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Design Principles and Multi-Level Structures for Multi-Functional and Multi-Material Design

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Abstract

Multi-functional design has high potential to overcome e.g. increasing weight and costs of products. However, the possible solution space for integrating functions is hardly manageable. This paper presents an approach to assist in the identification of multi-functional approaches. Therefore, hybrid design principles are developed that are combinable to complex structures including specific manufacturing routes. By this, multi-functional solutions can be provided on different resolutions in order to identify the most promising approach and position for the integration of additional functions.

Keywords: multi-functional design, hybrid design, design tools, product structure, product design

1. Introduction

Due to increasingly strict legislation regarding CO_2-emissions, industries and especially the automotive industry is obliged to reduce the CO_2-emission with focus on the entire life cycle. Beside numerous other measures, the reduction of the products' weight by lightweight design, seems promising. Hybrid design, which combines different materials in one component, is particularly interesting. In this way, lightweight materials can be applied target and load specific improving several development goals (Altach, 2020). However, a central challenge in the application of hybrid design remains the generally increasing costs due to the application of lightweight materials, which leads to a multi-objective optimisation task. One way to face this challenge is to exploit the opportunities given by the application of different materials to integrate additional functions in structural components. On the one hand, the weight can possibly be further reduced, and on the other hand, additional parts or components are not required, which can reduce costs and, in particular, assembly times (Klaiber et al., 2019). In addition, the omission of assembly steps and thus necessary accessibility offers the opportunity of a more integral design of components. By these secondary effects the aforementioned potentials can to be significantly increased once again.
The development of multi-functional structural components requires a precise analysis and harmonisation of the design approach of the adopting component/structure and the function or functional component to be integrated. In the context of this paper, the focus is on the integration of non-structural functions into structural components. Structural components are mainly load-bearing and have requirements such as stiffness or strength. In the case of automotive design, this applies in particular to the body or add-on parts such as doors and lift gates. Examples of non-structural functions are the conduction of electrical energy, which is usually realised by a separate cable harnesses. However, the integration of non-structural functions into structural components leads to additional challenges. On the one hand, the structural properties must not be impaired by the integration. On the other hand, the function-bearing elements within the component are potentially exposed to mechanical loads, which in turn must not impair the fulfilment of the function. In addition,

an integral application of different materials and elements in a single component increases the complexity of an afterlife separation for a subsequent recycling. Thus, precise planning and exhaustion of all possibilities for integration are required in order to identify the most promising solution.

Due to the numerous possibilities for implementing functional integration, a methodical support in the selection of suitable approaches is required. Since many approaches are based on specific designs or material combinations and there are limited possibilities for the free selection of design approaches in the development of components or products, the possibility of filtering solutions with regard to these restrictions is necessary. Furthermore, the feasibility of solutions for functional integration depends on the specific boundary conditions of the component or product to be developed. This applies, for example, to the mechanical loads that occur, the specific shaping or the series scale.

The overall research objective is a methodical assistance that supports the identification of possible integration approaches considering different opportunities for the component's designs. This requires a specification of different integration approaches regarding specific boundary conditions and development goals. However, before matching specific integration approaches to the multi-material structure or vice versa, it is necessary to provide a problem-oriented access to these solutions.

Currently, there is a fundamental lack of a suitable way to categorise multi-material structures for the purpose of multi-functional design. Therefore, the specific aim of this paper is the deduction of different design approaches of hybrid design and their connection to possible solutions for functional integration with regard to their multi-level structure. For this purpose, necessary aspects for the description of functionally integrated solutions are first identified. Subsequently, design principles for hybrid structures are derived. The combination of these individual structures is demonstrated by means of more complex multi-level structures with different possibilities for the integration of additional functions, taking into account different manufacturing possibilities. These results lead to a method that enables an application-specific selection of multi-functional solutions on different levels of concretisation or resolutions. Finally, the application is exemplified in case of different design problems.

2. State of the Art and Research

The aim of the paper is to develop design principles that offer the opportunity to create multi-level structures for hybrid design. These design principles are associated with different manufacturing routes in order to combine the resulting structure with solutions for functional integration. Therefore, the state of the art regarding categorization of hybrid design principles and data bases is evaluated as well as categorizations and design principles for functional integration.

2.1. Hybrid Design

Hybrid design can be defined as the joint application of different materials within a single component. Within this definition of hybrid design, different distinctions and classifications can be made, which are presented below.

Kleemann et al. (2017) distinguish between levels of hybrids by combining two materials at material level (e.g. steel A and steel B), material type level (e.g. steel and aluminium) and main material group level (e.g. metals and plastics). A wide variety of component designs can be realised from the materials that can be applied, their specific shape-related and topological divisions, and manufacturing processes. An overview of hybrid components is shown by Bader et al. (2019) on concept level as well as in industrial application. Altach et al. (2020) show an approach for categorising and combining monolithic and hybrid design on component level for automotive engineering. In addition to the variety of different designs at component level, distinctions can also be made for hybrid design on the basis of the material combinations in relation to the internal or the basic composition of the hybrid structures or hybrid materials. Between others, Kroll et al. (2019a) make a fundamental distinction between material composites and composite materials. Material composites are defined as a combination of at least two material components that are macroscopically heterogeneous (e.g. multi-layer composites). Composite materials also consist of at least two material components, but are macroscopically homogeneous (e.g. fibre reinforced plastics). Therefore, different materials and reinforcement components (e.g. particles and fibres) applied. Weißbach et al. (2018) also distinguish between fibre, particle and intersection composites.

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Ashby and Bréchet (2003) distinguish between different families of hybrid materials (composites, sandwich, lattice and segment) and give examples for each family. This classification takes into account not only the structure but also the resulting or possible properties or functions.
In addition to basic subdivisions of hybrid structures, also specific approaches can be further distinguished. In case of sandwich structures, for example, continuous (solid, foam, etc.) and discontinuous cores (corrugated, honeycomb, etc.) can be distinguished (Wiedemann, 2007). The choice of facings and cores has a decisive influence on the central properties of the composite (mechanics, acoustics, etc.) and the possible manufacturing processes. Examples of different sandwich structures and their resulting properties are presented by Palomba et al. (2021), Tarlochan et al. (2021) or Feng et al. (2020).

2.2. Multi-functional Design and Functional Integration

Functional integration can be described as the integration of additional functions into a system without increasing the number of parts (Roth 2000). It offers high potentials such as weight and cost reduction as well as a reduced installation space (Klaiber et al. 2019).
Gumpinger et al. (2009), for example, developed a light emitting cabin wall for an aircraft kitchen by a material selection method with focus on the functions to be fulfilled by the cabin wall. The solution was a sandwich structure with a foam core and glass-fibre reinforced plastics (GFRP) faces. The additional functions of light emission and the necessary electrical energy supply are integrated into one of the GFRP faces. The light emission is integrated by adding an electroluminescence film covered with GFRP on both sides. The inner GFRP layer is infiltrated by a conductive ink that provides the necessary electrical energy. This example shows an uncommon solution that fits the given requirements of the specific application. However, for the application under different conditions, such as automotive design, this solution would not fit the requirements. Consequently, possible multi-functional solutions also depend on the specific application.
In addition to the specific implementation of the function-fulfilling component, the integration of this component into the adopting structure in particular plays a decisive role. Both aspects cannot be considered independently, but are interdependent.
With regard to the integration of functions, according to Klaiber et al. (2019), basic strategies can be distinguished in which the number of required different function carriers decreases. They distinguish between mount integration, part integration, parts consolidation and function adoption. The strategies result in different integration potentials (such as a reduction in weight, installation space or costs) and challenges (flexibility, robustness, etc.). By integrating more than one function, different strategies can also be combined with each other. The strategies presented give a first insight into the different design possibilities within the framework of functional integration, but do not specify implementation possibilities with regard to specific functions, functional components or material composites.
Adam et al. (2018) distinguish functional integration on different size scales, whereby the degree of functional integration increases with decreasing size scale. The distinctions are illustrated by a structurally integrated battery in combination with a FRP component. At macro scale, integration is achieved by an additional thin-film energy storage, at meso scale by structural laminate capacitors and at micro scale by micro scaled coaxial fibre capacitors.
Hoßfeld and Ackermann (2020) show different principle solutions for integrating a wide variety of cables and sensors into a sandwich composite and evaluate them in terms of their applicability for specific functions. It is shown that initial statements about the feasibility of function-integrated solutions can also be made at the level of principle solutions.
Even on a higher level of detail, different principles for integration emerge. Elspass and Flemming (1998), for example, show different strategies for integrating sensors into FRP laminates. In addition to attachment on the outside, they distinguish between laminating with resulting deflection of the fibre layers and the creation of cavities by locally cutting out individual fibre layers.
Distinctions between different integration principles can therefore be mapped on the most varied levels of detail. These must be taken into account in the development of multi-functional components.
The possibilities for integrating functions are highly dependent on the manufacturing technology. The field of additive manufacturing in particular opens up completely new implementation possibilities, such as shown by Hilbig et al. (2021). The design freedom opens up much more opportunities for a geometric

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functionalisation. This is why special design principles for additive manufacturing are necessary as, for example, shown by Schumacher et al. (2019). By using manufacturing technologies suitable for large-scale production, other challenges arise in turn. On the one hand, the included functional components must not be damaged by the process conditions of e.g. pressing or injection moulding. On the other hand, the integration of additional functions must not complicate the manufacturing route.

3. Hybrid design principles for functional integration

The beforehand described extract of multi-functional solutions underlines the need for a structured categorization. In this context, the basic possibilities or specific characteristics of the integration of non-structural functions into structural components highly depend on the chosen design approach or applied materials. In order to demonstrate the possibilities of functional integration in multi-material design, it is necessary to describe different design principles for the creation of multi-material structures. A combination of single principles, again, enables the description of more complex structures. In addition, these principles must also enable possibilities for the integration of functions or functional structures. These requirements show a gap in the current state of technology and research. For this reason, on the basis of the existing approaches described in section 2 as well as extensive research in the field of hybrid and multi-functional design, design principles were derived and categorised, which can be combined into more complex multi-level structures and concretised by taking different manufacturing processes into account.

3.1. Basic design principles for hybrid structures

The hybrid design principles presented below describe the possibilities of subdividing, combining or integrating different materials or components. Since it is not determined, if individual materials, more complex components or similar are involved, the individual areas are referred to as elements in the following. For each category, subcategories can be defined in turn, which represent a more precise specification of the respective principle. Figure 1 shows the basic classification together with examples of the respective specification.

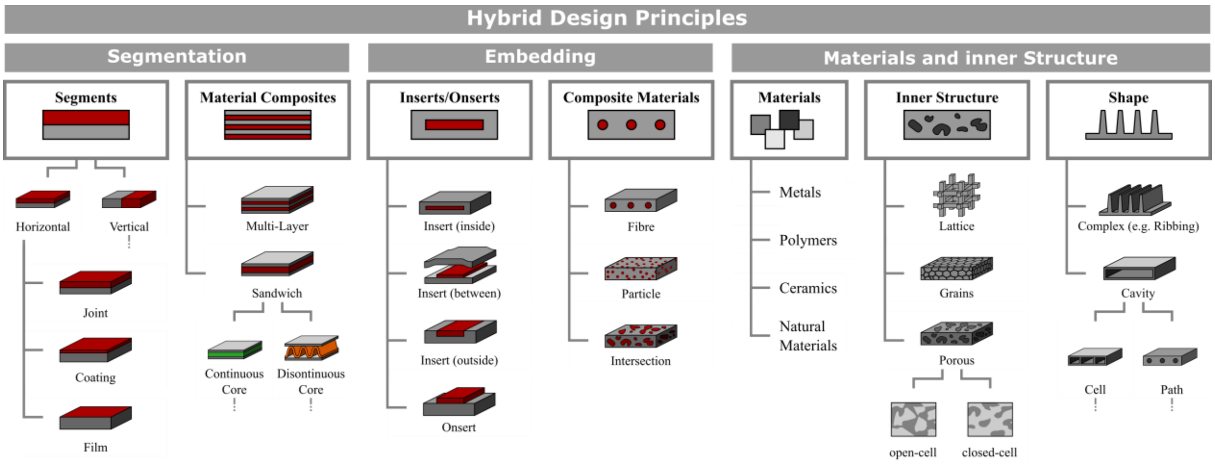

Figure 1. Categorization of design principles for hybrid design and functional integration

At the highest level, the principles are divided into principles for the combination of at least two elements as well as the more precise description of individual elements. Basically, a distinction can be made in the division between segmentation and embedding of elements. Taking into account the possibilities for functional integration, this distinction is of great relevance, as a different division of the individual properties of the elements involved results (Fröhlich, 2019). Depending on the specific principle of this division or combinations, there are different resulting properties of the resulting composite.
Segments describe the division into two elements. For vertical composites, this can be defined, for example, as equal (Joint), as a thinner layer (coating) or as a thin layer (film). Material composites mainly

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describe layered composites, such as multi-layer or sandwich structures, whereby in the case of the sandwich core, a more precise differentiation can be made between continuous and discontinuous cores.
Embeddings describe the embedding of elements into others. Inserts/onsets represent larger but locally applied elements. Inserts are integrated into the existing structure and can be internal or external. A special case are inserts that are placed between two other elements. Onserts, on the other hand, are placed on the outside. Composite materials describe a macroscopically homogeneous connection between two elements, considering fibre, particle and intersection composites.
The described principles are not defined to be entirely individual, but combinable to multi-level structures. In addition to the combination of several elements, the more precise specification of individual elements also plays a decisive role in the description of multi-functional hybrid structures. Beside the assignment of a material, its internal structure can also be described. For this purpose, porosity (e.g. foam), grain structures (particle foam) or lattice structures can be distinguished. Furthermore, geometric aspects can also be distinguished on a macroscopic level. For example, an element can have a complex shape such as a ribbed structure or possess cavities. Furthermore, it is necessary to distinguish very specific shapes. Examples of this are different sandwich cores (cf. section 2) or the exact definition of fibres in FRP in terms of length or linkage with each other (e.g. unidirectional or woven).

3.2. Manufacturing of hybrid structures

The previous descriptions of the principles or their linkage do not yet take into account the exact manufacturing of the individual structures or the entire manufacturing route of complex structures. However, the consideration of manufacturing is not only of elementary importance for the basic feasibility of the structures or integration. For example, the manufacturing processes and their sequence result in important influencing factors, such as temperatures and pressures, on the individual elements and especially on sensitive functional components. In addition, the choice of manufacturing process has a decisive influence on the exact definition or the resulting properties of the structure.

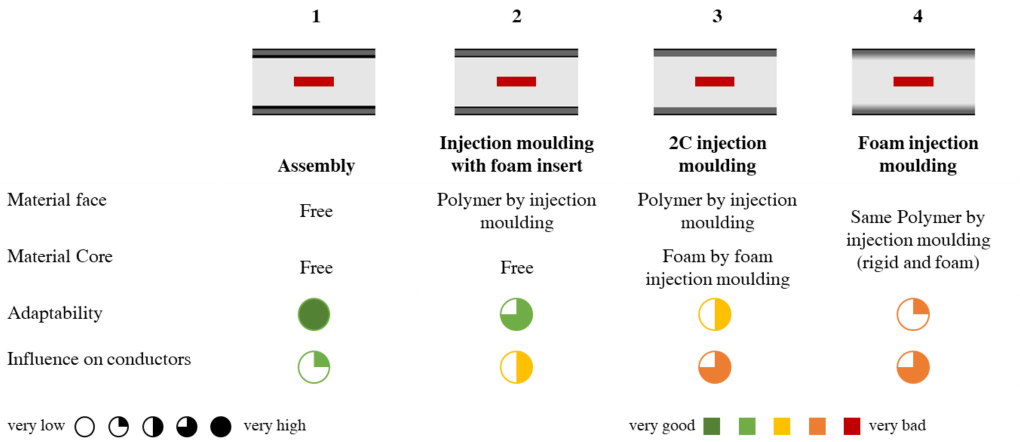

Figure 2. Different manufacturing processes and their influences

An example of this is the implementation of a sandwich composite with a polymer foam core and rigid polymer faces. A functional component is to be integrated within the foam core. Figure 2 shows an example of four implementation options with the resulting freedom regarding the choice of material and the design of the structure as well as influences on the functional component. From left to right, the freedom in the choice of materials and the adaptability to the individual boundary conditions decrease more and more. However, the negative influences on the functional component to be integrated increase. While there are hardly any influences from production on the functional component for solution 1, the functional component exposed to high temperatures and pressures in solutions 3 and 4, which can lead to damage.
This example is intended to exemplify the influence of the manufacturing process on both the definition of the receiving structure and the component to be integrated. Thus, the underlying manufacturing processes must be taken into account in more detailed examples of multi-functional hybrid structures.

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3.3. Multi-level structures

The derived design principles each represent only individual possibilities for subdividing elements. In hybrid components, however, several design principles are usually combined with each other at different levels, resulting in significantly more complex multi-level structures. In this way, functions or functional components can be integrated at different positions or on different size scales.

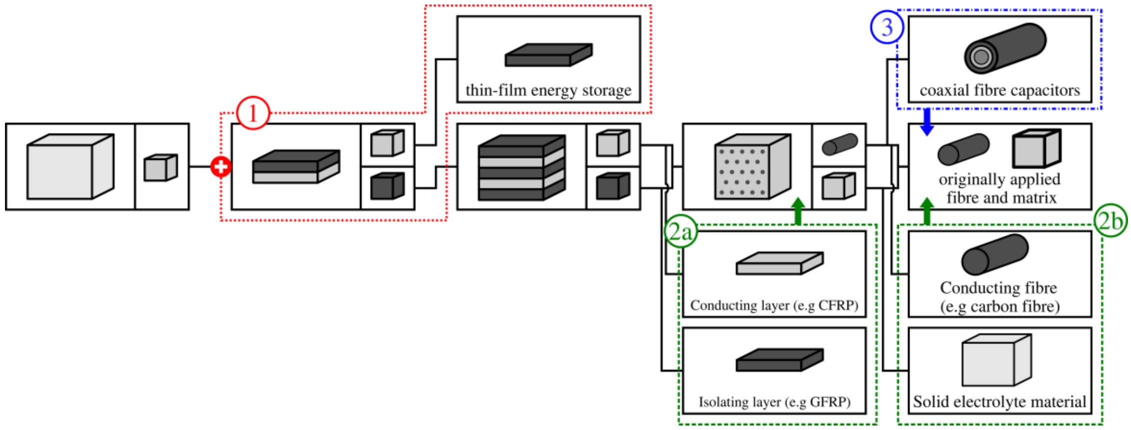

Figure 3. Example of a multi-level structure at the example of a integration of a structural battery into FRP on different level applied to the example of Adam et al. (2018)

Figure 3 shows an example of a multi-level structure using the example of the integration of a battery into an FRP structure according to Adam et al. (2018) already mentioned in section 2. The description of the multi-level structure is tree-like, so that the overall structure shown on the left as a "black box" is increasingly subdivided or defined on the right by the principles in section 3. This representation enables a more detailed consideration of the possibilities for integrating functions or functional components. In this example, the original solution without integrated battery (without additional boxes) is added by additional elements or adapted according to the three presented degrees of functional integration realized by: adding a battery layer in macro scale by an additional segmentation (1), a stacking of conductive layers and insolating layers as separators (2a), conductive fibres and a solid electrolyte material as matrix (2b) or coaxial fibre capacitors (3). As can be seen by this short example, the combination of hybrid principles in multi-level structures is able to represent complex multi-functional hybrid structures.

4. Structuring and provision of multi-functional designs solutions

As the previous explanations have shown, the derived principles can be used to illustrate any number of complex use cases. Thus, not only individual principles, but also more complex examples are relevant for a methodical support in the multi-functional design process. The examples in turn can be specified at different levels of detail. From the resulting variety of different solutions arises the requirement for a structured and application-specific identification of suitable solutions, which again can be provided in form of a database. Since different aspects can be relevant for the identification of suitable solutions, a predefined access logic, as for example in design catalogues, is not expedient. Rather, an attribute-based description of the solutions is required so that variable filtering is possible. Therefore, both principles for hybrid design and functional integration have to be combined to create multi-functional solutions on different resolutions regarding the resulting structure. By increasing the resolution different solutions can be assigned to the former element.
Figure 4 shows the principle of coupling solutions with increasing resolution from left to right at the example of a multi-functional cabin wall by Gumpinger (2009). In this example, only the function of the electrical energy supply by integrating a conductor is considered. The conduction function is realised by an infiltration of porous GFRP by conductive ink combined to a conducting intersection composite in one layer of a multi-layer composite that, again, represents one face of the sandwich. The overall principle is a conducting sandwich structure representing the entire example. By nesting the solutions on different resolutions in this way, a wide variety of partial solutions can be assigned to the respective superordinate

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solution, as a conductive ink in a porous GFRP, for example, is only one possible solution for a conducting intersection composite. Alternatively, the conducting intersection composite can be assigned to the sandwich core as a combination of conductive ink and polymer foam. The upper part of the Figure shows the assignment of a different integration principle of a conducting insert, which can be assigned to the sandwich face or to one layer of the multi-layer composite as well.

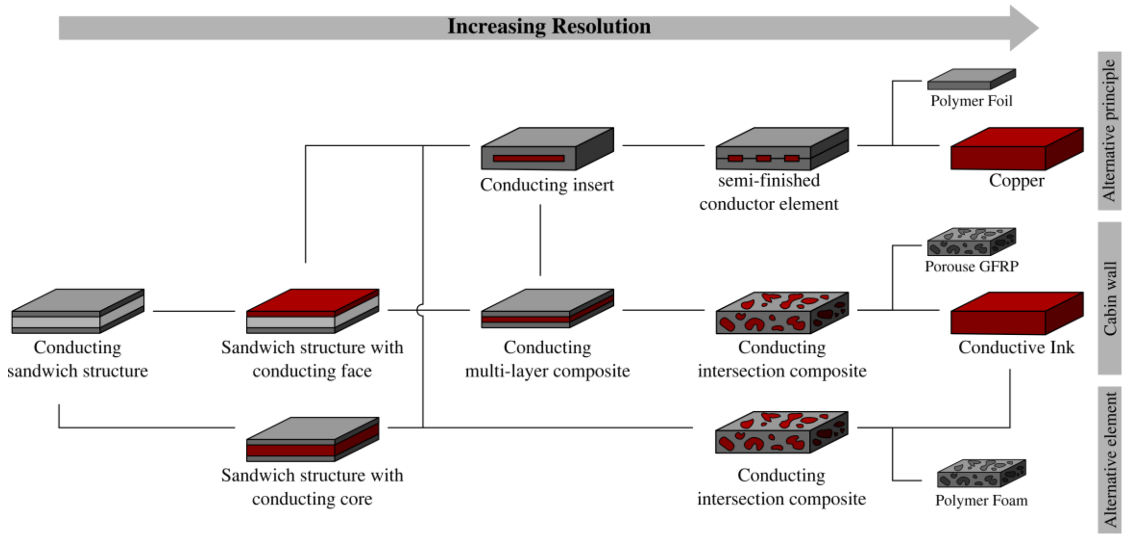

Figure 4. Principle of linking solutions with different resolutions

The result of linking different examples for multi-functional design like this is a database that enables filtering according to hybrid design principles (conducting sandwich structure, conducting multi-layer composite etc.) or principles for functional integration (conductive ink, conductive insert etc.). The abstracted description on the superordinate resolutions also enables an adaptation to the given boundary conditions, such as the application of specific materials. Nevertheless, each solution on higher resolution is assigned the entire real solution as an application example. This also includes the representation of the multi-level structure considering the production route, if this is evident from the application examples. In addition, the database can be supplemented with generic examples of possible implementations.

The filtering can be further optimised by assigning additional attributes for individual solutions. Thus, in addition to the underlying category of the design principles, the strategies for functional integration defined by Klaiber et al. (2019) can also be assigned to the individual solutions. Thus, by selecting the *insert* principle or the *parts integration* strategy, it is possible, for example, to search specifically for solutions for conductor structures that are integrated as inserts. These inserts, again, can be further described. An example is shown by a semi-finished conductor element combining copper wires and polymer foils holding and isolating the conductor. In addition, the solutions can be matched with relevant requirements. The realisation of the electrical conductor through conductive ink, for example, is hardly suitable for applications in which a large number of individual conductors is required.

5. Application for different design scenarios

The previously presented approach enables a structured provision of multi-functional solutions. Due to the different resolutions (see section 4), different questions in the development and thus different development scenarios can be addressed. In the following, three development scenarios with the corresponding questions regarding functional integration are presented as examples. Through this, the support within product development and thus the potential of the developed approach is addressed.

5.1. Scenario 1: Identification of entire solutions

In the first scenario, a multi-functional component is to be developed that enables the conduction of electrical energy. There is fundamental freedom in the choice of materials and manufacturing

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processes, so that an analysis of existing overall solutions is to be carried out first in order to serve as a basis or inspiration for the early development phase.

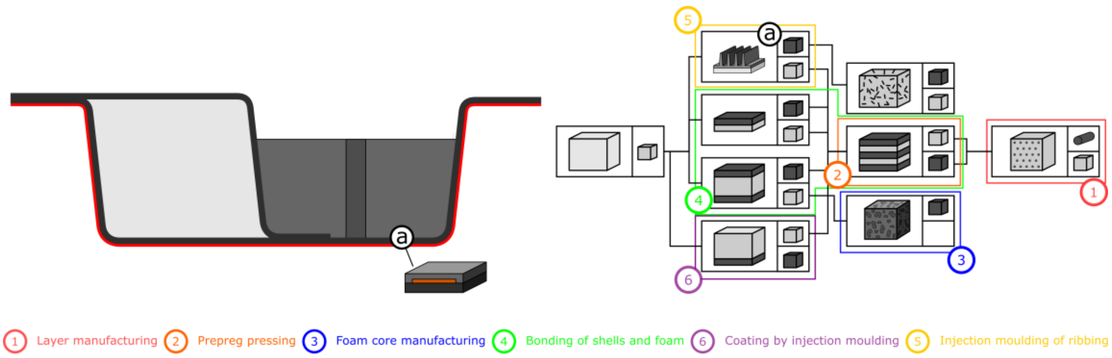

Figure 5. Hybrid profile with integration of conductor as an insert (left) and resulting multi-level structure including the manufacturing processes (right)

Figure 5 shows an example of a component with integrated conductors developed in a research project together with the representative multi-level structure and the associated manufacturing steps. The profile consists of a FRP shell as well as a cover shell over about half of the profile on the left side and contains a foam core. Both FRP shells are manufactured in their final shape by prepreg pressing. The core is made of an extrusion foam. The resulting sandwich structure is realized by a subsequent adhesive bonding under low pressure. The right side of the profile is filled with a polymer ribbing by injection moulding. An additional coating provides the necessary optical quality and colour variance by a separate injection moulding. The entire manufacturing route is shown on the corresponding multi-level structure considering the individual manufacturing processes in sequence of their application (1-6) and assignment to the influenced elements. The conductor insert is integrated in step 2 by overmoulding.
By showing the overall solution, conclusions can be drawn about the requirements to be met by the implementations and the feasibility. In addition, individual branches of the multi-level structure can be further considered for the development.

5.2. Scenario 2: Identification of partial solutions for a specific design

In the second scenario, electrical conductivity is to be integrated in an FRP multi-layer composite profile. Thus, there are already specifications regarding the design in the form of the materials to be used and the manufacturing processes. Therefore, it is possible to search for specific design principles in combination with the applied materials. However, the above-mentioned specifications also generally offer certain freedoms that can be used for the integration of functions.

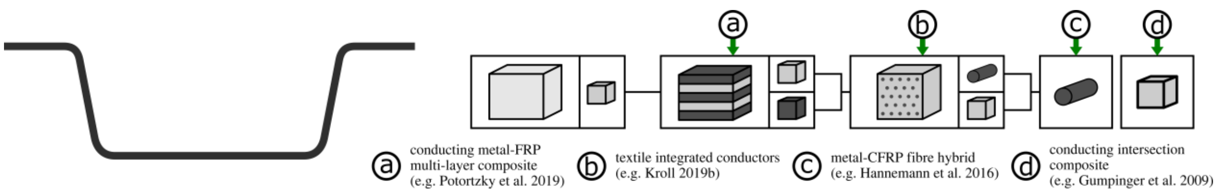

Figure 6. Multi-functional solutions basing on specific design principles

Figure 6 shows the multi-level structure of the component together with possible integration approaches. By linking solutions as shown in section 4, it is possible to find solutions for subordinate structures based on the multi-layer composite. The integration can, for example, applied by a conducting metal-FRP multi-layer composite, metal-CFRP Hybrids, conductive fibres or an intersection composite matrix. Generally, an integration of additional functions requires an alteration or additional elements. Therefore, it is of importance on which level the alterations can be made without influencing critical properties.

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5.3. Scenario 3:Identification of specific integration approaches

In this scenario, the design requires a specific integration of the conductor by an insert. This leads to a higher flexibility or adaptability in the design of the components as well as the conductor. The component and the multi-level structure is the same as in scenario 1.

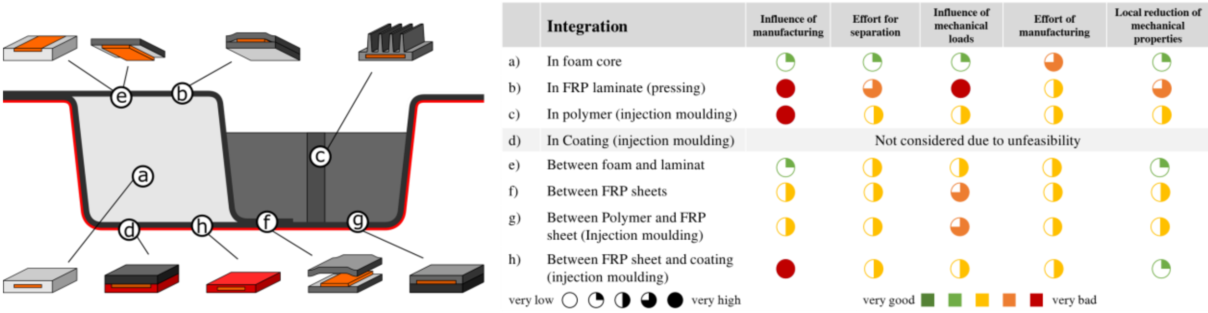

Figure 7. Possible positions of conductive inserts with different influences by manufacturing

Figure 7 shows possible positions of the insert. The different positions result in different requirements for the insert. The requirements result from different boundary conditions by the manufacturing, influences in the use phase and an end of life separation. As can be seen on the right, each position has very specific requirements. Therefore, different approaches for conductor inserts can be necessary. The influence of manufacturing by high pressures and temperatures, for examples, are low in case of an integration into the foam core. On the contrary, these influences are very high for an integration into the FRP laminate. These conditions require a solution that is either more resistant or less affected by the conditions.

6. Conclusion and Outlook

This paper presented an approach to identify suitable solutions for multi-functional design considering different design approaches or material combinations by a description and categorisation of different design principles. By combining these principles complex multi-level structures can be represented and associated to manufacturing processes. By this, suitable principles for function integration can be identified on different level and positions of the hybrid structure representing the component to be developed. The identification of different solutions can be provided by a database, including solutions for functional integration for different resolutions of the structure. Therefore, the resulting methodical tool can be a significant support in the design of multi-functional components.

As integrating a function can be realised in very different ways, the approach has to be extended by a further consideration of integration principles considering actual requirements on the function from different use cases. This allows an application-specific filtering and, thus, identification of solutions.

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