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NEW APPROACH FOR LIGHTWEIGHT DESIGN: FROM DIFFERENTIAL DESIGN TO INTERGATION OF FUNCTION

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ABSTRACT

For a lightweight design often the reduction of the part number is an important development aim. For realizing this, the principle of Integral Design is widely used. This principle basically increases the functional density of a part. By definition, an integral component has to be made from one material, thus all functions supported by the part have to be compatible to the same material. Taking this in mind, the presented approach gives a strategy to identify candidates for the further advanced principle of Integration of Function by comparing their requirements to the material.

Keywords: Product Development, Differential Design, Integral Design, Integration of Function, Material choice

1 INTRODUCTION

There is an increasing demand for an optimized lightweight design of products. Particularly affected is the automotive- and aerospace industry, because lightweight design directly saves fuel and increases payload capacities. Currently in designing products, the lightweight design by material dominates, which however often needs a redesign of the components due to changed material requirements and properties (e.g. due to modified joints).

By using advanced material developments, further weight savings still are achievable but lead to high costs. So for using lightweight design by material only, there are more and more limits set by economical reasons [1]. For improving the lightweight design of a product with existing materials the design principle of Integration of Function can be used. Using this principle, on one hand the total number of components can be reduced and on the other the use of advanced lightweight materials can become more economical, because the lightweight material fulfills more functions. Additionally, the principle of Integration of Function allows to generate unique product properties, which can improve the market position by creating a unique selling point.

However, often the direct utilization of the potentials for Integration of Function is complex. The system complexity often exceeds a manageable amount of relations. Therefore this paper describes an approach, which methodically identifies potentials of Integration of Function based on material compatibilities in an early development phase. Thus these can be considered before the principle technical solutions are selected.

The application of the procedure is particularly suitable for pre-defined modules, because an optimal module definition aims to create a high and likely closed functional range within a module (cf. [2]). In this context, the approach supports Lightweight Module Design: Using this principle, a possibly higher weight due to effects of the modularization (e.g. more interfaces) can be balanced or even outmatched. Accordingly, due to the modular product design scale effects can be used for balancing the potentially higher costs of lightweight design solutions.

2 TERMINOLOGIES

The terminologies Differential Design, Integral design and Integration of Function are commonly used in mechanical engineering design literature. Following, the terminologies as a basis for the description of the methodical procedure in section 3 will be explained and distinguished. Further below, a method for intergrational mode of construction according to Ehrlenspiel [3] is explained.

Differential Design

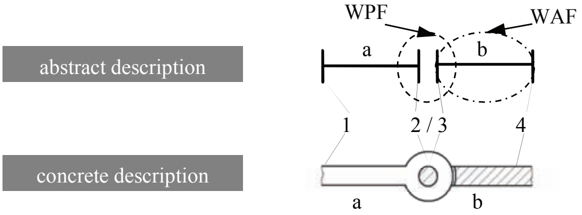
Differential Design separates the functions, which are represented by one part, into subcomponents. Afterwards these separated functions (represented by their subcomponents) are joined together in order to realize the previous defined functions in the assembled part. By separation, the complexity of the single subcomponents is reduced with respect to the original part. So for single function parts, fewer compromises in the part design have to be considered due to less interdependencies between the functionalities. By reduction of complexity, part design and dimensioning can be done more easily and precisely. The increasing number of interfaces likely effects a higher weight and more assembly steps.

Integral Design

Integral Design joins several functions into one solid part. Therefore the part uniformly has to consist of the same material. The material necessarily needs to meet the requirements of all principle technical solutions which are represented on the part. In order to meet all requirements, often it is needed to "oversize" the used material. Furthermore only the use of the material in a higher number of functions may allow an economic application of the material. Disadvantageous in Integral Design is the use of technical solutions with significantly different wear behavior. The technical solutions may interact with each other, which makes design and dimensioning more complex. The reduction of the overall part number can reduce the total product weight and the number of assembly steps.

Integration of Function

First the concept of the working-area-function (WAF) and working-surface-pair-function (WPF) are explained. According to Roth [4] a technical product can be described as an alternating chain of working-area-functions and working-surface-pair-functions. Working-area-functions can be derived from the relation of two working surfaces of the same working area. Whereas working-surface-pair-function describe the relation of the pairing of two working surfaces. Figure 1 shows a hinge in an abstract description and a concrete description. The hinge consists of a two part design. Part a has a WAF out of the surfaces 1 and 2 to transmit the force. On the contact point of part a and b the working surfaces 2 and 3 allow to transmit the force with a rotary degree of freedom. This represents the WPF of part a and b.



Working surface: 1, 2, 3, 4
Part: a, b
WPF: working-surface-pair-function
WAF: working-area-function

Figure 1. Terminologies for Integration of Function [4]

According to Ehrlenspiel [5], Integral Design differs from Integration of Function in the way that by Integration of Function the necessary working surfaces, movements and materials for the functions are merged together. So the Integration of Function further condenses the functions in one part. Such integrated technical solutions are according to Koller [6] often called "successful" or "ingenious".

Figure 2 visualizes in a model the differences between Differential Design, Integral Design and Integration of Function. The functions are condensed into the part with respect to the design principles. In case of the Differential Design the functions are separated into different parts. The Integral Design joins the functions into one part with seperated working surfaces. Using Integration of Function, the functions are not clearly separable anymore; they are merged into each other.

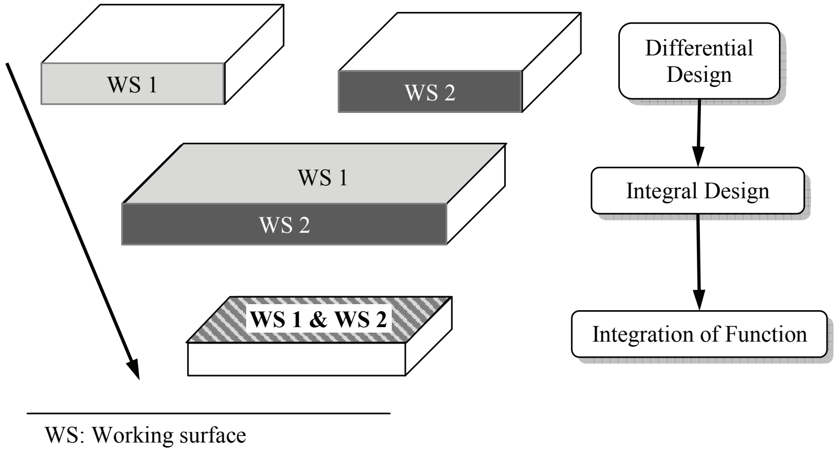


Figure 2. Visualization of Differential Design, Integral Design and Integration of Function

Procedure for Integration

Based on an existing product Ehrlenspiel [3] suggests the following procedure for reducing the part number: The product is considered as “one-part device”, made of one solid cast. Following, step-by-step the device is devided into “minimally necesarry part number”. This leads to a product with fewer parts than the parent one.

3 NEW APPROACH FOR IDENTIFICATION OF POSSIBILITIES FOR INTEGRATION OF FUNCTION

In this section a new approach for the identification of possibilities for Integration of Function is explained. The basic requirement for merging two or more functions into one integral part is the possibility for using the same material for the technical solutions of the functions. If this is not possible, the part has a Differential Design (cf. section 2).
Therefore the current method identifies candidates for integration by investigating the material compatibilities of principle technical solutions. For investigating a function, there is not only one possible principle technical solution considered but rather the variety of possible solutions for the functionality. Particularly advantageous in applying the method is the context of pre-defined modules, because modules have pre-defined and likely closed functionalities. For the module definition a modularization method can be applied. Currently the modularization method developed by the Institute [7] is used for this approach. The modularization method will not be discussed at this point.
The methodical consideration takes place before the functions are assigned to principle technical solutions. This offers advantages for Integration of Function due to the use of a not-predefined set of solutions. The methodical approach for identification of possibilities for Integration of Function consists of four steps, which subsequently are explained.

3.1 Definition of subfunctions and according principle technical solutions

In the first step, the functions of the product, respectively of the module, are analyzed and visualized in a Tree of Functions. Following for every subfunction there are possible and meaningful principle technical solutions derived. For these solutions, first operating principles according to Pahl/Beitz [8] can be considered, which provide the basis for the generation of alternative principle technical solutions for the function. For this derivation, tabular schemes (e.g. morphologic box) or design catalogues [4] can be used. According to Figure 3, there is aimed the generation of a variety of meaningful possible principle technical solutions for the realization of each single function. Thus a variety of possible principle technical solutions is mapped to the Tree of Functions.

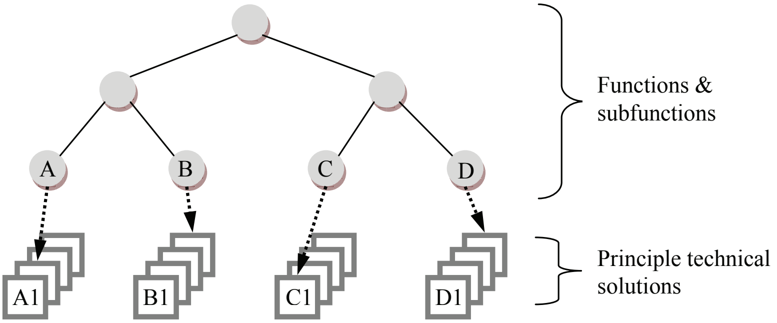


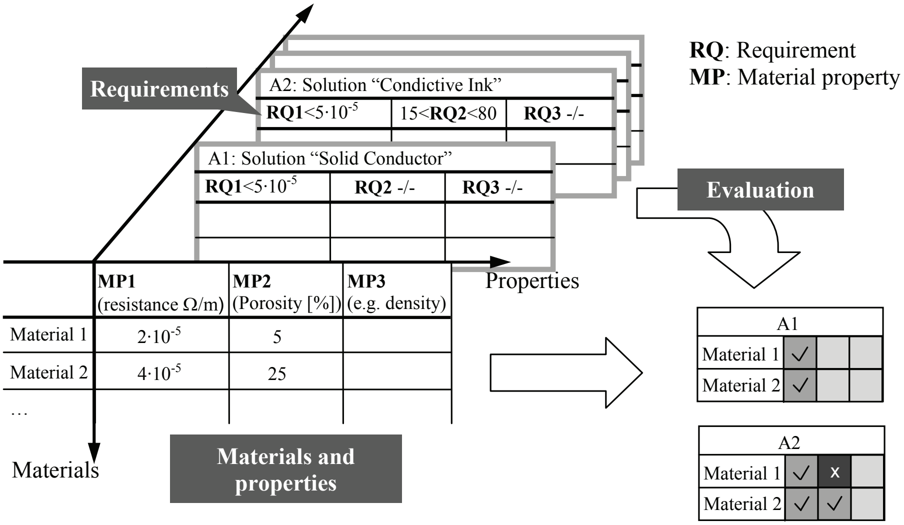
Figure 3. Tree of Functions and technical solutions

3.2 Mapping of materials and principle technical solutions

In the second step of the method, those material requirements are determined, which the technical solutions necessarily need. Valid are discrete values as well as ranges of tolerance. In case of using ranges of tolerance, the next steps of the method will identify more possibilities for Integration of Function. The determination of material requirements is performed for all principle technical solutions.

The types of material requirements, abbreviated with RQ, have a continuous enumeration for the whole product (or module, if meaningful). Based on these requirement types, the solutions are compared against each other in order to identify solutions with compatible material requirements. Those compatible solutions are candidates for Integration of Function.

Figure 4 shows an example of the Material-Relation-Chart (MRC), which gives the interdependencies between available materials, material properties and material requirements of the principle technical solutions. An evaluation is performed to identify which materials are usable for realizing functionspecific solutions.



A2: Solution “Condictive Ink”		
RQ1<5·10^-5	15<**RQ2**<80	**RQ3** -/-

A1: Solution “Solid Conductor”		
RQ1<5·10^-5	**RQ2** -/-	**RQ3** -/-

	MP1 (resistance Ω/m)	**MP2** (Porosity [%])	**MP3** (e.g. density)
Material 1	2·10^-5	5	
Material 2	4·10^-5	25	
…			

A1			
Material 1	✓		
Material 2	✓		

A2			
Material 1	✓	x	
Material 2	✓	✓	

Figure 4. Material-Relation-Chart (MRC)

Using the MRC, potentially suitable materials based on the requirements are mapped to the principle technical solutions (see evaluation results in Figure 4). For a solution with only few types of requirements to the material, a larger variety of possible materials will result, because only few material properties need to match a requirement. Due to the fact that in this case more materials are suitable for realizing the solution, more possibilities for integrating another solution will result, because fewer properties need to be compatible.

For the different types of requirements to the materials, databases can be created for easing the application of the procedure. Additionally, the method can be cross-linked with engineering design catalogues in such a way, that pre-defined catalogues contain principle technical solutions with corresponding generic material requirements. The solutions can be linked to their working principles. This allows a use of the described procedure as a subphase of the conceptual design in the Engineering Design Process according to Pahl/Beitz [8].

3.3 Identification of integrable subfunctions

After the material mapping, those technical solutions which are realizable of the same material are grouped together. Figure 5 shows such a grouping of potentially integrable technical solutions.

Due to the consideration of a not pre-defined set of principle technical solutions this approach can identify significantly more potentials for Integration of Function than only the consideration of an already selected design concept would give.

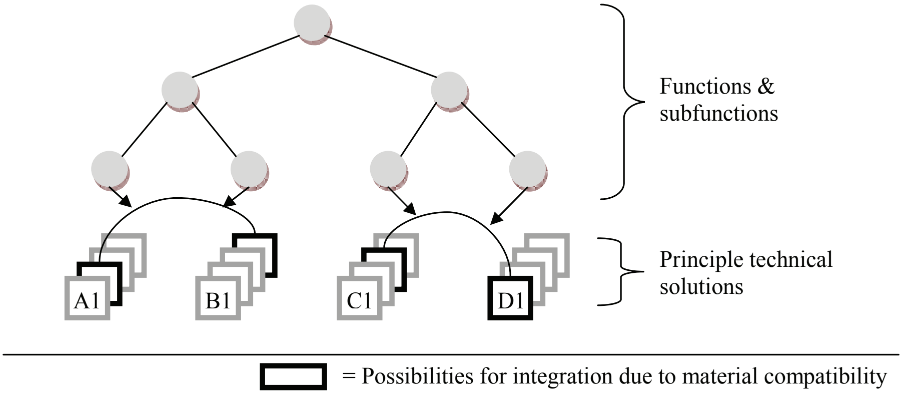


Figure 5. Summary of possible integrable technical solutions

3.4 Evaluation of identified possibilities

Subsequently, the identified candidates for Integration of Function need to be evaluated in terms of feasibility. Therefore it needs to be checked whether the physical and functional integration is possible and meaningful. For example the physical integration is not possible if the technical solutions need to be located in different areas of the product or module. From the functional perspective it needs to be ensured that the designated functionalities still can be fulfilled by the one common part. In case one solution is a feasible candidate for several alternative integration scenarios, it needs to be assessed which alternative is the best to use. The development of a feasible evaluation system is issue of future research work, potentially a basis is the compatibility matrix of Birkhofer [11].

4 PRACTICAL EXAMPLE

In the following section, the procedure described in section 3 is applied by example of an aircraft-galley module (Figure 6). For the further design of an aircraft-galley, there is a module definition given in [7]. For improving the lightweight design of the galley, potentials for increasing the functional density of modules by Integration of Function will be investigated subsequently. The structural-giving function of the galley is fulfilled by composite sandwich panels. Many technical solutions are attached (or installed) to these panels using the principle of Differential Design. Examples for these installed components are: lamps, inserts, cables, hose clips, impact edges or switches.

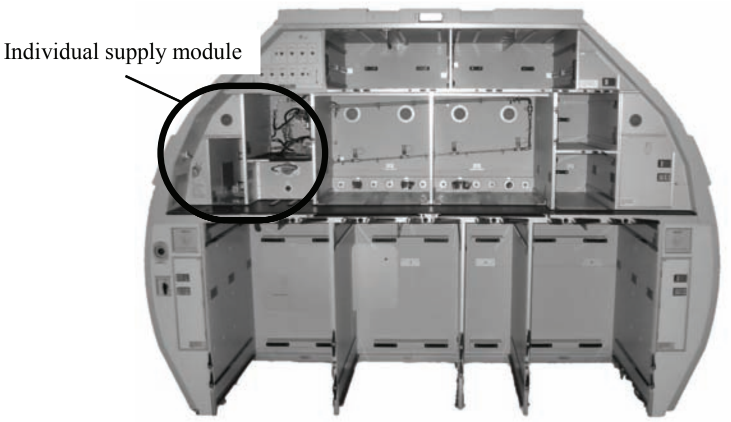


Figure 6. Galley for single aisle passenger aircraft (Mühlenberg Interiors)

To achieving weight improvements, the above described approach is used for finding possibilities to use the principle of Integration of Function. For the application of the method the "individual supply" module of the galley is taken. Exemplarily the subset of functions „electrically generation of light“ and „represent the structure“ will be investigated (Figure 7).

The defined subfunctions are assigned via an abstraction layer to principle technical solutions. The solutions were derived from the subfunctions using of proven methods of product development ([8], [9], [10]).

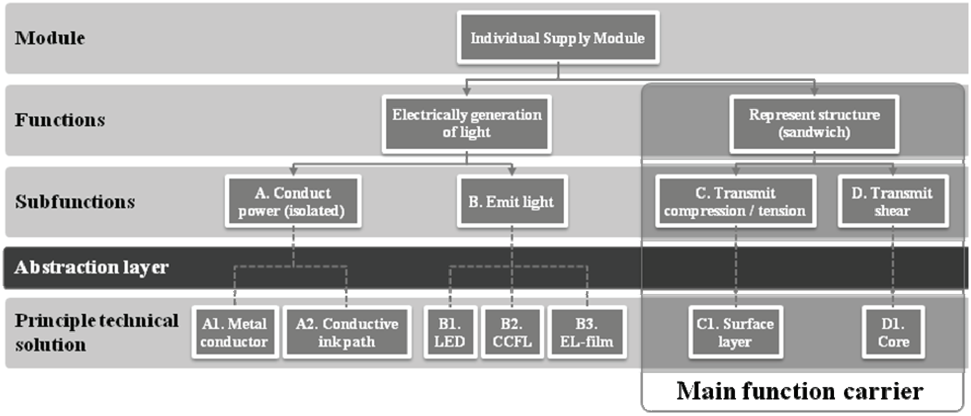
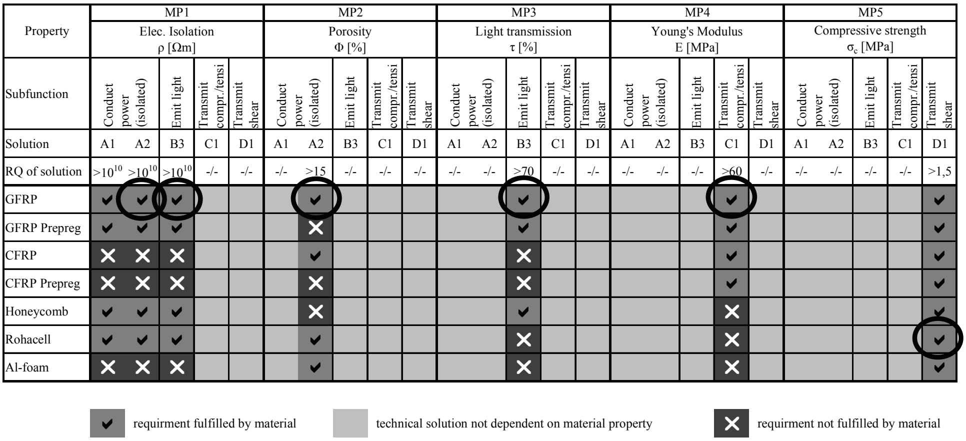


Figure 7. Tree of Functions and principle technical solutions for the current example

In the Material-Relation-Chart (MRC, Figure 8) the materials of the mainfunction carrier (sandwich panel materials) and the required material properties of the principle technical solutions are assigned. For this manual application the basically 3-dimensional representation of the MRC is transformed into a 2-dimensional table. For easing the example, LED (B1) and CCFL (B2)- solutions are not further considered here.

If a solution requires a certain material property, this property is checked for each material in the table whether it fulfills the requirement or not. A differentiation is considered between “requirement fulfilled by material”, “technical solution not dependent on material property” and “requirement not fulfilled by material”. This information is tagged in the table.



Property	MP1					MP2					MP3					MP4					MP5				
	Elec. Isolation ρ [Ωm]					Porosity Φ [%]					Light transmission τ [%]					Young's Modulus E [MPa]					Compressive strength σ_c [MPa]				
Subfunction	Conduct power (isolated)		Emit light	Transmit compr./tensi	Transmit shear	Conduct power (isolated)		Emit light	Transmit compr./tensi	Transmit shear	Conduct power (isolated)		Emit light	Transmit compr./tensi	Transmit shear	Conduct power (isolated)		Emit light	Transmit compr./tensi	Transmit shear	Conduct power (isolated)		Emit light	Transmit compr./tensi	Transmit shear
Solution	A1	A2	B3	C1	D1	A1	A2	B3	C1	D1	A1	A2	B3	C1	D1	A1	A2	B3	C1	D1	A1	A2	B3	C1	D1
RQ of solution	$>10^{10}$	$>10^{10}$	$>10^{10}$	-/-	-/-	-/-	>15	-/-	-/-	-/-	-/-	-/-	>70	-/-	-/-	-/-	-/-	-/-	>60	-/-	-/-	-/-	-/-	-/-	>1,5
GFRP	✓	✓	✓				✓						✓						✓						✓
GFRP Prepreg	✓	✓	✓				✗						✓						✓						✓
CFRP	✗	✗	✗				✓						✗						✓						✓
CFRP Prepreg	✗	✗	✗				✗						✗						✓						✓
Honeycomb	✓	✓	✓				✗						✓						✗						✓
Rohacell	✓	✓	✓				✓						✗						✗						✓
Al-foam	✗	✗	✗				✓						✗						✗						✓

✓ requirment fulfilled by material

▨ technical solution not dependent on material property

✗ requirment not fulfilled by material

Figure 8. Material Relation Chart (MRC) for the current example

With a combinatorial analysis possible integration partners can be identified. In this easy manageable example this can be done manually. An analysis of the MRC gives the following results:

- CFRP, CFRP Prepreg and Al-foam are no option for integrating A1, A2 and B3.
- GFRP Prepreg and Honeycomb are no option for an integration of A2.
- B3 is not integrable into Rohacell.
- For tension/compression loads only GFRP, GFRP Prepreg, CFRP and CFRP Prepreg are usable.
- For shear loads, all materials are usable.

The MRC indicates that the fibre-reinforced plastics could be used for the function “transmit shear”. This generally is possible but would significantly increase the weight, because shear transmission is done by the relatively thick core layer of the main function carrier (sandwich panel). Since density was not considered as a material requirement, there is no correlation given in the MRC for avoiding FRP’s for shear transmission. This basically shows the importance of considering all necessary material requirements for the principle technical solutions. The combination of technical solutions encircled in Figure 8 is subsequently taken for realizing a physical demonstrator panel (Figure 9). For the realization, density as a requirement to the core material (shear transmission) is considered. For preserving the main function carriers’ functionality, Differntial Design is used by surface layer and core. Integration of Functions is applied into the surface layer using the identified Material of GFRP.

In the surface layer, GFRP plies are combined with an electroluminescence film (EL-film) and a printed conducting path of conductive ink. The isolation layer of the electroluminescence film is saved by using a combination of the electroluminescence film with the electrically isolating and transparent GFRP top layer (approx. 50% weight savings of the EL-film). For the function „conduct power (isolated)“, the lower GFRP layer is used as substrate for the conductive ink. In the upper part, GFRP material is used for electric isolation. In this example, the Rohacell core only has the function to transmit the shear loads.

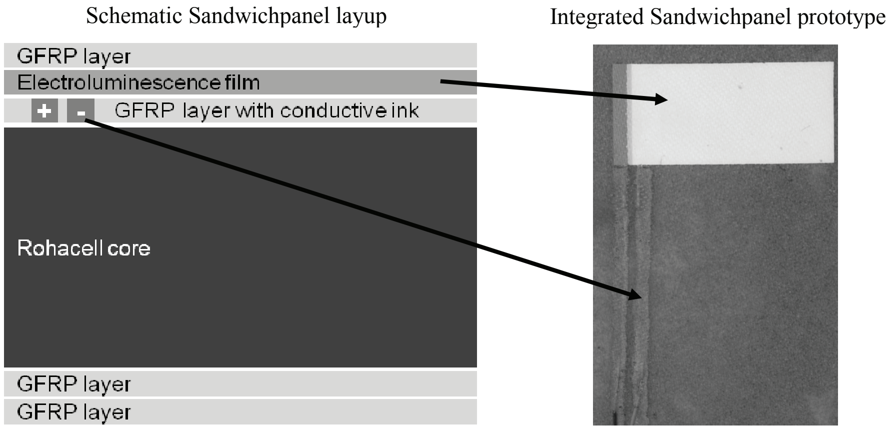


Figure 9. The integrated composite sandwich panel

5 CONCLUSION

The presented strategy supports the development engineer in systematically finding integration potentials by comparing different principle technical solutions for functions of the product or module. The procedure can be applied in an early stage of the product development process, which allows having only few restrictions with respect to pre-determined part designs. The approach is particularly suitable for supporting Lightweight Module Design, because modules typically have a dense and closed functionality, which supports the principle of Integration of Function. The procedure successfully was applied in example of a lightweight structural part for aircraft interior monuments.

For improved usability, future work relies on a 3D-visualization of the Material-Relation-Chart, which then can be supported by a software implementation. The approach would become more intuitively. Furthermore, the procedure needs to be applied in additional practical examples for verification and an evaluation system needs to be developed.

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