13TH INTERNATIONAL DEPENDENCY AND STRUCTURE MODELLING CONFERENCE, DSM'11
CAMBRIDGE, MASSACHUSETTS, USA, SEPTEMBER 14 – 15, 2011

TRACING OF WEIGHT PROPAGATION FOR MODULAR PRODUCT FAMILIES

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ABSTRACT

Modular product strategies are very popular in product development, especially for variant-rich products where modularity benefits economies of scale due to commonality. In weight-driven sectors such as aviation, modularity is not pursued consequently. Developers fear a performance loss caused by additional design constraints and weight. This paper demonstrates a way to effectively reduce this performance deficit in lightweight modular designs. Components or modules with high sensitivity to weight propagation across the product family system are traced using a DSM-based system model. This allows specific optimization of these modules.

Keywords: Lightweight design, product families, modularity

1 MOTIVATION

Modularity is a gradual property (Pahl and Beitz, 2007), therefore most products use hybrid modular-integral designs (Ulrich, 1993). In the range between modular and integral, modular design is not the ideal solution for performance-driven products (Hölttä et al., 2005). Despite the increasing use of modularization methods in product development, it is not used in the design of products where size, weight and efficiency are important (Whitney, 2004) but is used in products of mass customization with a high number of variants.

Both design drivers meet in the design of aircraft interiors. A highly customizable product that requires high weight performance is usually requested by airlines. Currently, interiors are individually designed and tested. Manufacturers face an ever-increasing demand for flexibility while retaining low shipping quantities per variant. They seek to meet this demand with modularization concepts. Blees introduced a modular concept for an aircraft galley in 2009 (Blees et al., 2009). The concept garnered broad acceptance, but the manufacturer was concerned about weight increase. Hence, the performance trade-off due to modularization should be efficiently reduced. A way to identify key modules for weight reduction by tracing module weight propagation is presented here.

2 MODULAR PRODUCT FAMILIES AND LIGHTWEIGHT DESIGN

The question of whether modularity inhibits the lightweight design of a product is the focus of this research. Modularisation alters characteristics of a product family's components so that they become modular. Salvador relates product system modularity to the following definitional perspectives found in literature: Component separability, component commonality and component combinability, which requires interface standardization and packaged function binding (Salvador, 2007). Interferences can be recognized when principle lightweight design rules (Wiedemann, 2007) are compared to the physical transformation of modularity perspectives. A modular structure adds weight because of additional interfaces, over-sizing (dimensioning) of the structure, and increasing complexity in requirement definition.

For many products, this weight increase can be tolerated, but for lightweight products, additional mass is critical. Extra mass in accelerated objects causes additional load, causing a reinforcement of the secondary structure, thus more weight is added. In aviation, such propagation of weight typically causes a four-fold weight increase over the original weight increase (Hertel, 1980; Wiedemann, 2007). For example, Figure 1 shows a cantilever composed of four modules. Variant 1 is designed for load F with no over-sizing of the modules. In variant V2, the force increases (F') so module M4 has to be reinforced. Ultimately, all other modules have to be adapted, with a weight increase across all modules. A snowballing of weight propagation occurs.

This module may be reused across products in a product family. In Variant 3, Module 4 has switched position with Module 3. In this case, M 3 influences M 4, hence a recursion occurs when reused within the product family. Therefore, instead of limiting the weight increase to one product, the whole product family is affected. In Figure 1, three steps of weight propagation of module M4 are shown.

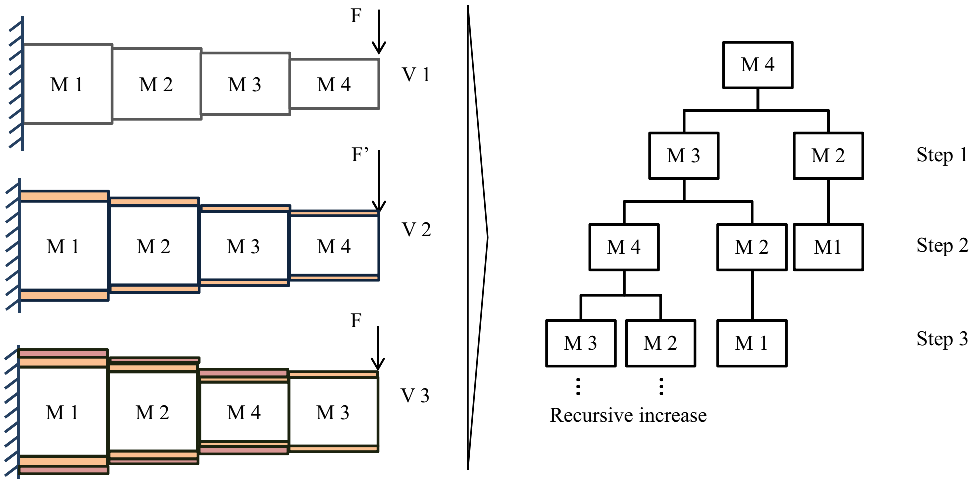


Figure 1. Weight propagation of a modular product family

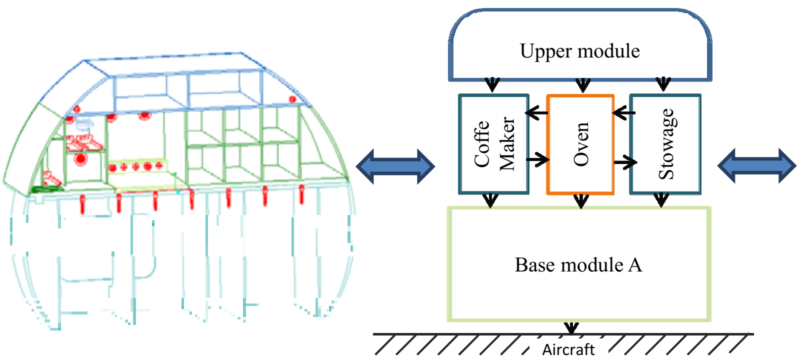
This effect of weight propagation is the same for weight reduction: decreasing the weight of one module can positively affect other modules (an analogy can be seen in risk propagation cf. Clarkson et al. 2001).

Lightweight design is not an end in itself, it has to fulfil a purpose (Klein, 2007). Hence, almost any product can be weight-optimized further. To optimize a modular product family's weight efficiently, the modules with the highest sensitivity to the whole system have to be identified. The weight propagation of each module has to be traced.

3 TRACING WEIGHT PROPAGATION

In this approach, the modules have been defined by a previous modularization (Blees et al., 2009). The focus is on finding an efficient weight reduction approach by selecting weight sensitive modules.

The load exchanged between modules is critical to describe the system. A DSM with the modules as elements and mechanical loads as relations is created. Figure 2 shows a simplified aircraft galley and the corresponding DSM.



	B_M	C_M	O_M	S_M	U_M	AC
B_M						x
C_M	x		x			
O_M	x	x		x		
S_M	x		x			
U_M		x	x	x		
AC						

Figure 2. Simplified aircraft galley with modules and corresponding DSM

For an initial estimation, a transmitted load ($F_{tB->A}$) from Module B to Module A is defined by a dynamic load due to acceleration (a) of the module's mass (M_{mB}) and transferred load (F_{tB}). Factor α is needed when the load is split into more modules.

$$F_{tB\text{->}A} = M_{mB} \cdot a \cdot \alpha_1 + F_{tB} \cdot \alpha_2 \quad (1)$$

This is used for a simplified description of the load interrelation between two modules. A row of the DSM gives the total load of a module in a specific variant. This DSM is carried out for each product family variant. Figure 3 shows an example of simplified aircraft galleys, the corresponding digraph network and DSMs.

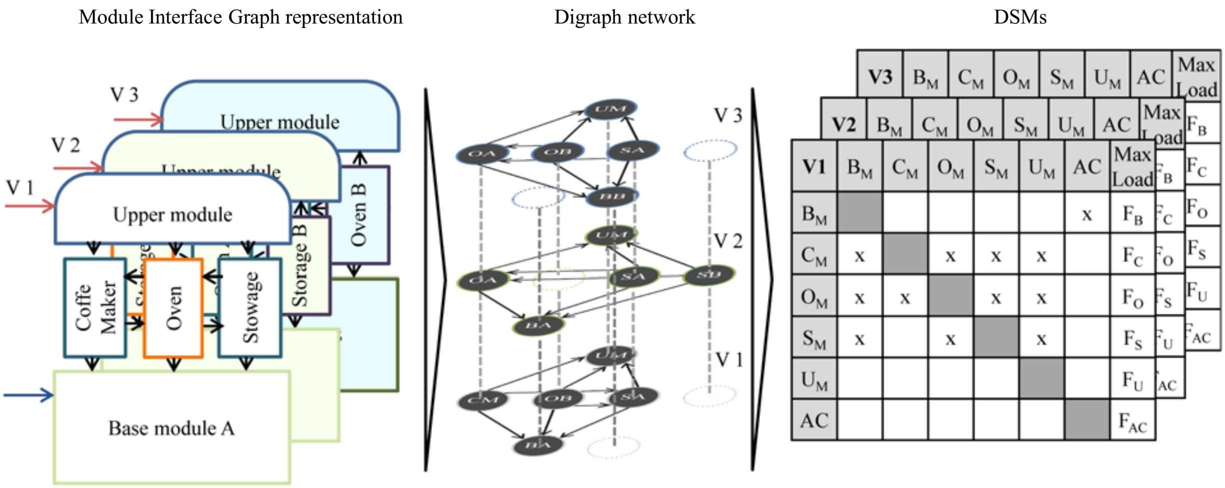
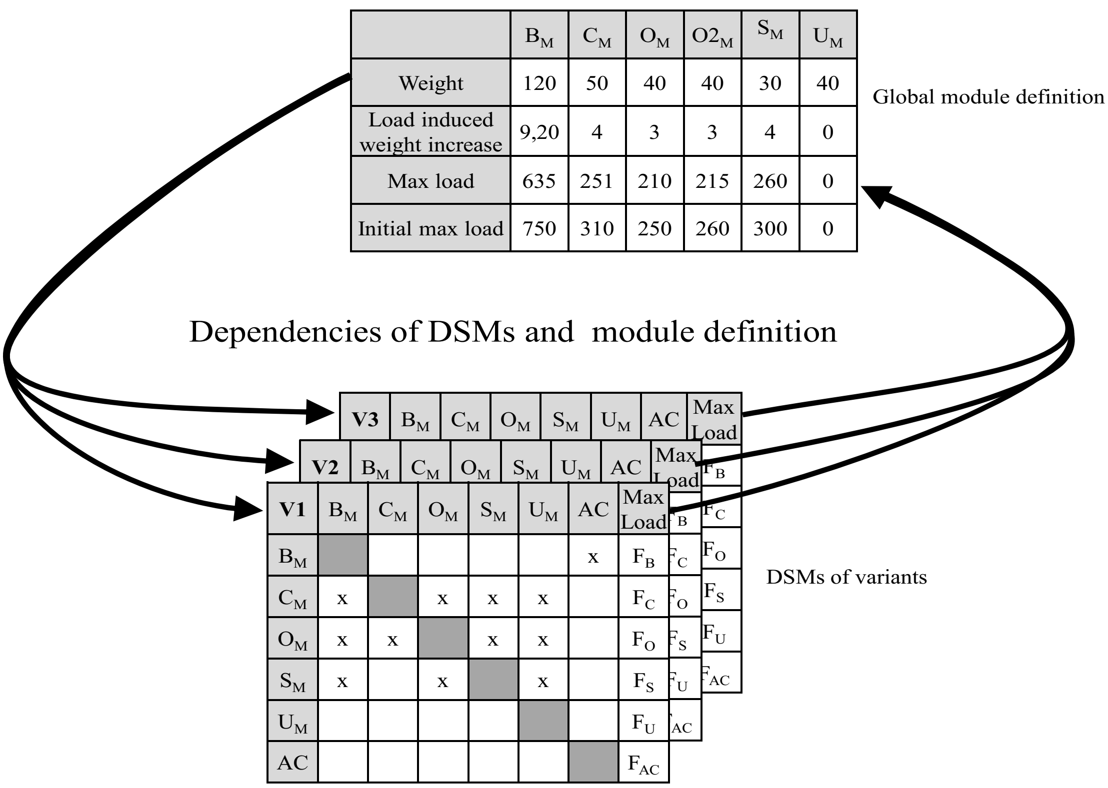


Figure 3. Simplified aircraft galley model

To relate the variants to each other, more information regarding the modules is needed. It is necessary to know how an increasing load leads to module weight change due to reinforcement. To accomplish this, an initial design of the modules is done. The designers have to estimate the module's weight reaction to a change in induced force. This can be either a factor (weight/force) or a table of force and corresponding weight. For more in-depth analyses, this can be a computational model (e.g. FEM).

The maximum load value per module is derived from the complete set of variants (Figure 4).



	B_M	C_M	O_M	$O2_M$	S_M	U_M
Weight	120	50	40	40	30	40
Load induced weight increase	9,20	4	3	3	4	0
Max load	635	251	210	215	260	0
Initial max load	750	310	250	260	300	0

V1	B_M	C_M	O_M	S_M	U_M	AC	Max Load
B_M						x	F_B
C_M	x		x	x	x		F_C
O_M	x	x		x	x		F_O
S_M	x		x		x		F_S
U_M							F_U
AC							F_{AC}

Figure 4. Relation of module definition and DSMs of variants

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; 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.

The matrices represent the weight and load dependencies between the modules across the variants. Because the modules are globally defined, a change propagates through all variants of the 3D DSM (analogies see Shooter et al. 2007). The specific sensitivity of the product family to weight change can then be determined (Figure 4). Tracing the weight propagation is carried out by carefully reducing the weight of a module. Due to interrelations, the variants respond to the change. All affected modules adjust their weight according to the induced load. The initial weight reduction and resulting reduction is correlated. A weight reduction gradient for each module is derived.

To evaluate the effect on the product family more objectively, the predicted sales numbers are taken into account to calculate a fleet weight. The modules with highest efficiency can be traced and are candidates for further weight optimization.

4 CONCLUSION

When technical constraints are dominant, modular products are at a performance disadvantage. However, modularity benefits the product and, with increased effort, these disadvantages can be reduced. In this approach, a way to trace weight propagation throughout a product family is described, creating the possibility of finding modules with high weight sensitivity to the product family. Optimizing these modules promises a higher overall reduction of weight because of the snowballing effect of weight propagation.

ACKNOWLEDGEMENTS

The authors would like to thank the Department of Economics and Labour of the City of Hamburg for funding the projects EFTEC and FlexGalley. We would also like to thank Mühlenberg interiors GmbH & Co. KG.

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INVEST ON VISUALIZATION

Tracing of Weight Propagation for Modular Product Families

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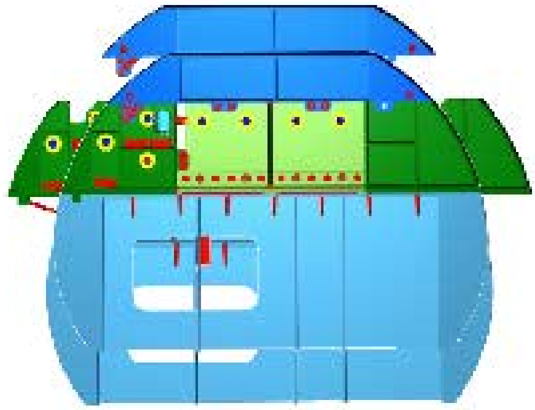
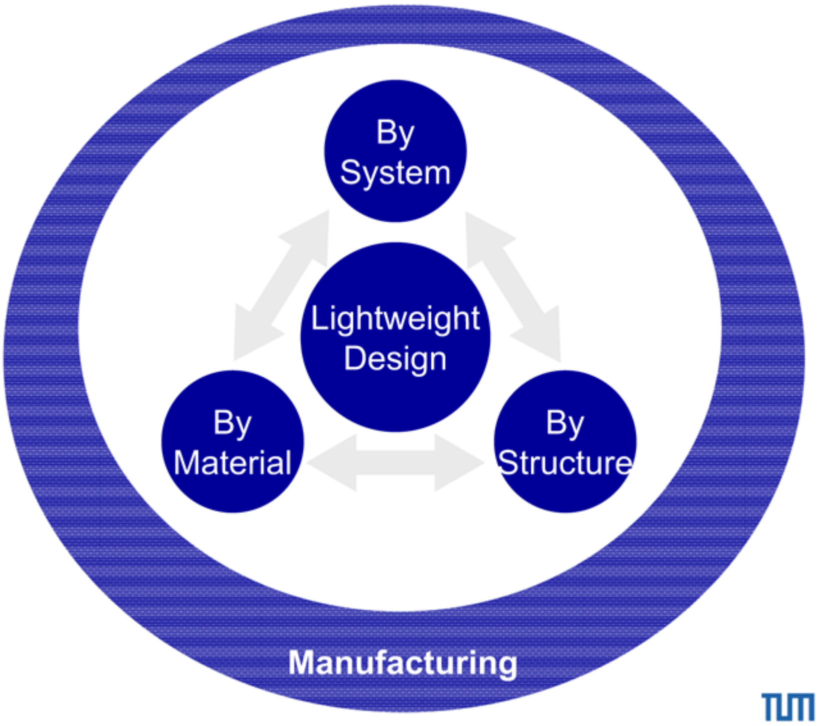
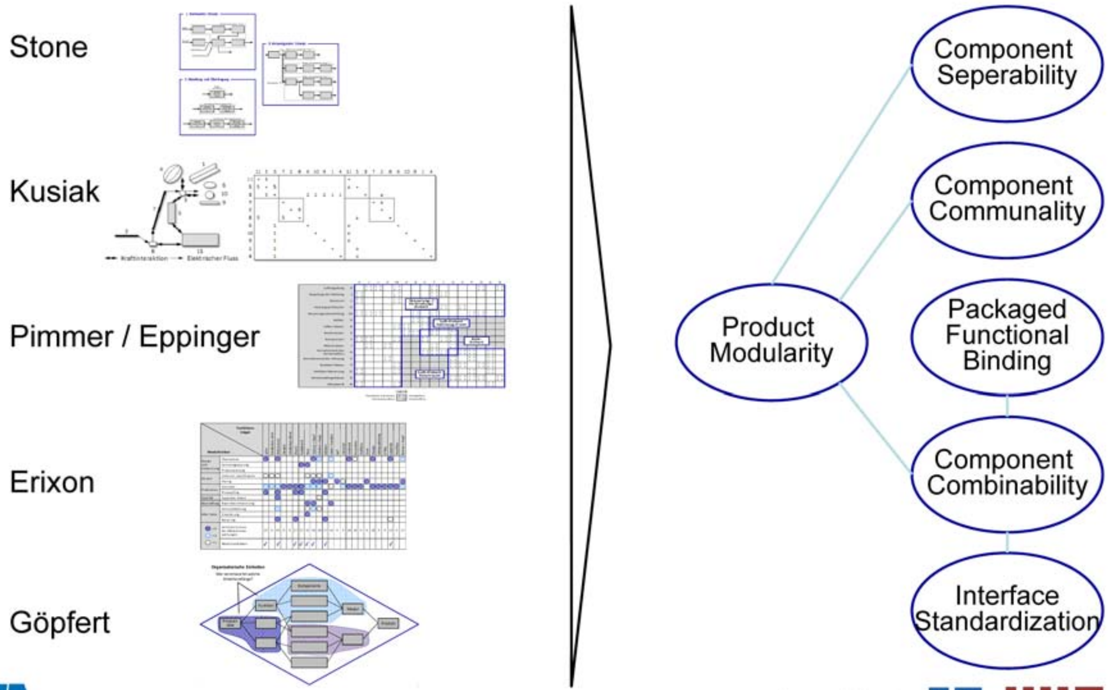
Introduction



Lightweight Design

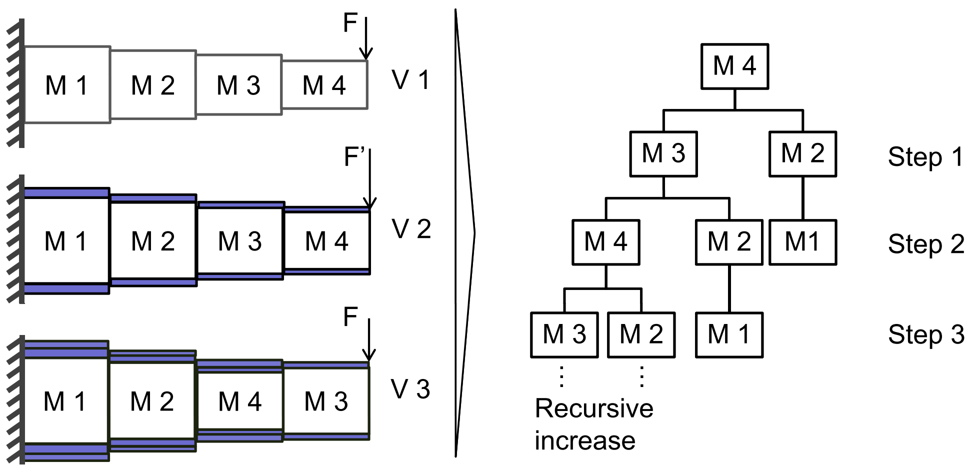


Modularization



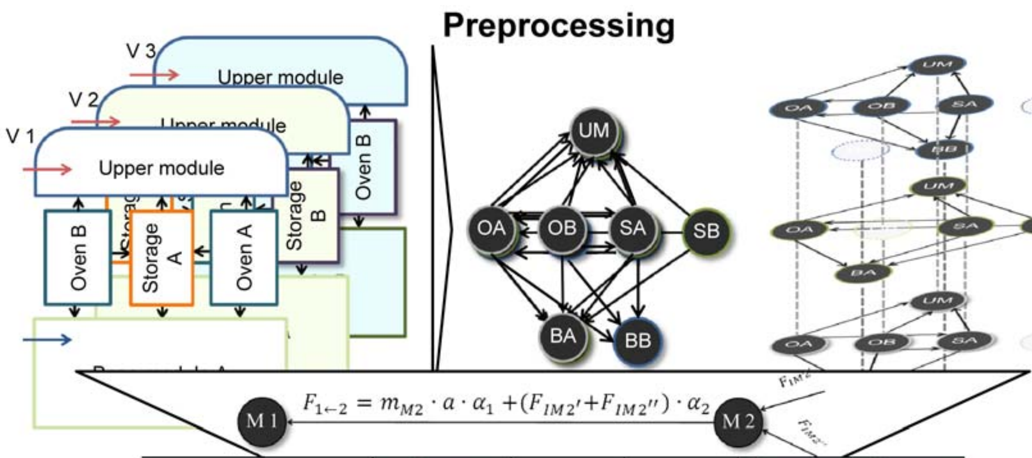
Source: Salvador

Lightweight design & modularization



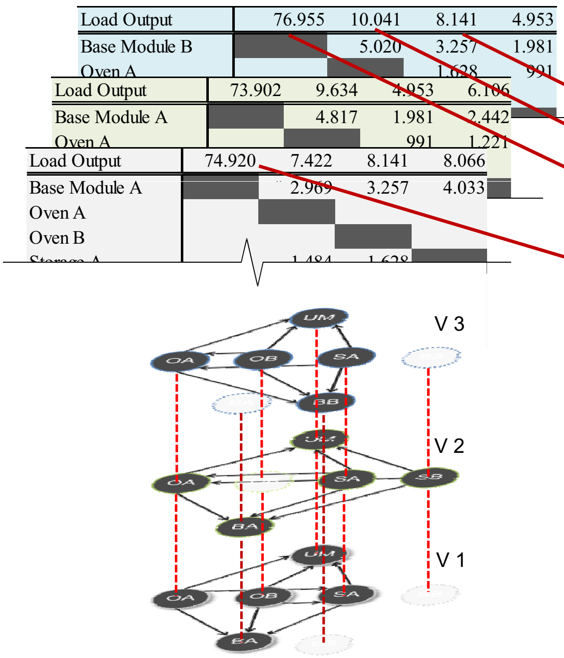
Goals of the approach

- Find and Trace root causes for weight increase
- Create awareness of weight change effects in a modular product family
- Responsibility for weight increase
- Matching of variants and modules
- Efficient lightweight design improvement for modular products



	Base Module B	Oven A	Oven B	Storage A	Upper Module
Load Output	76.952	10.035	8.141	4.953	25.051
Base Module B		5.018	3.257	1.981	
Oven A			1.628	991	
Oven B					
Storage A					
Upper Module		5.018	3.257	1.981	

Connecting the Variants



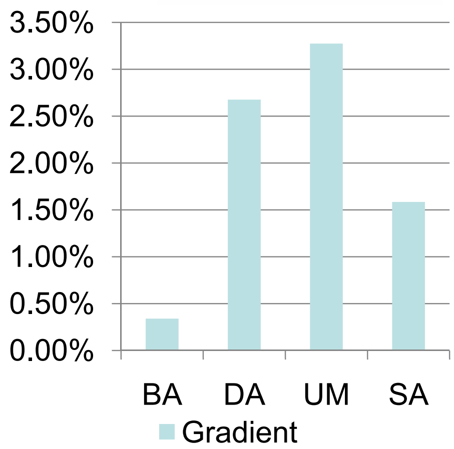
Maximum load values from variants

	Base Module A	Base Module B	Oven A	Oven B	St
Total Weight [kg]	732	755	84	92	
Payload [kg]	600	600	60	70	
Interface weight [kg]	10	12	2	3	
Load dependent strucutral we	122	143	22	19	
Max. Load [N]	74.920	76.955	10.041	8.141	
Max. Acceleration [m/s²]	88	88	88	88	

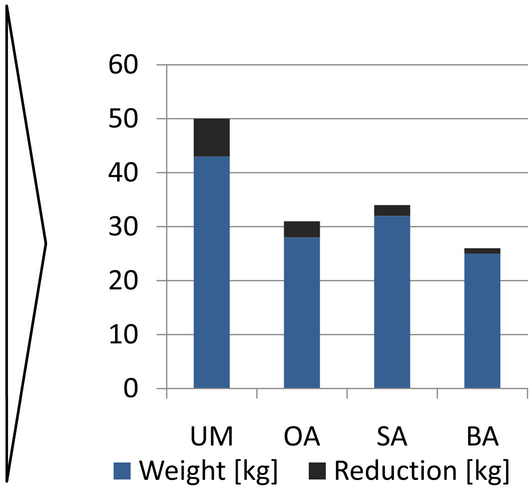
Weight Sensitivity and Tracing

Weight sensitivity of modules

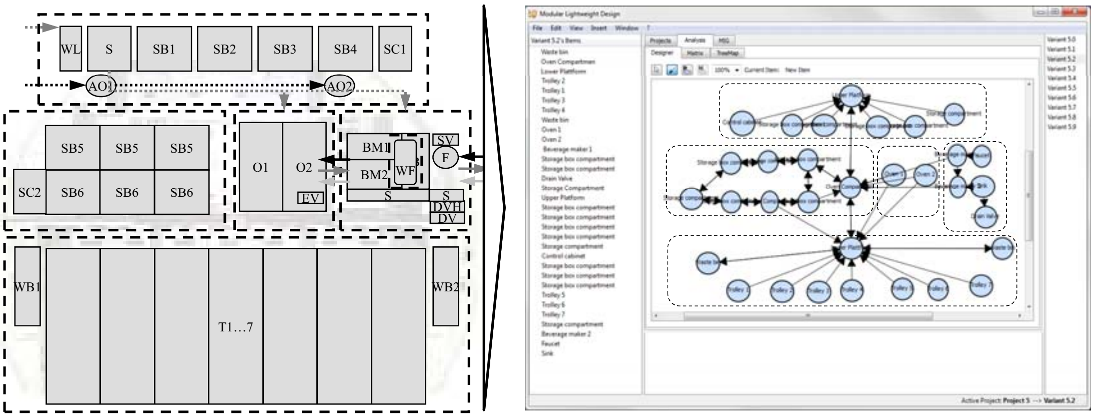
$$Grad = \frac{\Delta G_{rel}}{\Delta m \cdot G_{ges}} \; [\%]$$



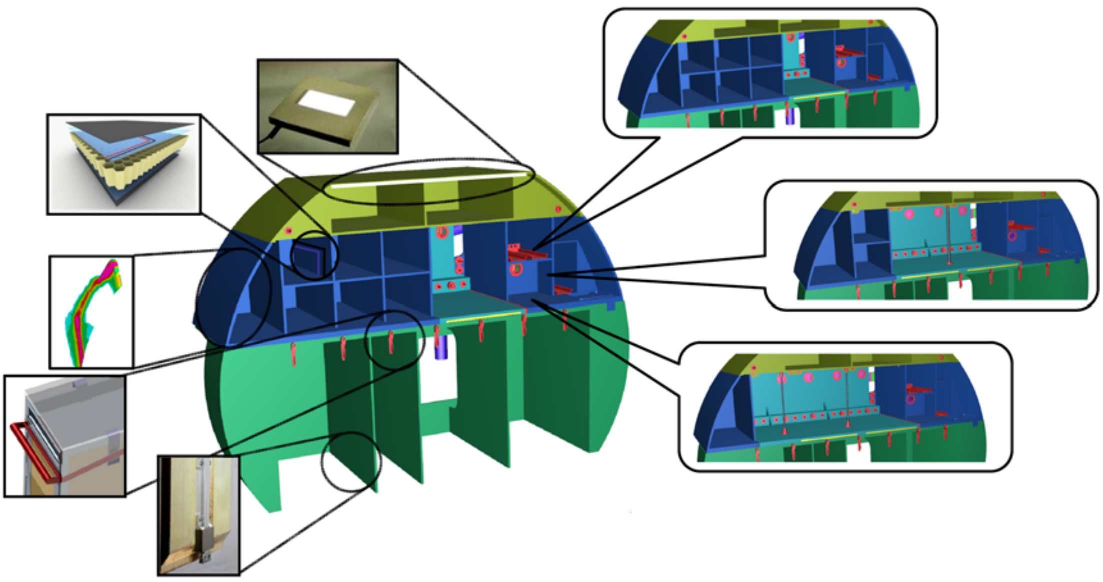
Traced weight reduction of a module



Software Tool



Optimization of a Galley Product Family



Source: Gumpinger / Jonas

Summary and Outlook

System model	Evaluate module fragmentation	Reduce oversizing	Module-specific optimization