21ST INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED17
21-25 AUGUST 2017, THE UNIVERSITY OF BRITISH COLUMBIA, VANCOUVER, CANADA

FIBER-REINFORCED COMPOSITE DESIGN WITHIN A LIGHTWEIGHT AND MATERIAL-ORIENTED DEVELOPMENT PROCESS

Kaspar, Jerome; Vielhaber, Michael
Saarland University, Germany

Abstract

The need for lighter, stronger and stiffer structures has long been of central importance for the product development of (high-tech) lightweight systems across several industries. Accordingly, apart from the today's extensive gain in constructive and technological engineering skills, particularly new high-strength materials lead to satisfy the present rigorous requirements (e.g. mandatory national CO2 regulations in automotive industry) for lightweight engineering in a much deeper dimension. Nevertheless, advanced composites such as fiber-reinforced plastics (FRP) are often used as "black metal" by simply keeping the geometry of a metal component and replacing the material, even though the predicted performance will rarely match expectations. As a consequence, and to address hitherto untapped potentials in terms of lightweight design, there is an urgent need for a systematic approach of a (intelligent) topology-optimized methodology focused on a detailed, but also integrated constructive and technological procedure to specify and optimize composite structures within nowadays requested multi-material systems. Therefore, a corresponding approach is presented in this contribution.

Keywords: Design for X (DfX), Design methodology, Design process, Fiber-reinforced composites, Lightweight design

Contact:
Jerome Kaspar
Saarland University
Institute of Engineering Design
Germany
kaspar@lkt.uni-saarland.de

Please cite this paper as:
Surnames, Initials: *Title of paper*. In: Proceedings of the 21st International Conference on Engineering Design (ICED17), Vol. 1: Resource-Sensitive Design | Design Research Applications and Case Studies, Vancouver, Canada, 21.-25.08.2017.

1 INTRODUCTION

Lightweight materials and design have long been of central significance for product development across several industries such as the highly sensitive sector of aerospace. Nevertheless, today the growing demand for technical capabilities in terms of more safety and comfort while simultaneously increasing the resource efficiency, and consequently reducing emissions (mandatory national CO2 regulations) with an improved mileage constantly, lead to further requirements for lightweight engineering as one of the key elements within the automotive industry (McKinsey&Company, 2012). Considering the aforementioned matter, this can not only be achieved with the broad band of new lightweight technologies and high-strength materials. In fact, there are also new lightweight concepts beyond classical construction methods needed, e.g., individual ways of component dimensioning (according to the optimal use of installation space and component loading) and functional integration. Therefore, and under this premise, the trend in modern lightweight systems is increasingly turning away from the singular steel and aluminium designs towards far more innovative composite constructions. Recent prominent examples such as the automobile (BMW Project i) and aircraft industry (Boeing 787 Dreamliner) already gradually lend evidence to this trend gaining momentum.

In general, the resultant ability of composite components to outperform conventional metal design originates from the necessity of lighter, stronger and stiffer high-tech structures along with the emerging constructive and technological engineering skills to get the best out of all materials, and consequently achieve optimized material properties. Notwithstanding the above, advanced composites such as fiber-reinforced plastics (FRP) are often used as “black metal” by simply keeping the geometry of a metal component and replacing the material, even though the predicted performance (e.g. unidirectional high strength values) will rarely match expectations. As a consequence, and due to the address of hitherto untapped potentials in terms of lightweight design, there is an urgent need for a systematic approach of a bionic-oriented and topology-optimized methodology focused on a detailed constructive and technological procedure to specify and optimize composite structures within nowadays requested multi-material systems.

Accordingly, the structure of the contribution is as follows. First, a short summary of the different general as well as domain-specific state-of-the-art methodologies will be given in section 2. On this basis, and followed by an appropriate determination of particular deficits, section 3 outlines a lightweight and material-oriented design (LMOD) methodology in view of multi-material systems as previously established by the authors. Consequently, this generates the fundamental framework for the further on elaborated approach according to composite components in particular with regard to an integrated view on the product, material and production process design in section 4. Finally, section 5 will discuss the findings and conclude by providing an outlook.

2 STATE OF THE ART

Systematic approaches in the area of product development retrospect on a long history. In light of the industrial and technological breakthrough due to social and economic changes occurring in the late 19th to early 20th century, the engineering sector was suddenly faced with completely different, i.e. largely more complex, conditions. Thus, methodological approaches for the conceptual design of versatile product systems were needed in order to systematically overcome these novel and application-oriented problem solutions. Bischoff and Hansen (1953) as well as Bock (1955) are today seen as the pioneers of such first, holistic representations of an engineering systematics (Pahl and Beitz, 1996). Ever since this time and during the past decades, the combination of individual relationships between science and product design or, more specifically, the transfer of scientific methods to the conceptual design and construction has received an ever increasing attention. As a consequence, a multitude of different (domain-specific) approaches for the development of technical products are nowadays available, as exemplarily listed in Pahl and Beitz (1996).

Standardized and internationally well-known product development processes, such as these developed by Ullman (2010), Pahl and Beitz (1996) or rather VDI 2221 (1987) as well as Ulrich and Eppinger (2000), frequently describe the general procedure in detail exclusively from a product designing perspective - starting from the actual product planning and clarification of the development task up to the detailed product design as well as further realizations (e.g. SOP). Corresponding differences and subsequently fundamental deficits of those development methodologies may be found in (Kaspar et al., 2017). Moreover, other approaches tend to be partially more material (Ehrlenspiel and Kiewert, 1990; Farag, 2014) or process-specific (Eversheim, 2002). However, concerning today's extensive gain in engineering skills (e.g. computational tools) and due to current technological developments (materials and manufacturing processes), it is absolutely necessary and required for composite structures to take all related aspects (possibilities but also restrictions) besides the constructive designing equally into account, including material types with an appropriate dimensioning as well as corresponding manufacturing techniques, see Figure 1.

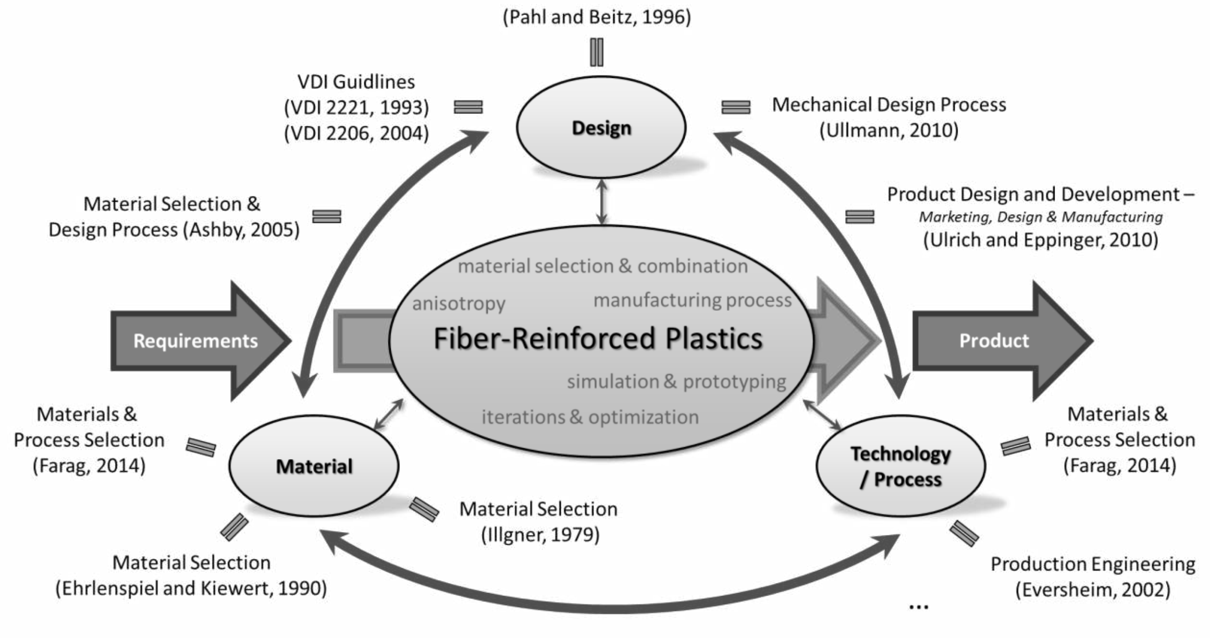


Figure 1. Problems within existing (illustrative) approaches

Although there are already isolated approaches (as pointed out in Figure 1), a holistic view of product design, material selection (dimensioning) and production process ("magical triangle" of future lightweight systems (Kaspar et al., 2016a), according to Bernst (1975)) will even not be applicable within the predestined area of lightweight design. Thus, e.g. Klein (2013), uses the classical approach of Pahl and Beitz (1996) in his lightweight-oriented product development methodology, but assigns exclusively basic aspects or thought-provoking impulses of a lightweight engineering design along its individual phases (clarification of the task as well as conceptual, embodiment and detail design). Besides this, Krause (2012) also describes a similar, but somewhat more detailed approach, e.g. especially concerning modern constructive methods and calculation tools primarily in the form of a computer-assisted structural optimization. Moreover, and compared to both predecessors, Ellenrieder et al. (2013) describe a different, three-phase systematic approach including various lightweight strategies in terms of constructive, technological and material-specific aspects while, at the same time, differentiating into both the overall system and individual components.

Despite these efforts, however, a real integration with simultaneous influences of the respective aspects, in particular the decisive structural and technological effects on and/or due to a changed material selection or dimensioning, remains largely unfulfilled.

Apart from this rather constructive approach in lightweight design, there are also various efforts, first and foremost pertaining to a systematic selection of materials (Ashby, 2005) and supplementary with partly concrete manufacturing interdependencies (Illgner, 1979; Ashby et al., 2004). At this point, and referring to the aforementioned traditional design phases, these procedures can basically also be classified into four material-relevant stages. Beginning with the gathering of material-relevant requirements and the subsequent screening according to permissible material classes (pre-selection) up to the specific selection of experimentally confirmed materials (fine-selection and specification), all stages are realized. In doing so, amongst others, Ashby (2005) also goes into detail in the design of hybrid materials as sandwich construction, but neglects, like other authors (e.g. Lauter (2014) with his goal-oriented and systematic approach to the development of hybrid lightweight structures integratively in light of product design, material selection and production process), a detailed design selection methodology for composite structures. But precisely this procedure is deemed to be indispensable, in particular due to the tremendous plurality of degrees of freedom, e.g. containing suitable matrix modifications for fiber selection and fiber combination as well as their volume content along with the appropriate fiber orientation, layer sequence and thickness (number of plies), when faced with these complex anisotropic fiber-reinforced composites.

Therefore, Davalos et al. (2006) and Monroy Aceves et al. (2008), amongst a few others, e.g. Bader (1996), already recognize the basic necessity of a systematic methodology for analysis and design of FRP composite structures, as shown in Figure 2.

Monroy Aceves et al. (2008) orient themselves fundamentally to the internationally accepted approach of Ashby and Johnson (2002) and provide a step-by-step guide in terms of a flowchart to the procedure, which is, in essence, built up on Weaver's methodology (Weaver, 2002) for laminate selection, but additionally introduces a structural analysis into the methodology. In this case, the design process starts with the design brief (framework for the design) and goes through the individual steps of the definition of the problem, the finite element analysis and the creation of a database up to the selection process and optimization and, finally, adequate results. Therein, all steps from the material family (e.g. CFRP, Kevlar or glass fibers) and the subsequent number of plies, determination of lay-up (e.g. $[0/90/\pm 45]$ or $[0/90_3]$) and much more are covered in a hierarchical way, notably by means of Ashby's selection methods (material performance indices, e.g. E/ρ, with corresponding design guide lines inside a material property chart) and the CES selection "engine" (Granta Design Ltd., 2015). Thus, in comparison to Davalos et al. (2006), the power of this alternative approach (non-complex / non-numerical optimization method) deals not only with the simplicity of which the material determination and dimensioning can be visualised, but also the ease of which the designer can interact with the amount of data.

Using a similar but more (mathematically) detailed procedure, Davalos et al. (2006) or, respectively, Qiao and Davalos (2013) represent a "bottom-up" approach for all-FRP structural components and systems. Being categorically split into three design phases, i.e. micro level (material and microstructure), macro level (structural component) and system level (structure), the procedure can be employed to design and optimize components solely being manufactured using the pultrusion process. According to this, an essential focus among all these activities is on the macro level, meaning the technical design of structural members (e.g. shape and strength of pultruded FRP panels). A corresponding elaboration on cross-component aspects and with it considerations to integrate (assemble) components / subsystems to an overall system are only be outlined marginally. Moreover, manufacturing changes and unavoidable influences are completely neglected.

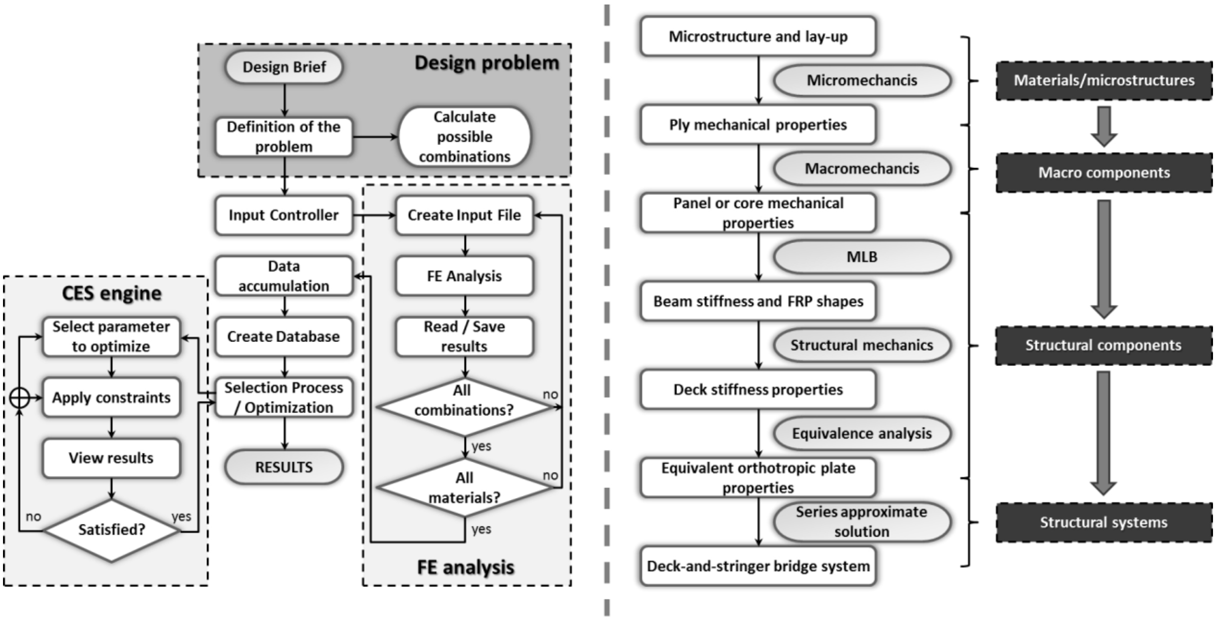


Figure 2. Systematic analysis methodologies (flowcharts) for FRP structural composites: Monroy Aceves et al. (2008) (left), Qaio and Davalos (2013) (right)

All in all, however, the scientific literature contains various approaches providing the link between the traditional product development process and fundamental lightweight aspects with regard to composite-specific measures. Nevertheless, and even though some approaches partly fulfill the common deficits of (according to Kaspar et al., 2017)

- an exclusive design on functional and constructive aspects, instead of a stronger integration of the respective production processes and the appropriate material selection (e.g. mostly material and process-independent evaluation and selection of solution principles and their combination, instead of an integrated assessment),
- an extensive neglect of modern computational tools (e.g. topology and shape optimization), and
- the predominant division into modules, but neglecting the joint section definition and design,

a holistic product development process of fiber-reinforced composites, and thus a detailed material specification (fiber and matrix material type, lay-up, etc.) due to an integrated view of design, material and process could not be traced inside a lightweight and material-oriented engineering approach. Nonetheless, this is necessary, precisely because of the nowadays demanded and more efficient cost-benefit ratio of the so-called multi-material systems, instead of complete product designs made of composites.

3 FRAMEWORK OF COMPOSITE-SPECIFIC LMOD

Considering the aforementioned facts, and given the significant spare capacities available, Kaspar and Vielhaber (2016b) describe an integrated and cross-component lightweight and material-oriented design (LMOD) methodology, as depicted in Figure 3. This sets the framework of the subsequent holistic product development process of fiber-reinforced composites (see section 4).

Accordingly, the framework methodology follows in principle the traditional development process (i.e. the four traditional phases to successively specify the product (VDI 2221, 1987)), but is being divided into a (system) analysis, detailing and integration phase, originating from the system to the component level and back again.

Unlike the VDI 2206 (2004) and its single integration phase, however, cross-components aspects are used herein as a key factor and meanwhile system validation (assurance of system requirements). Due to this explicit examination of the joint section design, and thus the demand of an integrated view of product design (yellow marked), material selection (red marked) as well as production process (blue marked), lightweight structures can structurally be adapted and optimized in accordance with new technological and scientific developments, or vice versa (Kaspar et al., 2016a). Therefore, the first half of the structural and technological W-shaped model gradually starts to converge (i.e. an increasing dependency) toward the joint section design, which coincides with the thoughts published in (Stoffels et al., 2015) and matches with direct interrelations corresponding to cross-component aspects.

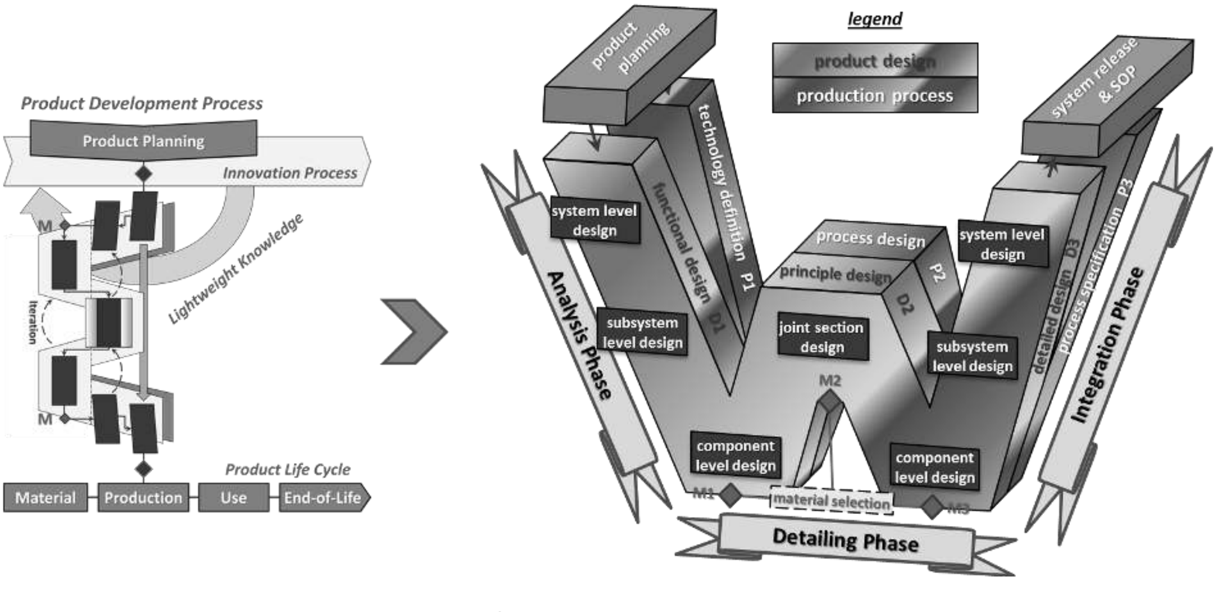


Figure 3. W-Model of the LMOD methodology, based on Kaspar et al. (2016a)

4 HOLISTIC FRP COMPOSITE PRODUCT DEVELOPMENT PROCESS

4.1 The Systematic Procedure

Assuming the above-mentioned framework of a lightweight and material-oriented design methodology, the partial use of different fiber-reinforced composites needs to be consistently addressed in addition to a global multi-material design. Thus, and according to the more general approach concerning hybrid additive materials presented in (Kaspar et al., 2017), a detailed flowchart of a holistic FRP composite product development process regarding an integrated view of product design, material design (selection and dimensioning) and process selection is depicted below (see Figure 4).

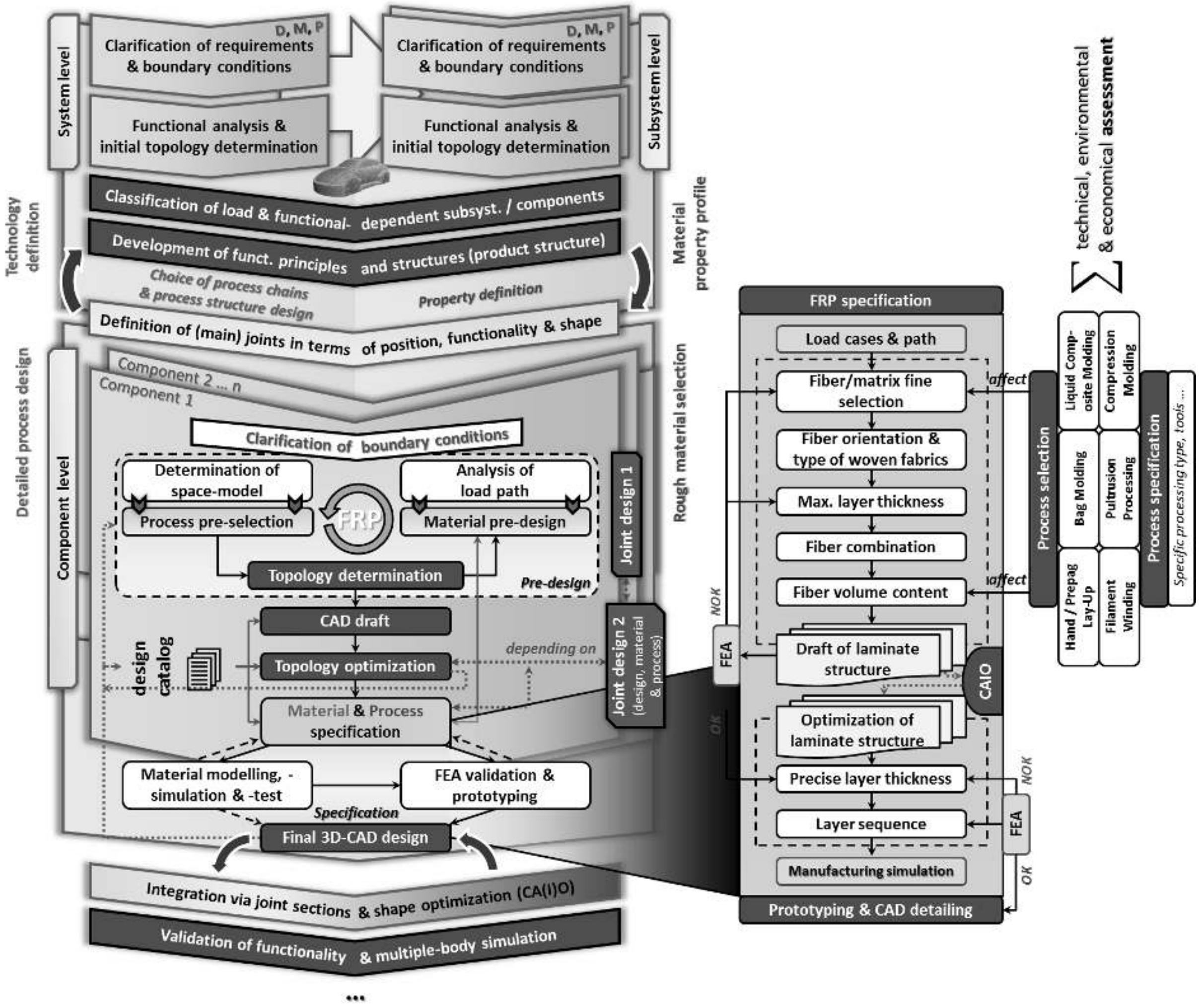


Figure 4. Fiber-reinforced composite design within a lightweight and material-oriented engineering approach

Starting with the clarification of certain requirements and boundary conditions (i.e. system space and load cases) in view of the overall system design (D) as well as production (P) and material-specific (M) technical specifications (e.g. information and infrastructures from pre-production series), a functional analysis along with an initial topology determination is carried out step by step on system and subsequently on subsystem level. This enables a first functional design, which can lead to first rapid prototypes (model making issue) concerning the rough visualisation of the considered concept (previously elaborated sketches / CAS). Afterwards, the respective development of various operating principles is subsequent to a corresponding classification into load-path and function-dependent components. In this manner, the creation of the product structure is subject to an iterative consideration by a general definition of the joint section design (position, functionality and shape) with regard to dependencies of an overall technology definition (i.e. process chain selection along with a suitable process structure design) and a suitable material property profile to be determined in parallel. The main reason for this are the production processes of fiber-reinforced composites, which are currently still not economically competing with classical production processes. As a result, multi-material systems are in demand within the vast majority of today's lightweight systems, in particular concerning extremely complex or functional structures. Following a corresponding rough design of the system, the detailing phase follows on component level for the herein focused fiber-reinforced composites.

Compared to traditional procedures for classic and well-tested construction materials and processes, a partly different procedure applies to the conception and design of composite structures, especially relating to the multifaceted design of FRP itself. As the production process and the material design in terms of selection and dimensioning are strongly influenced by each other, these decisions must categorically be made at an early stage. Accordingly, and based on the previously determined basic position, functionality and shape of the adjacent joints, the pre-selection of the fundamental process is first pursued depending on the present space-model of the component (separated out of the initial topology determination on subsystem level) and the appropriate boundary conditions (including cross-component (i.e. mainly material) aspects regarding the joint section designs). This is necessary to ensure the ideal manufacturability of the following (intelligent) determination of the process-optimized topology (so-called soft kill option (SKO)) due to individual restrictions of design (e.g. hand lay-up vs. pultrusion process).

According to the analysis of the consequent load paths, the material pre-design is concerned. In that regard, a first estimation or tendency is done in respect of what fiber material is being used in which matrix material with regard to an underlying orientation. The fine selection (i.e. dimensioning) of the material components takes place in a later phase of the design process and is based, amongst others, on more detailed knowledge about the ultimately acting stresses, and thus the required maximum layer thickness, but also costs. Nevertheless, the assumptions made for the pre-design can be iteratively repeated several times (notably for a number of material/manufacturing combinations) and are not fixed, but rather picked up again throughout the material and process specification. Thus, this is only intended as a guide for the engineers in order to take account of constructional measures in advance, whereby a first CAD draft emerges from the pre-design process.

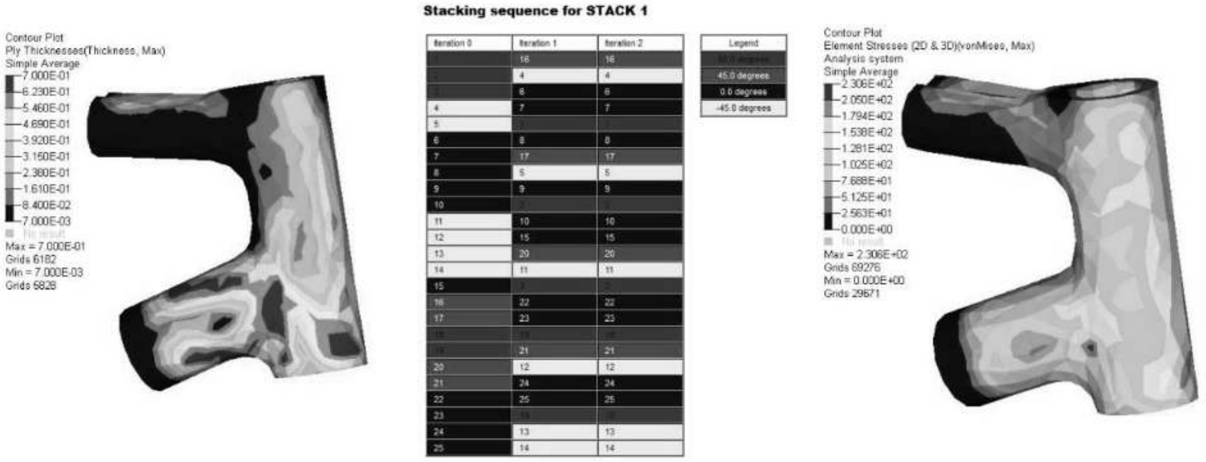
If the combination is suitable for the construction of the component, the holistic consideration of the joint section design can be started, which will not be discussed here in detail (further research work). However, different material types or even classes of the component and the corresponding joints are deemed to be very challenging and must be weighed in functional, but also environmental and economical balance. Consequently, and right after the detailed design of these adjacent joint sections, the topology optimization of the shared view of component plus joints is next. Here, the geometric shape of both the component and joints are adjusted in such a way that a homogeneous stress distribution can be aspired. Thereby, the shape is also redefined and adapted to the required design guidelines for fiber composite materials according to the design engineering measures described, amongst others, in VDI 2014 (1993). If there are no conflicts concerning the assurance of properties in terms of system space, linkage as well as material and process, the fundamental shape development can be finalized, and thus an advanced material and process specification can be applied to the holistically optimized component. Therein, the specification phase describes a diamond-shaped procedure which can be passed iteratively in various ways, including the main steps of the

- actual material and process specification,
- material modelling, simulation and test,
- FEA validation and, building on that, prototyping, and ultimately
- the final 3D-CAD design.

The material specification (i.e. construction) is the key part of the designing with fiber composite materials and can be seen as an optimization step inside the specification process of the component. As already stated in the flowchart model on the right side, it quickly becomes obvious that the multitude of degrees of freedom, and hence the design variables, have a clear tendency to several iterations or rather optimization steps. The material design is based on the topology-optimized CAD draft. This also means, conversely, that changes to the CAD model also result in a new or modified material construction. But, altered values of the material construction can also force a change to the CAD model, for example, by larger layer thicknesses. Nevertheless, the material construction per se remains an independent optimization process (exception: the locally affected process selection and specification), despite the strong influences from the outside.

The preliminary procedure of the material construction consists of, among other things, the choice of the fiber/matrix combination, the fiber orientation and type of woven fabrics, the maximum required layer thickness and the combination of different fiber types. For a precise selection of suitable materials, the applied stresses on the CAD model must first be established, e.g., by means of approximate FEA calculations or known forces. The rough selection of materials (material pre-design) already defined a material class, by which only suitable types of specific fiber/matrix materials have to be selected here. Afterwards, the FRP specification process then progresses gradually with the support of the FEA results after the first iteration on the draft of the laminate structure. While doing so, the upper optimization cycle of the laminate pre-design is partly influenced or rather affected by the individual manufacturing process (e.g. achievable fiber volume content by the selected process). However, the process simulation and hence the resulting insights are only supplemented after the fine adjustment of the laminate within the FRP specification cycle. Nonetheless, and based on the already selected manufacturing process, boundary conditions can be used in the first run of the optimization, for example, in the choice of textile type. Subsequently, the preliminary design of the laminate is achieved with the estimation of the maximum layer thickness along with potential fiber combinations.

By means of suitable FEA tools with composite support (so-called computer aided internal optimization (CAIO) including coordinate systems and layer-wise calculation possibilities), the obtained results are further elaborated, as shown in Figure 5.



Stacking sequence for STACK 1

Iteration 0	Iteration 1	Iteration 2
1	16	16
2	4	4
3	6	6
4	7	7
5	1	1
6	8	8
7	17	17
8	5	5
9	9	9
10	2	2
11	10	10
12	15	15
13	20	20
14	11	11
15	3	3
16	22	22
17	23	23
18	18	18
19	21	21
20	12	12
21	24	24
22	25	25
23	19	19
24	13	13
25	14	14

Legend
90.0 degrees
45.0 degrees
0.0 degrees
-45.0 degrees

Figure 5. Optimized results of the laminate structure due to CAIO (bicycle head tube)

Depending on the selected layer thickness and the required distribution, an adequate thickness optimization and therefore a mass reduction can be achieved by calculating the exact layer thickness. Based on this, the layer sequence (preferably balanced symmetric laminate) can be adapted in a subsequent step, by which the stresses can continuously be minimized. Again, subject to the distribution and sequence of the layer, different material properties may result from this approach. This small optimization cycle is complemented and carried out by repeatedly using FEA. Once an adequate solution is being found by the fine optimization with respect to the provided parameters, the pure material construction process is completed and followed by the aforementioned manufacturing simulation. With the application of this measure for quality assurance purpose, possible draping or displacement errors can be indicated and prevented (depending on the type of fault and behaviour) by appropriate iterations in the entire FRP specification process just before the actual prototyping starts. In this latter case, final material errors, shape problems or, in rare cases, design errors are recognized and often lead to last process-related adaptions. At the end of the material optimization, a defined composite material along with its required geometric structure is available, which has precisely been adapted to the current (final) 3D-CAD model and its loads for the actual investigated component.

Finally, each individual component (of the multi-material design) is being interlinked with the integration through the specific component joints, designed and transferred from the respective joint section design (detailing phase). In addition, this allows final form optimizations (CA(I)O) depending on the material-specific construction of the particular component along with the adjacent joints. A subsequent modelling and simulation step, including a multiple-body simulation combined with the actual validation of functionality, as well as a prototype manufacturing for concrete, realistic statements on the subsystem behaviour (concerning assembly-related impacts) provide a further vertical integration via the main joints to the "system level design".

4.2 Validation of the Systematic Approach Using the Example of a Bicycle Frame

This complete procedure has exemplarily been carried out for a multi-material bicycle frame with the intention to validate the outlined fiber-reinforced composite engineering approach within the lightweight and material-oriented development framework. Therefore, the above Figure 5 already presented an extractive material construction of a FRP component. A more general design of the FRP bicycle chain stay in conjunction with the adjacent joint sections is further on illustrated in Figure 6. To realize this complex design, the innovative technological and procedural conception of a hybrid manufacturing process in terms of a selective laser-sintered core structure is applied, which serves as a base for the cladding with fiber-reinforced plastics (Kaspar et al., 2017).

Figure 6. Final design of the bicycle chain stay in conjunction with the adjacent joint sections

5 DISCUSSION AND OUTLOOK

To sum up, and as a result of current technological advances, especially in terms of the ever-increasing use of certain fiber-reinforced composite structures (and its corresponding plurality of degrees of freedom), this contribution faces the actual deficits within the broad range of engineering approaches. Based on this, a systematic FRP design methodology within a lightweight and material-oriented development process is developed to provide an even better support for the design and engineering of competitive lightweight systems. Thus, originating from the determined position and functionality of the individual joints (based on the preliminary topology determination of the subsystems) and the ensuing fundamental joint section design up to the subsequent detailed construction of the particular FRP components and their final integration through the minor modified joint sections, the above described approach leads to a topology-optimized and tailor-made (anisotropic) material and process-specific system design.

Although this contribution provides a holistic and systematic procedure for the fiber-reinforced composite design, a concrete assessment and reciprocal selection of the technically, environmentally and economically best material and process solution is desirable in the future. Actual scientific efforts are currently investigating this complex issue with the aim of developing a corresponding concept of a material and process selection tool fundamentally based on the selected operating principle regarding the individual functional structure (continuing work of Stoffels et al. (2017)). On this basis, moreover, cross-component aspects will particularly be pursued in future.

REFERENCES

Ashby, M.F. and Johnson, K. (2002), *Materials and Design*, Butterworth-Heinemann, Oxford.

Ashby, M.F., Bréchet, Y.J.M., Cebon, D. and Salvo, L. (2004), "Selection strategies for materials and processes", *Materials and Design*, Vol. 25 No. 1, pp. 51–67. http://dx.doi.org/10.1016/S0261-3069(03)00159-6

Ashby, M.F. (2005), *Materials Selection in Mechanical Design*, Butterworth-Heinemann, Oxford.

Bader, M.G. (1996), "Materials selection, preliminary design and sizing for composite laminates", *Composites Part A*, Vol. 27 No. 1, pp. 65–70. http://dx.doi.org/10.1016/1359-835X(95)00003-K

Bernst, R. (1975), *Werkstoffe im wissenschaftlichen Gerätebau*, Akademische Verlagsgesellschaft Geest & Portig, Leipzig.

Bischoff, W. and Hansen, F. (1953), *Rationelles Konstruieren: Ein Beitrag zur wissenschaftlichen Systematik und zur Rationalisierung der schöpferischen Ingenieursarbeit*, VEB Verlag Technik, Berlin.

Bock, A. (1955), *Konstruktionssystematik - die Methode der ordnenden Gesichtspunkte*, Feingerätetechnik 4.

Davalos, J.F., Qiao, P. and Shan, L. (2006), “Advanced fiber-reinforced polymer (FRP) structural composites for use in civil engineering”, In: Wu, H.C. (Ed.), *Advanced civil infrastructure materials*, Woodhead Publishing Limited, Cambridge, pp. 118–202.

Ehrlenspiel, K. and Kiewert, A. (1990), “Die Werkstoffauswahl als Problem der Produktentwicklung im Maschinenbau”, *VDI-Berichte 797: Ingenieur-Werkstoffe im technischen Fortschritt*, VDI-Verlag, München.

Ellenrieder, G., Gänsicker, T., Goede, M. and Herrmann, H.G. (2013), “Die Leichtbaustrategien”, In: Friedrich, H.E. (Ed.), *Leichtbau in der Fahrzeugtechnik*, Springer Vieweg, Wiesbaden, pp. 43–118. http://dx.doi.org/10.1007/978-3-8348-2110-2_3

Eversheim, W. (2002), *Organisation in der Produktionstechnik*, Springer-Verlag, Berlin.

Farag, M.M. (2014), *Materials and Process Selection for Engineering Design*, CRC Press, New York. http://dx.doi.org/10.1201/b16047

Granta Design Ltd. (2015), *CES Selector, version 15.10.8*. Cambridge. Available at: www.grantadesign.com.

Illgner, K.-H. (1979), “Werkstoffauswahl für den Konstrukteur”, *VDI-Z*, Vol. 121 No. 10(II), pp. 1027–1030.

Kaspar, J., Baehre, D. and Vielhaber, M. (2016a), “Material Selection Based on a Product and Production Engineering Integration Framework”, *Procedia CIRP*, Vol. 50, pp. 2–7. http://dx.doi.org/10.1016/j.procir.2016.04.181

Kaspar, J. and Vielhaber, M. (2016b), “Cross-Component Systematic Approach for Lightweight and Material-Oriented Design”, *DS 85-1: Proceedings of NordDesign 2016*, Vol. 1, Trondheim, pp. 332–341.

Kaspar, J., Häfele, T., Kaldenhoff, C., Griebsch, J. and Vielhaber, M. (2017), “Hybrid Additive Design of FRP Components - Fiber-Reinforced Sandwich Structures Based on Selective Laser Sintering Technology”, *Procedia CIRP, Proceedings of the 27th CRIP Design Conference*, Cranfield, 10-12 May 2017.

Klein, B. (2013), *Leichtbau-Konstruktion: Berechnungsgrundlagen und Gestaltung*, Springer-Verlag, Berlin. http://dx.doi.org/10.1007/978-3-658-02272-3

Krause, D. (2012), “Leichtbau”, In: Rieg, F. and Steinhilper, R. (Ed.), *Handbuch Konstruktion*, Carl Hanser Verlag, München, pp. 465–484.

Lauter, C. (2014), *Entwicklung und Herstellung von Hybridbauteilen aus Metallen und Faserverbundkunststoffen für den Leichtbau im Automobil*, doctoral dissertation, Paderborn University.

McKinsey&Company (2012), *Lightweight - heavy impact*, Advanced Industries.

Monroy Aceves, C, Skordos, A.A. and Sutcliffe, M.P.F. (2008), “Design selection methodology for composite structures”, *Materials and Design*, Vol. 29 No. 2, pp. 418–426. http://dx.doi.org/10.1016/j.matdes.2007.01.014

Pahl, G. and Beitz, W. (1996), *Engineering Design: A Systematic Approach*, Springer, Berlin. http://dx.doi.org/10.1007/978-1-4471-3581-4

Qaio, P. and Davalos, J.F. (2013), “Design of all-composite structures using fiber-reinforced polymer (FRP) composites”, In: Uddin, N. (Ed.), *Developments in fiber-reinforced polymer (FRP) composites for civil engineering*, Woodhead Publishing Limited, Cambridge, pp. 469–508. http://dx.doi.org/10.1533/9780857098955.2.469

Stoffels, P., Bähre, D., Frey, G. and Vielhaber, M. (2015), “Energy Efficiency Engineering - Towards an Integrated Method Framework for Energy-oriented Product and Production Development”, In: Oral A.Y. et al. (Ed.), *2nd International Congress on Energy Efficiency and Energy Related Materials (ENEFM2014)*, Springer International Publishing, Cham, pp. 291–297. http://dx.doi.org/10.1007/978-3-319-16901-9_35

Stoffels, P., Kaspar, J., Bähre, D. and Vielhaber, M. (2017), “Holistic Material Selection Approach for More Sustainable Products”, Procedia Manufacturing, Vol. 8, pp. 401-408. http://doi.org/10.1016/j.promfg.2017.02.051

Ullman, D.G. (2010), *The Mechanical Design Process*, McGraw-Hill Higher Education, Boston.

Ulrich, K.T. and Eppinger, S.D. (2000), *Product Design and Development*, Irwin/McGraw-Hill, Boston.

Verein Deutscher Ingenieure (VDI) (1987), *VDI-Guideline 2221: Systematic approach to the development and design of technical systems and products*, Translation of the German edition 11/1986, VDI-Verlag, Düsseldorf.

Verein Deutscher Ingenieure (VDI) (1993), *VDI-Richtlinie 2014: Entwicklung von Bauteilen aus Faser-Kunststoff-Verbund - Konzeption und Gestaltung*, VDI-Verlag, Düsseldorf.

Verein Deutscher Ingenieure (VDI) (2004), *VDI-Guideline 2206: Design methodology for mechatronic systems*, VDI-Verlag, Düsseldorf.

Weaver, P.M. (2002), “On laminate selection and design”, *43rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, Denver, 22-25 April, American Institute of Aeronautics and Astronautics, Vol. AIAA-2002-1220, pp. 1–11. http://dx.doi.org/10.2514/6.2002-1220