**NordDesign 2016**
**August 10 – 12, 2016**
**Trondheim, Norway**

# Cross-Component Systematic Approach for Lightweight and Material-Oriented Design

**Jerome Kaspar, Michael Vielhaber**

*Institute of Engineering Design, Saarland University, Germany*
*kaspar@lkt.uni-saarland.de*

## Abstract

Apart from the emerging futuristic vision of a fourth industrial revolution, the issue of lightweight design is one of the most predominant innovation drivers and technology trends within the industrial product development (*BMWi*, 2015; *McKinsey&Company*, 2012). Due to the continuously increasing introduction of high- and super high-strength steel as well as the partial use of different aluminium alloys and FRC (fibre-reinforced composites), the present design exclusively or rather mainly attributed to metal or composite materials is being replaced more and more by a multi-material construction, especially in the transport sector (e.g. aviation and automotive industry) (Lieberwirth & Kampitz, 2015). Consequently, many choices have to be made when designing in multi-material systems, which increase the design freedom whilst making the process more complex. However, to achieve the full potential, hybrid concepts require a holistic approach including a significantly stronger integration of the respective conceivable production process (form, join and finish) besides the common material selection primarily based on the developed design. In addition, the frequently neglected or just inadequately supported essential lightweight aspect of functional interrelations between different system components should be considered.

Therefore, this contribution presents a cross-component lightweight and material-oriented design (LMOD) methodology. The approach highlights the material selection which takes the product design, the production process and material knowledge/information into account in an integrated way, whereas a key role is particularly attributed to the joining process and thereby the joint section design.

***Keywords: Lightweight design, material selection, cross-component approach, consideration of joining technologies, product development process***

## 1 Introduction

Apart from the emerging futuristic vision of a fourth industrial revolution – a collective term including, amongst others, Cyber-Physical-Systems, the Internet of Things & Services as well as Cloud Computing (Bleom, 2014) –, the issue of lightweight design is one of the most predominant innovation drivers and technology trends within the industrial product development (*BMWi*, 2015; *McKinsey&Company*, 2012). In addition, more and more complex systems with enormous requirements and conditions necessitate load- and weight-optimized and equally function-integrated multi-material structures for the today's demand on the cost-benefit ratio of optimized material properties, innovative potentials in lightweight constructions as well as the corresponding energy and resource efficiency (sustainable product engineering). Nevertheless, lightweight and material-oriented design is still being used mainly as an optimization task (e.g. material substitution) instead of an actual development target.

Considering this matter on the one hand as well as the continuously increased but also more challenging design freedom due to multi-material systems on the other hand, a systematic methodology for a lightweight and material-oriented design (LMOD) is indispensable.

Due to this overarching research issue, section 2 of this paper will first give a representative overview of the current state of the art in research regarding both a lightweight and material-oriented development methodology. After summarizing the main ideas of a further elaborated lightweight design framework, section 3 will additionally introduce a cross-component approach concerning the individual component connections (joint section design) based on load-specific and functional interrelations within the LMOD methodology. Finally, section 4 will discuss the findings and conclude by giving an outlook.

# 2 State of the Art

Before addressing the novel approach on a cross-component lightweight and material-oriented design (LMOD) methodology centred by (functional) interrelations between different system components and thus the joint section design, the current state of the art is presented below.

## 2.1 Lightweight Design

Starting with the up to now existing general lightweight design approaches, there are several individual methods up to holistic development methodologies. After a brief definition of the terminology 'lightweight design' and some fundamentals, the focus is on an overall lightweight-oriented product development process within this contribution. Therefore, no detailed description of each single methods will need to be disclosed in the following section and readers should refer to e.g. (Ponn & Lindemann, 2011; Luedeke et al., 2014).

### *2.1.1 Definition and Fundamentals*

In the past, there have already been many scientific attempts to define the terminology 'lightweight design', e.g. (Schapitz, 1963). Beside other scientists, Linke et al. (2015) and Njuguna (2016) (functional), Chatti (2006) and Wiedemann (2007) (functional, economic), Klein (2013) (functional, economic) and Henning & Moeller (2011) (functional, economic, environmental, social) consider lightweight design as a holistic optimal solution regarding a combination of different aspects in addition to the primary focus of weight reduction. As a result of the present progress in materials engineering, especially in multi-material construction techniques, the authors unite and expand the consisting definitions into one overall terminology.

> *'Lightweight design represents a holistic and systematic design philosophy, which aims not only on a load- and stress-optimised weight reduction to ensure continuous reliability, but also creates other application-specific as well as economic and environmental benefits, functional improvements and extensions such as function-integrated multi-material structures and, consequently, completely new design capabilities for innovative developed products.'*

According to the definition used by Schmidt (2004), the complex and interdisciplinary process to develop lightweight products or even systems is subject to the application of lightweight design strategies, techniques and principles. Although these instruments certainly refer to the same subject, they deal almost exclusively with different concepts.

Lightweight design strategies are primarily needed to generate optimised structures, but partly also with regard to new individual components and/or assemblies. They unify a goal-oriented application of different lightweight construction methods as well as material and manufacturing technologies and can also be classified into five categories: an overarching conditional lightweight design in conjunction with both form and conceptual lightweight design, lightweight material design as well as manufacturing lightweight design (Henning & Moeller, 2011; Schmidt, 2004; Ellenrieder et al., 2013). As mentioned above, these different strategies can be implemented by certain construction techniques, such as differentiated, integrated, hybrid, modular, and/or composite design (Ellenrieder et al., 2013). To achieve an optimum lightweight system, multiple strategies along with the appropriate techniques can be applied at the same time.

### *2.1.2 Lightweight Development Methodologies*

However, until now, there is no generally valid or accepted lightweight-oriented development process. Existing procedures, for instance the VDI guideline 2221 (1987), the traditional product development process based on the problem-solving cycle (Haberfellner et al. 2002) with its four phases, are applied and adapted to the particular lightweight design task. Thus, in addition to the traditional design phases (task clarification as well as conceptual, embodiment and detail design), Klein (2013) and Krause (2012) integrate special lightweight expertise along with individual steps at each relevant spot within their systematic procedure, as shown in figure 1.

Compared to their predecessors, Ellenrieder et al. (2013) describe a systematic approach during the development process of lightweight vehicle concepts. Beside the separate consideration of system and single components, the stated development process is divided into three successive phases roughly referring to the traditional product development process: strategic (task clarification and target identification), tactical (planning and conceptual phase) and operational lightweight design. Thereby, the previously mentioned lightweight design strategies are used inside the tactical lightweight design phase (see figure 1).

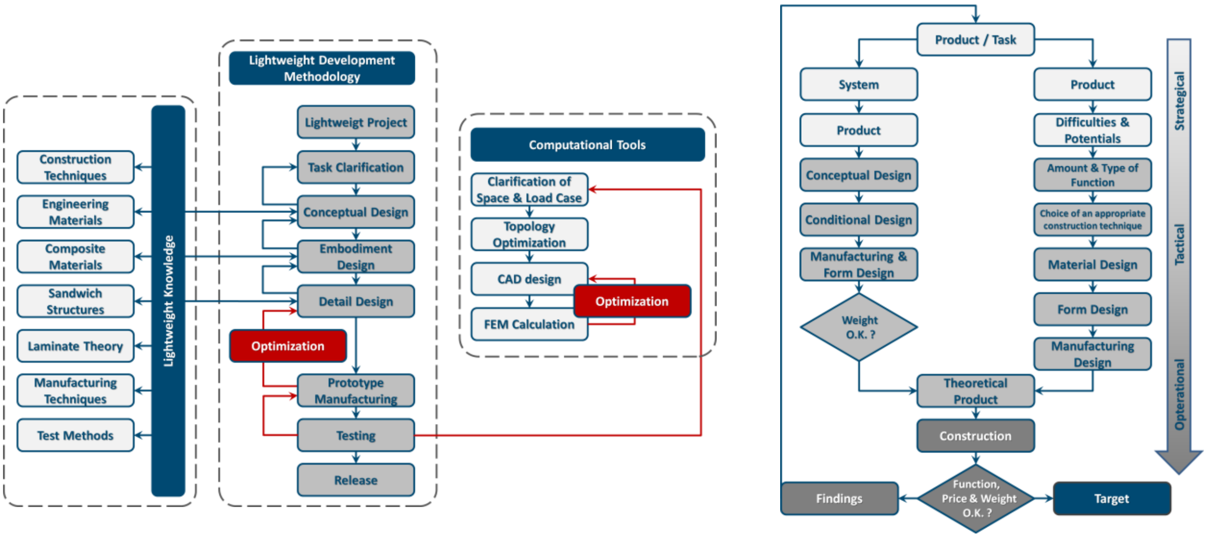

**Figure 1. Lightweight development methodologies – left: Krause (2012), right: Ellenrieder et al. (2013)**

Luedeke & Vielhaber (2012, 2013) have taken a similar approach to Ellenrieder et al. (2013) in terms of considering a separation of system and component design as well as a classification of the different lightweight design strategies along their approach towards a development process of light mechatronic products. In contrast to the consistent pursued design phases of the traditional product development, Luedeke et al. (2012) follow the generic procedure for designing mechatronic systems in form of the V-model characterised framework (system design, domain-specific design and system integration) of the VDI guideline 2206 (2004).

To mostly complement the above-mentioned measures with respect to a lightweight-oriented development process, Feyerabend (1991) presents the so called 'value analysis weight' as a methodical weight reduction concept. Therefore, the well-known value analysis methods of DIN 69910 and VDI 2800 (meanwhile also refined and registered as DIN EN 12973), which have their origin in the cost analysis, are adapted to the weight issue, e.g. a weight-benefit analysis and technical-weight related evaluation instead of cost-oriented methods. Finally, another procedure for the systematic weight reduction is suggested by Schmidt (2004). His 'innovative lightweight design' can be structured into two phases; starting, amongst others, with the identification of the mass distribution, the key modules and the interrelations as well as appropriate weaknesses and lightweight potentials (analysis phase) up to the choice and the implementation of various lightweight design strategies and techniques along with the conception of innovative solutions regarding determined risks and efforts (synthesis phase).

## 2.2 Material-Oriented Design

Engineering design represents the process of translating a new idea or a market need through a more detailed concept, or rather a technical draft, into an ultimate construction a product can be manufactured from. Therefore, each of these stages requires decisions about feasible materials depending on the product itself, commonly dictated by the design, as well as the production process (form, join and finish).

Anyway, material has already been a central point of research and also of practice agendas for decades in product design (Manzini, 1986). Nowadays, the variety of available engineering materials placed at the constructor's disposal is large; according to Reuter (2014) approximately 40,000 of metallic and non-metallic each. Thus, without guidance, the selection of the few best suited materials with regard to the respective system or product requirements is difficult and time-consuming, but still insufficiently precise only and furthermore no longer up-to-date. Due to this fact, there is an urgent need for a systematic approach of a material-oriented product development process.

The scientific literature, however, contains numerous approaches, methods and procedures for a systematic material selection. Indeed, these closely resemble the common problem-solving cycle, but are still different in terms of their priorities. Thus, Grosch (1986) and Ehrlenspiel & Kiewert (1990) first provided the link between the traditional product development process and an overall systematic approach to material selection, highlighting material-relevant decisive fields.

An internationally accepted and well-known standard for material selection is represented by Ashby (2010). Although this guideline provides a basic methodology of a suitable choice of material, that collates material-related requirements, followed by a screening and a subsequent ranking process up to the final material selection, there is primarily a more detailed procedure for the fundamental pre-selection of material groups. By using the appropriate computer-based material data (Cambridge Engineering Selector / Granta Design), a detailed material selection within the eligible material classes can be determined based on the particular required material specifications and the resulting property charts. In his approach, Ashby also targets to bring product-related material information closer together with relevant process information. This attempt, however, is limited to the proposal of suitable manufacturing processes for previously selected materials, or vice-versa, and thereby does not provide sufficient support for truly integrated product and process-based decisions.

Based on the aforementioned approaches, in particular regarding the represented guideline by Ashby (2010), Reuter (2014) summarizes all these considerations into one ‘standardized’ approach for a systematic material selection integrated into the general product development process. Referring to the traditional design phases (VDI guideline 2221 / 2222-1), this procedure is also classified into four material-relevant stages (Reuter, 2014):

- determination of material properties (task clarification)
- pre-selection of suitable materials (conceptual design)
- fine-selection of remaining materials (embodiment design)
- specification (selection of the most appropriate material options)

As a result, a systematic material decision-making can be achieved with the help of individual instruments for the actual process step, such as the ABC analysis (task clarification) or browsing different material database systems (solution seeking), as well as the resulting process documents (outputs).

Further specific methods regarding a systematic material selection based on steel (Weddige, 2001), composites (Brinkmann, 2011) and today’s multi-materials systems (Kromm et al., 2007) as well as additional developed computer-based material databases (Große, 2001) make up the state of the art mentioned here.

## 2.3 Conclusion

The scientific literature, however, contains various approaches providing the link between the traditional product development process and specific lightweight aspects (lightweight design strategies, techniques and principles) e.g. (Ellenrieder et al., 2013; Krause, 2012) or an overall systematic approach to material selection e.g. (Reuter, 2014; Ashby, 2010). The further detailed combination of both could not be traced. Even though some approaches (Luedeke & Vielhaber, 2013) target a separate consideration of both system and components, most lightweight-oriented methodologies focus basically on component design. Thus, in the latter – mainly material-oriented – case, a general classification into four stages including individual operations can be made for the methodical procedure (Reuter, 2014). A more detailed, computer-aided methodology is developed by Ashby (2010), particularly for an initial rough through to a detailed selection. With this unique technical approach it is possible to select a strategic material (e.g. strength- and/or stiffness-optimized towards density) for a specific component in consideration of possible chosen manufacturing processes.

Although this examination of the full material variety (early design-stage) leads to a few best suited engineering materials for one product part, the essential lightweight aspect of functional interrelations between different system components is neglected. But precisely the wide-ranging joining technologies represent a key position particularly in hybrid and/or multi-material design, as every system is influenced by its surroundings, even the human being. Against this background, and by taking into account that many new technologies (for instance multi-material construction techniques) have not yet or just inadequately been supported, there is an urgent need for a cross-component systematic approach within a lightweight and material-oriented design (LMOD) methodology.

# 3 Cross-Component Lightweight and Material-Oriented Design (LMOD)

Common product development processes partly support the material selection, here in terms of lightweight materials, besides the familiar lightweight construction methods. However, to achieve the full potential, hybrid concepts – targeted on the right material in the right place while considering the optimum costs, sustainability and quality – require a holistic methodology including a significantly stronger integration of the respective conceivable production process besides the conventional material selection primarily based on the developed design. Thereby, a key role is attributed to cross-component aspects, in particular in form of the joining process and, consequently, in the joint section design (see figure 2).
This fact is derived from the various new challenges and requirements entailed by the trend towards multi-material construction techniques, because newly developed lightweight materials and constructions can only be realised if tailored joining techniques are cost-efficiently and reliably available at any time.

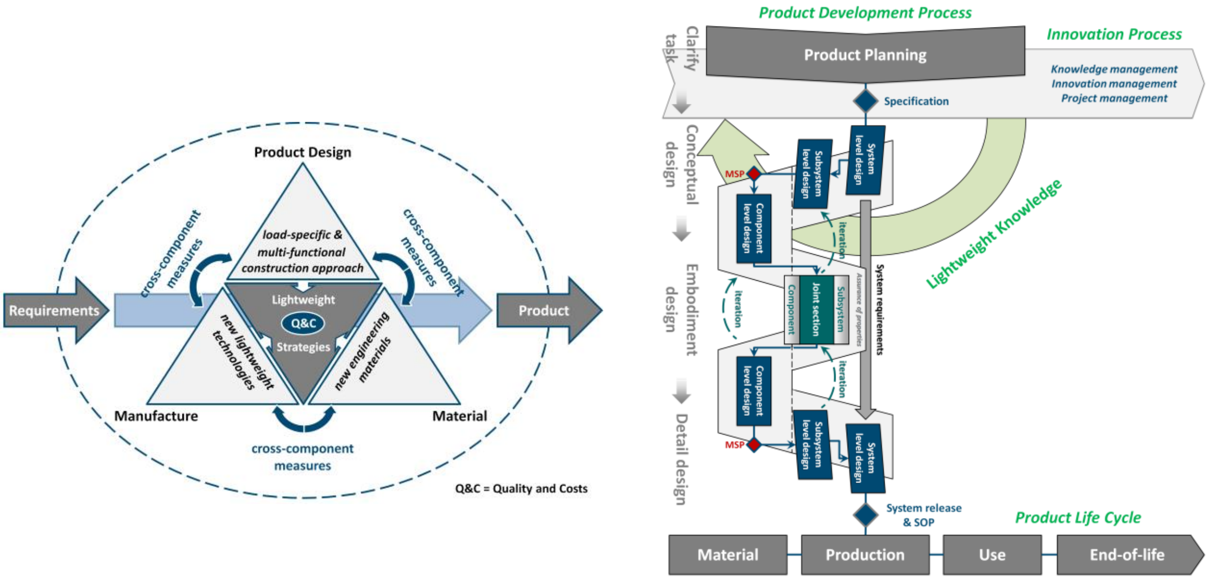

**Figure 2. a) Triangle of the lightweight design framework, b) cross-component lightweight and material-oriented design (LMOD) methodology**

The depicted cross-component procedure in figure 2b) follows the traditional design phases but in accordance with an integrated view of the entire system and its respective components divided into three phases, starting with the system analysis through the detailing up to the system integration phase. Thus, it portrays a double V-shaped or W-shaped product development process similar to VDI 2206 centred by the joint section design and is integrated within the entire product life cycle (bottom horizontal line). Based on the 1993 published VDI 2221 directive, the design process is initiated by the pre-phase of product planning and a concurrent innovation process along the product life cycle, including a knowledge, innovation and project management. The resulting product specification represents the origin of the following systematically focused W-shaped model, according to figure 3.
Classified into the three main levels ‘system’, ‘subsystem’ and ‘component level design’ (according to VDI 2206), this procedure aims at a simultaneous top-down as well as a bottom-up approach partly influenced by appropriate lightweight knowledge out of the previously mentioned innovation process and available expertise.

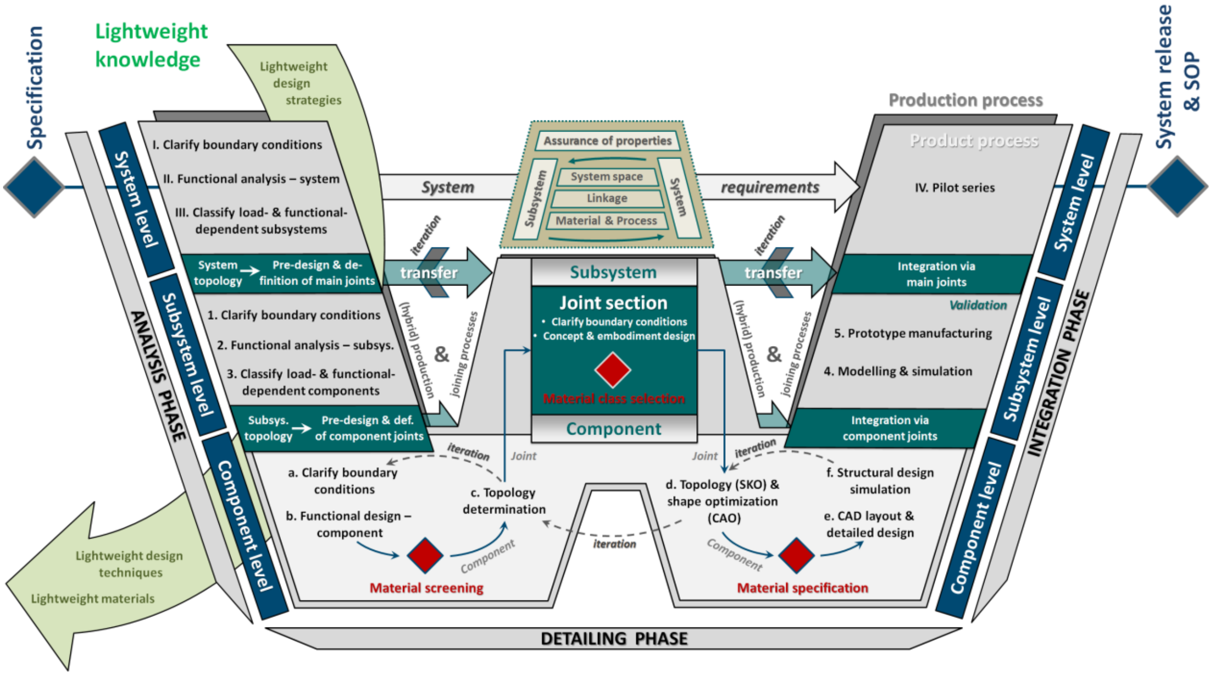

**Figure 3. W-model of the cross-component LMOD methodology**

## 3.1 System Analysis Phase

Starting with the first wing of the upper V-shaped model, the system analysis phase targets the functional product specification provided by the application of extensive lightweight knowledge. Initially, the respective boundary conditions, including the analysis of the system space and the load cases, must be clarified and documented as system requirements just as the ensuing adequate functional analysis has to be conducted for the 'system level design'. As a result, and coupled with the determination of an initial system topology, the classification into load- and functional-dependent subsystems takes place; whereby this first split leads to the pre-design, or rather the functional design of the whole system. In consequence, the actual definition of the (main) joints in terms of type, position and functionality can be developed.

To ensure a furtherly detailed penetration of the today's growing complexity of the development task, similar but extended operations (additional determination and selection of feasible operating principles) should be repeated for the 'subsystem level design' with the goal to achieve a physical product specification at component level. Compared to the system level and the definition of the main joints over there, the joints on component level should now be defined in view of possible but also available production and joining processes as well as the aforementioned physical component character initially independent on material.

## 3.2 Detailing Phase

At the 'component level design' (bottom level), the respective fundamental shape of one component has to be determined after the renewed clarification of the actual boundary conditions with the output of a component-based list of requirements.

In the next step, the material selection process starts with the determination of material properties (in respect of task clarification and preassigned requirements specification) and the derivation of a specific material requirement profile. Thus, the material screening process provides the favourable material classes regarding both the components and their surrounding joints based on possible and permitted properties. By taking into consideration the previously selected limitations with the complying technology definition (concurrent production process) in mind, the (product) design process of the central task – the joint section design – starts with a furtherly detailed topology determination, followed by the conceptualization of the junctions between each component within one subsystem as well as the subsystems within the entire system. In comparison to other lightweight approaches e.g. (Ellenrieder et al., 2013; Krause, 2012), this offers a further penetration of feasible potentials in lightweight design, particularly with regard to reliable and cost-efficient (cross-component) multi-material systems.

Based on a more detailed comparison of necessary but also targeted system requirements (containing the dictated ambitious weight reduction goals) and the corresponding assurance of system properties (olive-green trapezoid) as well as the transfer of the previously determined pre-design and definition of main and component joints, the material class selection takes place. Considering the direct surrounding components and the respective feasible joining process of possible and required multi-material systems, the embodiment design of each joint is developed, followed by a fine-selection of most appropriate individual materials within the selected material class. Bearing in mind e.g. the force transmission points, subsequently, a topology (SKO) and shape optimization (CAO) is applied first for the joint section only and second along with the including components. As a result a material specification can be made, potentially, e.g. for hybrid materials, with regard to a validation of the demanded material properties by material experiments closely connected to design geometry.

Therefore, based on the preceding optimization, the generation of a weight- and material-optimized CAD layout and thus a prematurely detailed design can be completed. The next and at the same time last step on component level describes the structural design simulation, comprising a FEA simulation in consideration of the concerning material modelling.

If the lightweight objectives have not yet been fully achieved in terms of necessary safety factors relating to stress and strain per weight or even there is a noticeable optimization potential with respect to permissible costs, the product development requires a further iteration. In this case, the return to the aforementioned stage of optimization (the embodiment design and fine-selection of individual materials), the material screening (immediately before the conceptual design of the joint section) or even going back to the origin of the component design and its determination of the materials requirements and boundary conditions is necessary and allowed. Is a detailed design accomplished after several iterations, which considers all (lightweight) targets, the second phase is followed by the system integration phase.

### 3.3 System Integration Phase

In the final phase of the presented holistic cross-component LMOD methodology each component is being interlinked with the integration through the specific component joint, designed and transferred from the respective joint section design (detailing phase). 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 production-related impacts) provide a further vertical integration via the main joints to the ‘system level design’. If difficulties do not arise in respect of the chosen (hybrid) production and joining processes, which would lead to an iterated joint section design, finally, the successful development of a pilot series permits the system release and paves the way for the start of production (SOP).

## 4 Discussion and Outlook

Starting from a broad range of engineering methods and approaches to support the design and engineering of competitive lightweight systems, this contribution stresses the need for a holistic cross-component lightweight and material-oriented design methodology.

Consequently, the presented systematic lightweight design approach – centred by the joint section design along with the decisive consideration of (hybrid) production and joining technologies – set the fundamental development framework for the future-orientated load-specific and function-integrated multi-material product design, particularly regarding functional and technological interrelations between several adjoining system components.

An extension and completion of this methodology in respect of a detailed material selection based on an integrated view of product, production and material knowledge will be elaborated more in detail in the follow-up, e.g. (Kaspar et al., 2016; Stoffels et al., 2016). Furthermore, the relevance and impact of application-independent and application-specific sustainable aspects inside the initially introduced holistic cross-component LMOD methodology will be developed in (Kaspar & Vielhaber, 2016) concerning the entire value chain (material, production, use, end-of-life).

In future work, a special view of a detailed carbon-fibre-reinforced plastic (CFRP) product development process will be pursued based on the presented W-shaped methodology as well as their linking with the significant joint section design task, just as the extension of a detailed production development process almost simultaneously fitted into the current approach and integrated into the intended locations (dark gray writing). Finally, an application example – consisting of various structural components – should lead to illustrate the individual steps within the three main phases and apply single operations and methods during the respective stages of the presented cross-component approach.

## References

Ashby, M.F. (2010). Materials Selection in Mechanical Design. (4th ed.). *Butterworth-Heinemann, Oxford.*

Bleom, J., van Doorn, M., Duivestein, S., Maas, R., & van Ommeren, E. (2014). The Fourth Industrial Revolution: Things to Tighten the Link Between IT and OT. *VINT research report 3 of 4, Sogeti VINT, Groningen*.

BMWi (2015). Bestandsaufnahme Leichtbau in Deutschland. In *Project I C4-10/15: VDI Zentrum Ressourceneffizienz*.

Brinkmann, T. (2011). Handbuch Produktentwicklung mit Kunststoffen. (1st ed.). *Carl Hanser Verlag, München.*

Chatti, S. (2006). Production of Profiles for Lightweight Structures. *Books on Demand, Norderstedt.*

Ehrlenspiel, K., & Kiewert, A. (1990). Die Werkstoffauswahl als Problem der Produktentwicklung im Maschinenbau. In *VDI-Berichte 797: Ingenieur-Werkstoffe im technischen Fortschritt, VDI-Verlag, München, Germany,* 47-67.

Ellenrieder, G., Gänsicker, T., Goede, M., & Herrmann, H.G. (2013). Die Leichtbaustrategien. In H.E. Friedrich (Ed.): *Leichtbau in der Fahrzeugtechnik, ATZ/MTZ-Fachbuch, Springer Vieweg, Wiesbaden.*

Feyerabend, F. (1991). Wertanalyse Gewicht: Methodische Gewichtsreduzierung – am Beispiel von Industierobotern. (11th ed.). *Verlag Industrielle Organisation, Zürich.*

Grosch, J. (1986). Werkstoffauswahl im Maschinenbau. *Kontakt & Studium Band 199, Expert Verlag, Sindelfingen.*

Große, A. (2001). Interdisziplinäre Werkstoffauswahl durch Aufbau eines Material Data Mart. (Doctorial dissertation). *Papierflieger, Clausthal-Zellerfeld.*

Haberfellner, R., Nagel, P., Becker, M., Büchel, A., & von Massow, H. (2002). Systems Engineering: Methodik und Praxis. (11th ed.). *Verlag Industrielle Organisation.*

Henning, F., & Moeller, E. (2011). Handbuch Leichtbau: Methoden, Werkstoffe, Fertigung. (1st ed.). *Carl Hanser Verlag, München.*

Kaspar, J., Baehre, D., & Vielhaber, M. (2016). Material Selection Based on a Product and Production Engineering Integration Framework. Submitted and accepted at 26th CIRP Design Conference (PROCIR-D-15-01454R2). *Stockholm, 15-17 June 2016.*

Kaspar, J., & Vielhaber, M. (2016). Sustainable Lightweight Design - Relevance and Impact on the Product Development & Lifecycle Process. Submitted to 14th Global Conference on Sustainable Manufacturing (GCSM). *Stellenbosch, 3-5 October 2016.*

Klein, B. (2013). Leichtbau-Konstruktion: Berechnungsgrundlagen und Gestaltung. (10th ed.). *Springer-Verlag, Berlin.*

Krause, D. (2012). Leichtbau. In F. Rieg et al. (Ed.): *Handbuch Konstruktion, Carl Hanser Verlag, München.*

Kromm F.X., Quenisset J.M., Lorriot T., Harry, R., & Wargnier H. (2007). Definition of a multimaterials design method. *Materials and Design*, 28, 2641-2646.

Lieberwirth, H., & Kampitz, T. (2015). Entwicklungstendenzen für den Einsatz von Leichtbauwerkstoffen im Fahrzeugbau und Auswirkungen auf das Recycling. In K.J. Thomé-Kozmiensky et al. (Ed.): *Recycling und Rohstoffe – Band 8,* 207-218.

Linke, M., & Nast, E. (2015). Festigkeitslehre für den Leichtbau. (1st ed.). *Springer Vieweg, Berlin.*

Luedeke, T., & Vielhaber, M. (2012). Towards a Process Model for the Development of Light, Mechatronic Products. In P.K. Hansen et al. (Ed.): *Proceedings of the 9th NordDesign Conference, Paper ID 47, Aalborg, Denmark,* 384-401.

Luedeke, T., & Vielhaber, M. (2013). Consideration of Weight Properties during the Design of Weight-Optimized Mechatronic Products. In U. Lindemann et al. (Ed.): *Proceedings of the Engineering Design ICED'13, Design for X/Design to X, Seoul, South Korea,* 291-300.

Luedeke, T., Bonertz, R., & Vielhaber, M. (2014) Weight Optimization Approach for Conceptual Design – Requirements, Functions, Working Principles. *Proceedings of NordDesign 2014*, 805-814.

Manzini, E. (1986). The Material of Invention. *Arcadia Edizioni, Milan, Italy.*

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

Njuguna, J. (2016). Lightweight Composite Structures in Transport. (1st ed.). *Woodhead Publishing / Elsevier Ltd., Duxford, UK.*

Ponn, J., & Lindemann, U. (2011). Konzeptentwicklung und Gestaltung technischer Produkte: Systematisch von Anforderungen zu Konzepten und Gestaltlösungen. (2nd ed.). *Springer-Verlag, Berlin.*

Reuter, M. (2014). Methodik der Werkstoffauswahl – Der systematische Weg zum richtigen Material. (2nd ed.). *Carl Hanser Verlag, München.*

Schapitz, E. (1963). Festigkeitslehre für den Leichtbau. (2nd ed.). *VDI-Verlag, Düsseldorf.*

Schmidt, W. (2004). Methodische Entwicklung innovativer Leichtbau-Produkte. *Fortschritts-Berichte VDI, VDI Reihe 1 Nr. 369, VDI-Verlag, Düsseldorf.*

Stoffels, P., Kaspar, J., Baehre, D., & Vielhaber, M. (2016). Holistic Material Selection Approach for More Sustainable Products. Submitted to 14th Global Conference on Sustainable Manufacturing (GCSM). *Stellenbosch, 3-5 October 2016.*

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

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

Weddige, H.-J. (2001). Stahl im Wettbewerb der Werkstoffe. *Selbstverlag, Freiberg.*

Wiedemann, J. (2007). Leichtbau: Elemente und Konstruktion. (3rd ed.). *Springer-Verlag, Berlin.*