conveying structure.
- Weight of interfaces: Estimated weight of additional interfaces due to previous modularisation.
- Weight/load correlation: Increase or decrease of the structural weight, due to additional or reduced loads. For simple components, such as slender struts, the load-dependent weight can be calculated analytically [9]. Depending on experience and development status, this factor can be estimated or calculated. Discrete steps of weight and maximum load can often be identified, for example, additional layers of Carbon Fibre Reinforced Plastic in a sandwich panel rise in discrete steps in weight and maximum load.
- Max. structural load: The module's maximum structural load from the corresponding variants. This is a requirement for the module weight/load correlation.
- Max. acceleration: Maximum acceleration of the module is necessary as we consider lightweight design of moving masses.

Derive Module Variant Dependency Matrices

Node-link diagrams and matrices are both visualisations for graphs. They can be transferred from one to another. In this case, the modules are the nodes and are represented by a row and column in the matrix. An entry in the matrix links two modules together. The entry value is identical to the link value from the node link diagram. It describes the conveyed load between two modules. The total load output is summarised for each module.

The previously described properties of the modules are entered into a matrix. The maximum load value per module is derived from the complete set of variants (Figure 6). This guarantees that the highest requirements are included in the development of the modules.

As the maximum load has an impact on the structural weight, a higher load increases the module's weight. The interface loads in the variants are module weight sensitive; hence, a higher weight increases the interface load. Because of this correlation, a circular dependency between the matrices occurs. For a stable system, this circular reference has to converge. In most cases, the initial modularisation is over-sized, therefore all modules fulfil the maximum requirement and the system is valid. If this is not the case, the modules that do not fulfil the requirements can be traced back in the system model and adapted accordingly.

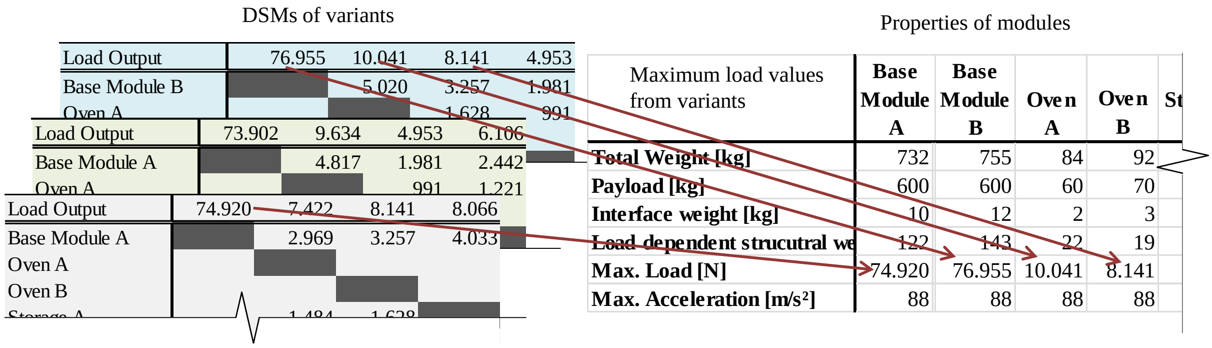

Figure 6 Matrix representations of the variants and modules.

The matrices represent the weight and load dependencies between the modules across the variants. This Module Variant Dependency Matrices is the basis for the following optimization.

3.2 Optimization of the module variant matching

A good balance between decision criteria needs to be found for a good optimization. The system model of the modularised product family must provide evaluable information to make these decisions. As per the conflicts outlined above, the interfaces have to be evaluated whether they are needed or not, the oversizing of the modules has to be reduced, and an efficient lightweight design has to target product weight-sensitive modules. Execution of the steps is described below.

Evaluate module fragmentation

Pahl and Beitz portray the risk of unnecessary increases in interfaces with unnecessary maximisation of modularity [10]. The additional weight of the interfaces in a modular design has an adverse impact on the lightweight design of a product. To reduce this effect, the interfaces are critically evaluated. First, the necessity of an interface is reconsidered, then the weight increase impacts of the remaining interfaces are evaluated, and, if required, appropriate actions are applied.

To achieve this, a search in the system model for modules that are directly connected with each other throughout all variants is conducted. If such a combination of modules is found, the modules can be merged together. In this context, Salvador refers to a “weak product system modularity” concept [4]; this combination of modules lacks the requirement of interface reversibility. The adverse effect of the interface on product weight is eliminated, but the degree of modularity decreases. The remaining interfaces have to be critically evaluated in a decision matrix. Therefore, the weight/load factor of the interface is rated against its importance. The interface importance of the module is taken from a review from the former perspective-based modularisation. The weight/load factor is taken from the interface weight and the conveyed load. The decision matrix indicates whether to weight-optimize, realize, remove or decide on the interface (Figure 7).

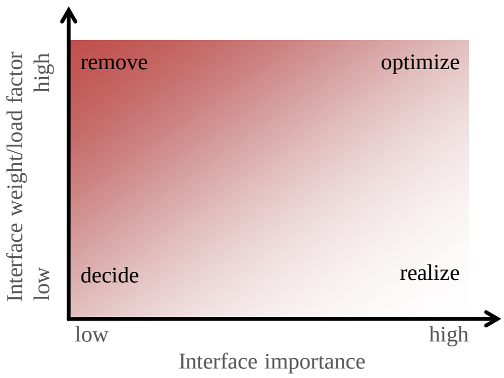

Figure 7 Decision matrix for interfaces

Reduce over-sizing

The requirements across the variants and the resulting weight propagation cause the over-sizing of a modularised product family. For a minimum of over-sizing, the requirements of the variants have to be matched. Due to the complexity of the module variants network, this is not really achievable by hand. The system model can be used to match this over-sizing. The first step is an incremental decrease in the weight of one module where the maximum load is below the module’s load capacity. With the decrease in weight, the load capacity of the module converges to the necessary one. Secondly, the load conveyed to the connected modules also drops because less weight is accelerated and so less force is conveyed. Hence, the connected module’s weight can be reduced as well. This is incrementally done until a minimum is reached. The over-sizing of each module is minimized and matches the variants overall. If this iterative decrease in requirements, corresponding load and weight only reaches a local minimum, enhanced algorithms can be used to find a global minimum. Figure 8 shows the weight reduction propagation of module OA, from the example above. The structural weight of the modules influenced reduces with a snowballing effect.

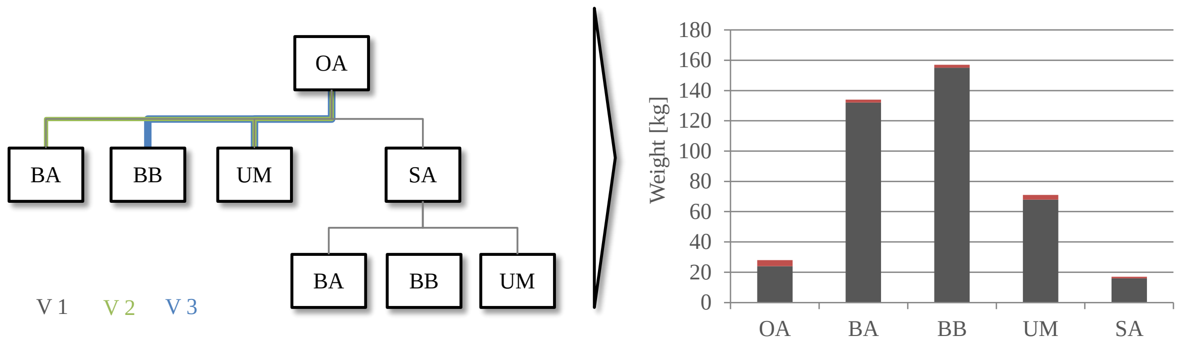

Figure 8 Weight reduction propagation of module OA and resulting effects on other modules

Module-specific lightweight design optimization

The previous two optimizations may have relatively low costs because they do not alter the basic design of the modules or apply costly lightweight design optimizations. However, if the weight target of the product family is not reached, additional lightweight design optimization steps have to be taken. To achieve this, the weight/load factor of specific modules is optimized (minimized): the module's load capacity is increased while maintaining the weight or the load capacity is kept while reducing the module's weight.

For optimum efficiency, the goal is to select modules that have a big impact on the product family's overall weight. The weight sensitivity of a module describes how the overall system reacts to a weight change in the module. Therefore, weight change of the whole product family is set in relation to the weight change of the module.

$$\varepsilon \equiv \Delta W_{PF} / \Delta W_M \qquad (1)$$

If this is correlated with the effort (cost) of reducing the weight of the module, an optimization efficiency plot can be drawn (Figure 9). The modules to optimize can be determined with this efficiency plot. The maximum reasonable number of modules is limited by modules in the upper right side of the plot. An evolutionary algorithm (EA) is then run on the module definition matrix. The EA has the goal of decreasing the weight/load to minimize the product family weight until the target weight is reached. The EA has the following boundary conditions:

- Change modules with high weight sensitivity (ε) and high ratio of module weight reduction to effort
- Keep a specific minimum weight per module
- Keep over-sizing of optimized modules equal
- Keep a specific minimum over-sizing

As the algorithm tries to reduce the weight, the secondary weight reduction of modules, as described above, is also included. This ensures an efficient weight reduction that incorporates the whole system rather than isolated modules. The percentage of weight decrease after each optimization step is presented on the right side of Figure 9.

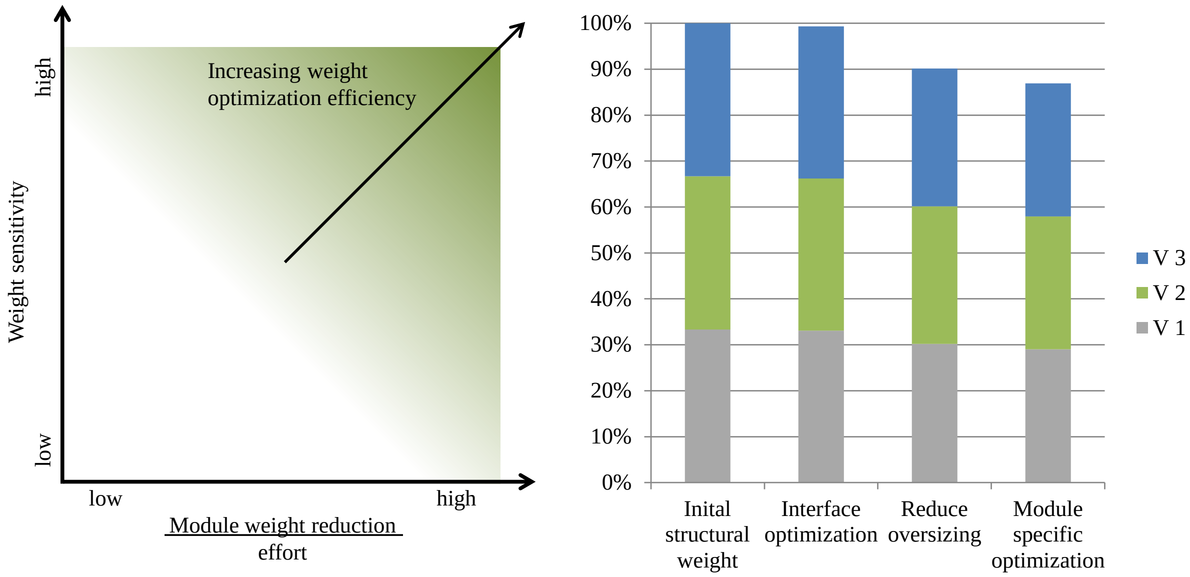

Figure 9 Optimization efficiency plot and weight reduction after each optimization step

The result of the EA provides the input for the development of the modules. The requirements are all matched for an efficient lightweight design of the modularised product family. With this matching of modularisation and lightweight design, additional information for efficient development is created. As the development of the product family matures, the information for the system model gets more exact, hence the prediction and optimization becomes more accurate.

4 EXAMPLE

The aircraft galley is used as an example. Previous projects, a modularisation concept [1] and its CAD realisation of the aircraft galley [9], are the input. The CAD model showed that the modularised concept, despite other optimizations [2], led to a too-heavy structure, hence, this approach was created. The MIG visualisation of the previous modularisation concept [1] was the starting point for validating the approach. The MIG was converted into a node-link diagram using a customized software tool (Figure 10). Module boundaries and components are both visualized in the MIG and the software tool. The pre-processing was carried out for ten different configurations of the galley family.

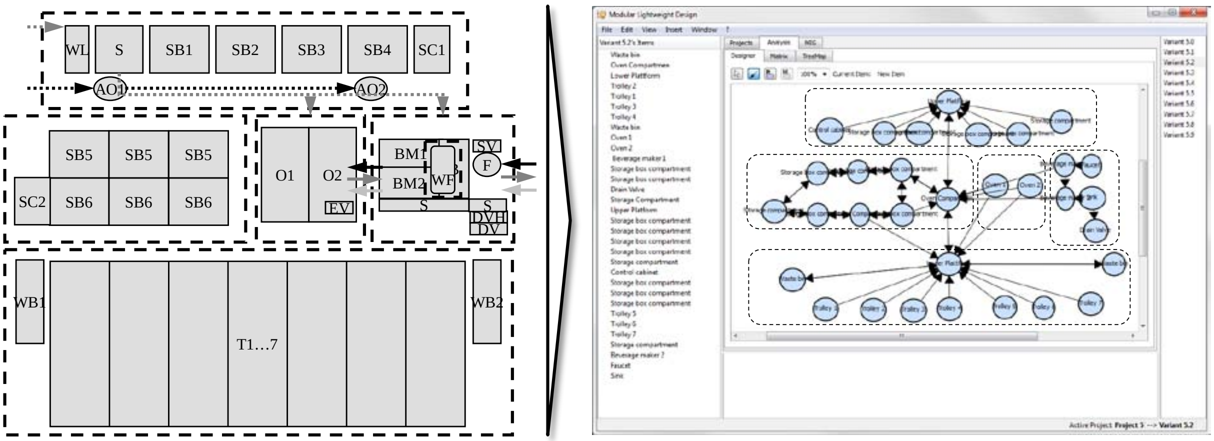

Figure 10 MIG of Galley (according to [1]) converted into a node-link diagram

Following this step, the information for the modules was gathered. The CAD model (Figure 11) enabled accurate aggregation of the initial structural weight, payload, and interface weight. The maximum acceleration is also specified to 9 g. From a former FEM analysis, some interface loads could be calculated and serve as reference points. The interface loads were then interpolated. In the first step, the weight/load correlation was estimated with a high, medium and low strength design per module. The correlation was then interpolated using these points.

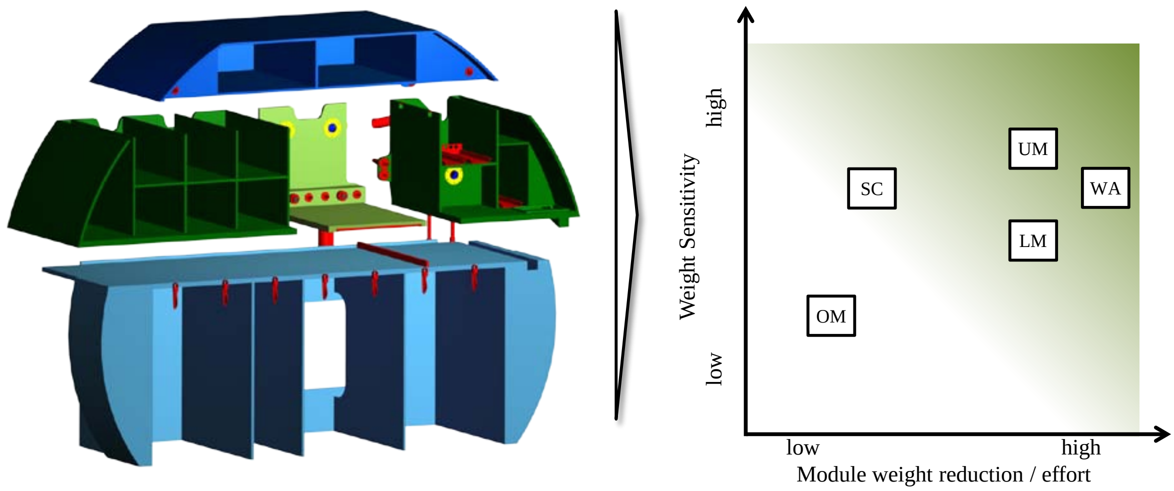

Figure 11 Modularised Galley (according to [11]) and optimization efficiency plot

The product family was optimized according to the steps above (Figure 11). The lightweight design matching of modules and variants provides the basis for further development of the modularised product family.

5 CONCLUSION

This approach attempts to add more transparency to the development process in modularised lightweight design products. A good balance between the decisions of which interface to reduce, which maximum load is required and which module has to be optimized is required to even out the conflicts between modularisation and lightweight design. An initial validation using the example of an aircraft galley proved the substantial benefits of the outlined approach.

Undoubtedly more work needs to be done. More in-depth research of the relationship between modularisation and lightweight design is needed to ensure that all important aspects are covered. The possibility of interlinking the system model with enhanced CAx tools, such as FEM and topology optimization, should be investigated to more accurately predict weight propagation. Nevertheless, the need and opportunities for efficient modularised lightweight design for product families is clear.

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