Forschungsberichte

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am Karlsruher Institut für Technologie

Viktoriia Butenko

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Approach to support knowledge transfer and decision making in product development with fibre-reinforced plastics through situation-specific design guidelines

Band 121

Systeme ▪ Methoden ▪ Prozesse

Univ.-Prof. Dr.-Ing. Dr. h.c. A. Albers
Univ.-Prof. Dr.-Ing. S. Matthiesen
(Hrsg.)

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Approach to support knowledge transfer and decision making in product development with fibre-reinforced plastics through situation-specific design guidelines

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DISSERTATION

von

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aus Dzerginsk

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Vorwort der Herausgeber

Wissen ist einer der entscheidenden Faktoren in den Volkswirtschaften unserer Zeit. Der Unternehmenserfolg wird mehr denn je davon abhängen, wie schnell ein Unternehmen neues Wissen aufnehmen, zugänglich machen und verwerten kann. Die Aufgabe eines Universitätsinstitutes ist es, hier einen wesentlichen Beitrag zu leisten. In den Forschungsarbeiten wird ständig Wissen generiert. Dieses kann aber nur wirksam und für die Gemeinschaft nutzbar werden, wenn es in geeigneter Form kommuniziert wird. Diese Schriftenreihe dient seit mehr als 20 Jahren als eine Plattform zum Transfer und macht damit das Wissenspotenzial aus aktuellen Forschungsarbeiten am IPEK - Institut für Produktentwicklung Karlsruhe* am Karlsruher Institut für Technologie (KIT) verfügbar. Die Forschung des IPEK ist dabei strukturiert in die Kategorien Systeme, Methoden und Prozesse, um so der Komplexität heutiger Produktentwicklung ganzheitlich gerecht zu werden. Erst die Verknüpfung dieser drei Kategorien ermöglicht die Synthese innovativer Systeme durch Nutzung neuester Methoden und Prozesse. Gleichzeitig werden durch die Systemsynthese die erforschten neuen Methoden und Prozesse validiert und deren Mehrwert für die Praxis abgesichert. Dieses Forschungskonzept prägt nicht nur das IPEK-Leitbild sondern auch den Charakter dieser Schriftenreihe, da immer alle drei Kategorien und deren Wechselwirkungen berücksichtigt werden. Jeder Band setzt hier individuelle Schwerpunkte und adressiert dabei folgende Forschungsgebiete des IPEK:

- das Entwicklungs- und Innovationsmanagement,
- die Entwicklungs- und Konstruktionsmethodik,
- der Leichtbau von der Ebene des ganzen Systems bis hinunter zur Optimierung des Bauteils,
- die Validierung technischer Systeme auch unter Berücksichtigung der NVH Aspekte (Noise, Vibration, Harshness) mit dem Fokus auf Schwingungen und Akustik an Komponenten und in den Gesamtsystemen sowie deren subjektiver Beurteilung durch den Menschen,
- die Antriebssystemtechnik mit den Schwerpunkten komplette Antriebslösungen für Fahrzeuge und Maschinen,
- das Design, die Tribologie und Erprobung von Kupplungen und Bremsen sowie
- die Gerätetechnik mit dem Schwerpunkt auf Power-Tools.

Die Forschungsberichte stellen Ergebnisse unserer Forschung sowohl anderen Wissenschaftlern als auch den Unternehmen zu Verfügung um damit die Produktentwicklung in allen ihren Facetten mit innovativen Impulsen zu optimieren.

Albert Albers und Sven Matthiesen

* Eh.: Institut für Maschinenkonstruktionslehre und Kraftfahrzeugbau, Universität Karlsruhe (TH)

Vorwort zu Band 121

Die Herausforderungen für die moderne Produktentwicklung technischer Systeme – egal in welchen Branchen – folgt drei wesentlichen Trends. Es gilt, in den heute oft gesättigten Märkten Produktdifferenzierungen durch neue Merkmale darzustellen. Ferner müssen die Herausforderungen nach einer immer höheren Leistung und Performance der Produkte in den Märkten bedient werden und dabei kommt einem dritten Aspekt, der Berücksichtigung der ökologische Wechselwirkungen des Produktes bei Erstellung, Nutzung und Außerbetriebnahme (Recyclingpotential) – z. B. bezogen auf den CO_2-Haushalt, bzw. die Klimagasemission – eine weitere zentrale Bedeutung zu.

Die entstehenden Produktlösungen werden dabei durch die vielfältigen neuen Möglichkeiten zur Funktionsgestaltung natürlich zunehmend komplex und kompliziert. Es ist eine sehr große Menge an Wissen bei der Definition und Gestaltung zukünftiger Produkte erforderlich. Der Umgang mit diesem Wissen ist dabei immer noch eine große Herausforderung. Wissen ist sehr oft implizit bei den Mitarbeitern in den verschiedenen Unternehmen – bezogen auf die Zulieferkette und natürlich den Bereichen im Unternehmen selbst - verteilt. Gleichzeitig fordert die zunehmende Interdisziplinarität dazu auf, dieses Wissen zu teilen und nutzbar zu machen. Für das Feld des Leichtbaus, als einer zentralen Strategie um die Herausforderungen der Energieeffizienz und auch Performance moderner Produkte zu realisieren, ist der Umgang mit dem Wissen zentral. Beim Leichtbau können unterschiedliche Leichtbauarten unterschieden werden.

Diese sind:

- der Bedingungsleichtbau
- der Stoffleichtbau
- der Formleichtbau und
- der Konzept- bzw. Systemleichtbau.

Beim Stoffleichtbau wird versucht, durch die gezielte Gestaltung mit Werkstoffen niedriger Dichte bei gleichzeitig relativ hoher Festigkeit das Gewicht einer Struktur zu reduzieren. Der Formleichtbau geht auf die Gestaltfindung ein und nutzt zum Beispiel Versteifungspotenziale von geeignet angeordneten Rippenstrukturen. Der Bedingungsleichtbau erfasst die Fragestellungen des Einsatzes der geplanten technischen Lösung und deren Randbedingungen und der Konzept- oder besser Systemleichtbau führt jetzt Leichtbaupotenziale zusammen und identifiziert sie auf der Systemebene, zum Beispiel die Wirkung einer mechatronischen

Drehmomentbegrenzung in Antrieben auf die notwendigen Tragstrukturen der Antriebsstrangkomponenten.

Schon aus dieser kurzen Schilderung ist zu erkennen, dass unter dem Begriff Leichtbau ein komplexer Gestaltungsprozess definiert wird. Die Leichtbaupotenziale gezielt zu nutzen, erfordert ein sehr breites gestaltendes Denken auf allen Ebenen der geplanten technischen Lösungen. Hier ist auf allen Gebieten sehr viel an Wissen erforderlich, um die richtigen Lösungen zu definieren. Bezogen auf den Stoffleichtbau stellen faserverstärkte Kunststoffe heute eine wichtige Werkstoffklasse dar, die gezielt im Leichtbau eingesetzt werden kann. Hierbei versucht man, durch entsprechende Faserverstärkungen anisotrope Belastungen gezielt abzufangen. Die Faserverbundwerkstoffe sind heute im Bereich des Maschinen- und Fahrzeugbaus allerdings erst in geringem Umfang bereits im Einsatz. Ihr Potenzial wird noch lange nicht genutzt. Hintergrund ist dabei, dass die Werkstoffklasse sowohl in ihrem Materialverhalten, ihren Fertigungsverfahren und ganz besonders in **der Gestaltfindung im Rahmen der Konstruktion** sich gravierend von den typischen Metallen unterscheidet.

An dieser Stelle setzt das Graduiertenkolleg *CoDico* der DFG am Karlsruher Institut für Technologie (KIT) an. Im Rahmen des Graduiertenkollegs soll die Werkstoffklasse der faserverstärkten Kunststoffe gezielt in den drei Aspekten *Modellierung und Simulation, Fertigungstechnik und Gestaltfindung und Konstruktion* wissenschaftlich untersucht werden, um dann Methoden und Prozesse abzuleiten, die diese interessante Werkstoffklasse der Produktinnovation in Unternehmen zugänglich macht. Um dies leisten zu können, ist es notwendig, das Wissen gezielt aufzubereiten und für den Konstruktionsprozess zur Verfügung zu stellen. Hier setzt die wissenschaftliche Arbeit von Frau Dr.-Ing. Viktoriia Butenko an. Sie hat sich zum Ziel gesetzt, einen Ansatz zum Wissenstransfer und zur Entscheidungsfindung in der Produktentwicklung für die Werkstoffgruppe der faserverstärkten Kunststoffe zu finden und methodisch aufzubereiten. Dazu führt Sie sehr gezielt eine Bestandsanalyse der heutigen Konstruktionsunterstützung auf diesem Gebiet durch, erfasst die Bedarfe der Praxis und erarbeitet ein Modell zur Wissenserfassung und –bereitstellung auf Grundlage der wissenschaftlichen Ansätze der KaSPro - Karlsruher Schule für Produktentwicklung. Ihre Arbeit leistet einen wesentlichen Beitrag zum Thema Wissensmanagement in der Produktentwicklung, sowohl in der Wissenschaft als auch für die Praxis der Konstruktion.

August, 2019 Albert Albers

Kurzfassung

„Denn Wissen selbst ist Macht" ist ein Satz, der vor langer Zeit von Francis Bacon geschrieben wurde. Im Laufe der Zeit hat nicht nur das Wissen an Bedeutung gewonnen, sondern vor allem auch der Umgang damit. Die Aussage "Wenn wir nur wüssten, was wir wissen" (Davenport & Prisak, 1998) ist zutreffend für viele Unternehmen. Es ist nicht mehr ein Mangel an Informationen, sondern ein Informationsüberschuss, der problematisch geworden ist. Die Möglichkeit, erfahrungsbasierte sowie entwicklungsrelevante Informationen in jeder Phase der Produktentwicklung zu finden und anzuwenden, hat zunehmend an Bedeutung für mittelständische und große Unternehmen gewonnen.

Computergestützte Systeme leisten zusammen mit den Fortschritten der Informations- und Kommunikationstechnologien in den letzten Jahrzehnten einen wesentlichen Beitrag zur Unterstützung des Wissensmanagements. Eine Herausforderung liegt derzeit weniger in den Informationstechnologien als vielmehr in der Entwicklung, Einführung und der kontinuierlichen Weiterentwicklung von Methoden für einen effizienten Umgang mit Wissen. Nicht nur die Unterstützung bei der Suche nach Informationen, sondern auch Methoden, die die qualitative, zielorientierte Erfassung und Dokumentation von relevantem Erfahrungswissen unterstützen, sind notwendig.

Diese Arbeit trägt dazu bei, die Entscheidungsfindung in den frühen Phasen der Produktentwicklung mit faserverstärkten Kunststoffen zu unterstützen. Einerseits steht die Entwicklung eines Ansatzes zur Verbesserung des Wissenstransfers durch repräsentative Informationsdokumentation in Gestaltungsrichtlinien im Vordergrund. Als Grundlage für die Entwicklung des Ansatzes dient eine umfassende Analyse der bestehenden Gestaltungsrichtlinien für faserverstärkte Kunststoffe in der Literatur, Interviews mit Industrievertretern und die Durchführung von Studien. Andererseits steht auch ein Ansatz zur effizienten Entscheidungsunterstützung durch die Bereitstellung von situationsgerechten Informationen in Gestaltungsrichtlinien im Vordergrund. Eine Analyse verschiedener Methoden der multikriteriellen Entscheidungsunterstützung, einschließlich deren Bewertung auf die Eignung für den Einsatz, sowie die Erstellung einer Testumgebung zur Validierung des entwickelten Algorithmus zur Bereitstellung interaktiver Informationen in Gestaltungsrichtlinien trugen zur Konzeptentwicklung bei.

Abstract

"For knowledge itself is power" is a sentence long ago written by Francis Bacon. Over time, not only has knowledge gained in importance, but even more so the handling thereof. The statement "If we only knew what we know" (Davenport & Prisak, 1998) still applies to many companies today. It is no longer a lack of information, but rather a surplus of information that has become problematic. The possibility of finding and applying experience-based development-relevant information during any product development phase has become increasingly important, especially for medium-sized and large companies.

Computer-aided systems, together with the progress of information and communication technologies in recent decades, make a significant contribution to supporting knowledge management. A challenge currently lies less in information technologies and more in the development, introduction and continuous management of methods for an efficient handling of knowledge. Not only support in the search for information, but also methods that support qualitative gathering and documentation of relevant experience knowledge, are necessary.

This work contributes to supporting knowledge-based decision making in the early phases of product engineering with fiber-reinforced plastics. On the one hand, the focus is on the development of an approach to improve knowledge transfer from research to practical application based on a rework concept for information documentation in design guidelines. As a baseline, this approach involves an in-depth analysis of existing design guidelines for fiber-reinforced plastics, interviews with industry representatives, and the conducting of several investigation studies. On the other hand, an approach for efficient decision support through the provision of situation-related information in design guidelines is also in the foreground. An analysis of various methods of multi-criteria decision support, including their testing and evaluation, as well as the creation of a test database for the validation of an algorithm for providing interactive information in design guidelines, contributed to the concept development.

Acknowledgements

This work was developed as part of my three-year research work carried out in the research project “Integrated engineering of continuous-discontinuous long-fiber-reinforced polymer structures” (IRTG), funded by the German Research Foundation (DGF).

I would like to thank Prof. Dr-Ing. Dr. h. c. Albert Albers, my main supervisor, for outstanding professional discussion on the research subject and for his trust and motivation to approach the researched challenging topic. I am grateful for the possibility to contribute to strengthening the research collaboration between the Institute of Product Engineering with the University of Windsor by having Prof. Jennifer Johrendt as my second supervisor. On that account, I would like to express my great appreciation to Prof. Dr. Jennifer Johrendt for her professional support during my stay at the University of Windsor and for providing necessary industry contacts in North America, allowing me to conduct qualitative research.

I would like to thank all IRTG scientific colleagues and supervisors Prof. Dr.-Ing. habil Thomas Böhlke, Dr.-Ing. Luise Kärger and Prof. (apl.) Dr.-Ing. Kay Andre Weidenmann for their support in the field of fiber-reinforced plastics (FRPs), for their stimulating professional discussions, and for their support in providing industry contacts in the field of FRPs in Germany, allowing me to conduct qualitative and quantitative studies.

Furthermore, I would like to thank Norbert Burkardt and Markus Spadinger for their support during the three-year research work in the IRTG project and for their great support in the final discussion of the presentation for the defense of my PhD degree.

Further thanks go to my research group colleagues of the Design Methods and Design Management (EMM) for their numerous scientific discussions, which have always brought me forward and advanced my understanding.

Karlsruhe, June 2020

Viktoriia Butenko

For my father and my brother who sadly did not have the opportunity to witness the completion of this work.

„Man kann Wissen nicht managen. Aber man kann ein Umfeld schaffen, in dem Wissen gedeiht.“

Larry Prusak

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Abbreviations

BMC	Bulk molding compound
C&C²-A	Contact and Channel approach
CFRP	Carbon fiber reinforced plastic
CoDicoFRP	Continuous discontinuous fiber composite structures
CoFRP	Continuous fiber composite structures
DFG	German Research Foundation
DicoFRP	Discontinuous fiber composite structures
DRM	Design Research Methodology
FRP	Fiber reinforced plastic
GFRP	Glas fiber reinforced plastic
GMT	Glass mat reinforced thermoplastic
IRTG	Integrated engineering of continuous-discontinuous long-fiber-reinforced polymer structures
iPeM	integrated Product engineering Model
LFT	Long fiber reinforced thermoplastic
MADM	Multi attributive decision making
MCAP	Multiple Criteria Aggregation Procedure
MCDA	Multi-criteria decision analysis
MODM	Multi objective decision making
PEP	Product engineering process
SMC	Sheet molding compound
WSP	Working Surface Pairs

1 Introduction

This research work is carried out as a part of a research project “Integrated engineering of continuous-discontinuous long-fiber-reinforced polymer structures” (IRTG), funded by the German Research Foundation (DGF).

The aim of the IRTG project is to develop concepts for the production, modeling and dimensioning of hybrid continuous-discontinuous fiber composite structures (CoDicoFRPs) to facilitate new application fields for this material. The combination of continuous (CoFRPs) and discontinuous fiber composite structures (DicoFRPs) has a significant potential for the development of complex geometric parts with a high lightweight design potential and high specific stiffness and strength (Böhlke et al., 2019, p. 2). Scientific doctoral students from various fields, namely, material characterization, simulation, technology and design, worked together in the last three years (2015-2018) and carried out numerous experiments that produce important findings. These findings are an important knowledge source not only for the research conducted for the IRTG project but also for industry representatives who may work with this material in the near future. However, in order to enable applicability, the findings shall be appropriately documented and provided to the target group.

A widely used form of experience documentation for engineering purposes is design guidelines, also called design recommendations (Butenko, Gladysz, et al., 2018). Most manufacturing companies have their own internal design guidelines, which are regarded as a valuable source of information that contributes to preventing repeated failures as long as the relevant information is meaningfully documented and up to date.

Nowadays, design guidelines can be found in various information sources, such as books, publications or scientific papers, on various topics and materials. The successful dissemination of design guidelines for traditional materials led to the adoption of this concept of documenting information for fiber-reinforced plastics (FRPs) as well. However, a design process with FRP materials differs greatly from one with metals, and it has significantly more influencing factors that must be taken into account during the embodiment design. (Butenko & Albers, 2018) These factors are currently not fully considered in existing design guidelines for FRP materials.

The aim of this work is to examine what information a design guideline for FRP materials should contain and how it should be documented to support the analysis and synthesis activities of product developers. Industry representatives working with FRP materials are of interest and provide important input and incentives needed for the definition of necessary topics and contents in design guidelines. Another focus is on a methodological approach that supports the identification and situation-specific compiling of information in design guidelines in order to efficiently support decision finding.

This work consists of eight chapters. The introduction is followed by **Chapter 2**, which provides a detailed overview of the scientific basis and the state of research in the thematic context of this work. First, the basics of product engineering and the importance of methods to support analysis and synthesis activities in an embodiment design are discussed. Thereafter, important basics on FRP materials in general, as well as specific challenges associated with embodiment design activities, are described. Next is an overview and analysis of current design guidelines for FRP materials and an assessment of their suitability for supporting analysis and synthesis activities. Finally, the basics of decision support methods and existing knowledge management approaches to support product development with FRP are presented.

Chapter 3 describes a research profile of the work. It comprises research hypotheses and research questions and objectives. In addition, the methods used to achieve the objectives of this work are presented and classified in the context of established design research methodology.

Chapter 4 contains a procedure and the main results of qualitative and quantitative empirical studies applied to determine the needs of industry representatives with regard to design guidelines for FRP materials.

Chapter 5 describes the experiments that were carried out and the observations that were made in a framework of three investigation studies. The first study provides information on an analysis of different forms of information representation regarding their suitability for knowledge transfer. The second study deals with an examination of design guidelines available in literature regarding their applicability to the concrete design tasks (embodiment design of a demonstrator in the framework of the IRTG project). The last study investigates methodological aids that support the creation of target-oriented design guidelines for FRPs.

Chapter 6 presents a process model for the development of a method to support product developers in the early phases of product engineering with FRP materials through the provision of situation-related design guidelines and other specific information. In addition, a process model for the development and documentation of design guidelines for FRPs is presented with various examples.

Chapter 7 describes the procedure and results of the conducted validation studies. The aim of these is to demonstrate whether the application of the developed method contributes to decision support.

Chapter 8 summarizes the most important contents and provides suggestions for further research projects that build on the results presented.

The structure of this work is visualized in Figure 1.

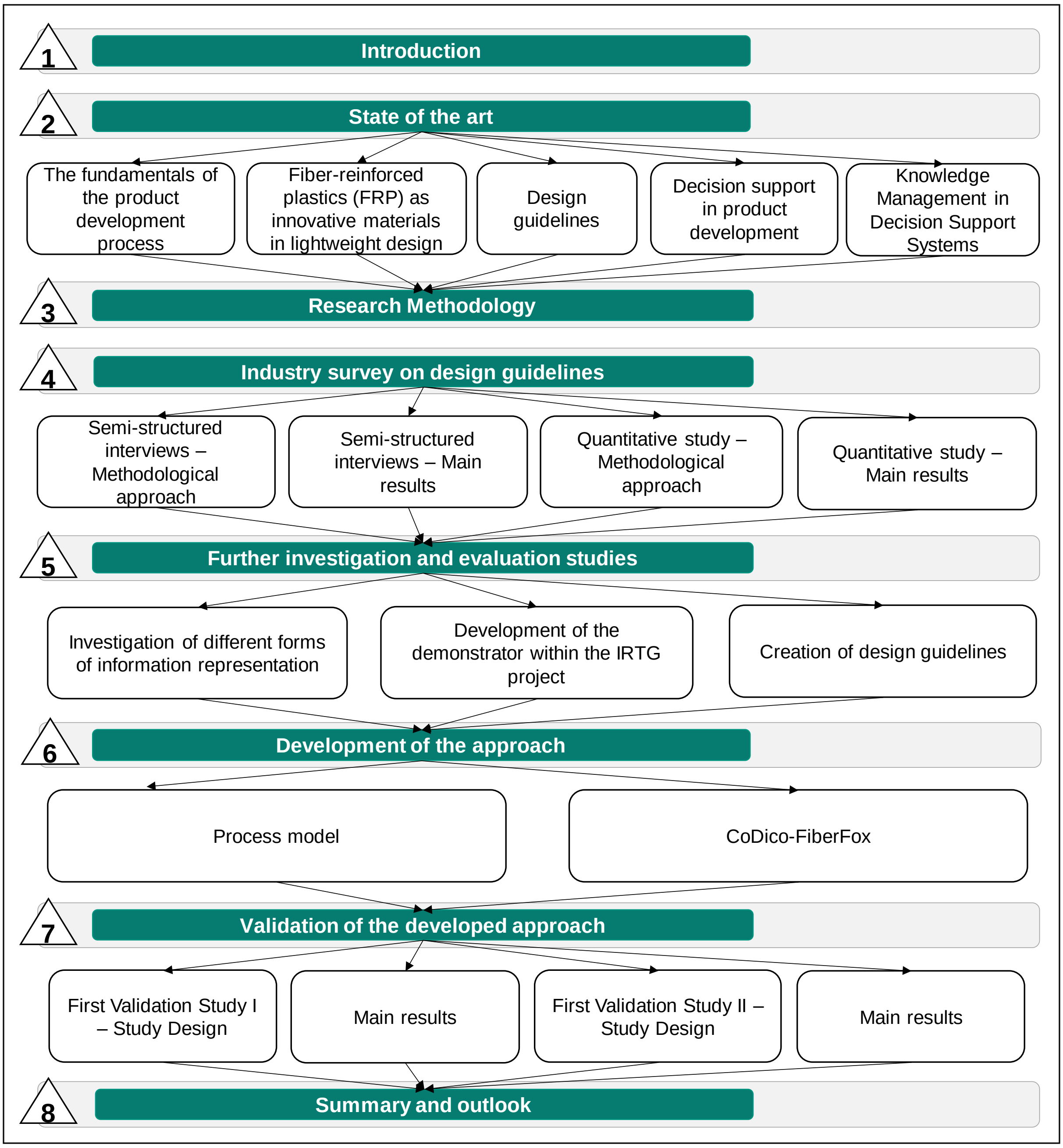


Figure 1: Structure of the work

2 State of the art

This chapter serves to create a scientific basis for the present work and to distinguish it from the current state of the art. First, the product development fundamentals are presented in Section 2.1, followed by the introduction of important terms and basics in the field of FRP materials in Section 2.2. The current design guidelines existing for FRP materials to support product developers during the embodiment design process as well as their presentation form and contents are described in Section 2.3. The basics of decision support in product development are presented in Section 2.4. Finally, knowledge management in decision support systems and existing decision support tools are introduced in Section 2.5.

2.1 The fundamentals of the product engineering process

Product engineering processes (PEP) are characterized by a high degree of complexity (Albers, Braun, et al., 2010) and a high number of changes throughout their entire life cycle (Vianello & Ahmed-Kristensen, 2012). Increasing time and price reduction pressures, rising material costs, market volatility and improving product quality requirements in the context of international competition pose a special challenge to manufacturing companies (Custom Research and Kronos Incorporated, 2016). Various sources have listed the following factors as key elements for successful product development: a superior and differentiated product, market orientation, pre-development work, early product definition, a product innovation and technology strategy, organizational culture, top management support and, cross-functional teams (Cooper & Kleinschmidt, 2010; Ernst, 2002). In fact, an effective product engineering process is a basis for successful products (Lewis, 2001) and assists in the achievement of these key factors (Albers, Reiss, et al., 2016).

The majority of engineering processes can be described according to the "Model of PGE – Product Generation Engineering" of Albers et al. (Albers, Bursac, et al., 2015) and are defined as follows:

> Product generation development is understood to be the development of a new generation of technical products by both a specific carryover and new development of partial systems. The shapes of new technical developments of individual functional units result from the activity of embodiment variation and the variation of solution principles, hereinafter referred to as the activity of principle variation. New product generations are always based on a reference product that defines large parts of the basic structure (Albers, Bursac, et al., 2015).

Further research in the field of product generation development has highlighted the need for an additional element, "reference system," to consider all interactions that form the basis for the development of a new product generation (Albers et al., 2019).

> The reference system for the development of a new product generation is a system whose elements originate from already existing or already planned socio-technical systems and the associated documentation and are the basis and starting point for the development of the new product generation (Albers et al., 2019).

As stated in the definition above, new product generation is based on at least one existing technical system. Consider the simple example of mobile phones: The iPhone 6 represents a reference system for the iPhone 6S. When comparing the embodiment of the iPhone 6 and its successor 6S, two differences between these generations can be seen, as visualized in Figure 2: First, the wall thickness of the case has been almost doubled in the newer model, and a different material alloy has been used. The variation of these parameters in the 6S was due to the low bending stiffness and thus the bending of the housing in the previous generation (Curry, 2015). New development by means of embodiment variation can contribute to increasing competitiveness, performance or the quality of functional performance and is one of the partial system elements of a product that can be distinguished in a new product generation (Albers, Bursac, et al., 2015). In addition to embodiment variation, the carryover of known solutions from the reference systems is also a part of product generation development. In the example of the mobile phone, the screen diagonal is a carryover share, that is, the takeover to the new product generation 6S and adaption to the requirements only at system-integration interfaces.

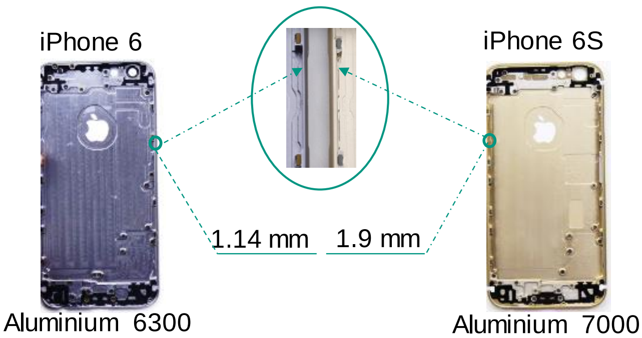


Figure 2: Example of reference system[1]

New development of a subsystem based on adaptation from products that fulfil similar functions and properties but in different contexts (Albers, Bursac, et al., 2015)

[1] Image of the iPhone case adapted from (Schwuchow, 2015). Data on aluminum alloy available in (Bell, 2015).

represents the other part of the new product generation – the principal variation. The change from manual input of the number code to Touch ID via fingerprint sensor for screen unlocking is an example of principle variation. The proportion of new development through embodiment variation, principle variation or carryover depends on the goals and requirements of the new product generation (Albers, Bursac, et al., 2015).

Faults at transitions between product generations are quite typical, especially for new developments through embodiment and principle variation. By varying the embodiment or principle solution, the characteristics obtained can be improved, but there is also a high risk that the modification will lead to the unexpected deterioration of other characteristics. A methodical procedure, which is applied during product development and supported by the company management, can contribute to a general improvement of product development success (Albers & Schweinberger, 2001). Selected models for product development support are described in the next sections.

2.1.1 Models for product engineering support

“Every engineering process is unique and individual” (Albers, 2010). An explanation for this uniqueness and individuality is that the objectives, requirements or boundary conditions that underlie an engineering process are different and thus lead to a unique course of the process (Albers, 2010). Nonetheless, within a product generation development, recurring procedures and patterns can be observed in the engineering process. These repetitive procedures can be described abstractly in the framework of a PGE model. (Albers et al., 2019)

Albers and Mebold (2007) describe product engineering based on the ZHO model – Z: system of objectives; H: operating system; and O: system of objects[2] – developed by Ropohl in (1979) and define these terms as follows:

> The operation system is a socio-technical system that is composed of structured activities, methods and processes as well as the needed resources for the realization, e.g. design staff, budget, material, machines, etc. The operation system creates the system of objectives and the system of objects. The system of objectives and the system of objects are linked by the operation system; there is no direct interdependency between the system of objectives and the system of objects (Albers & Meboldt, 2007).

[2] German: Ziel-, Objekt-, und Handlungssystem.

A system of objectives comprises all explicit objectives of a product that is to be developed, including their dependencies and boundary conditions, within a defined area of interest (i.e. within a system of interest) at a certain time. (Albers & Meboldt, 2007)
A system of objects is the realized solution of the system of objectives and is completed as soon as the planned specified condition of the objective system corresponds to the actual condition. It includes tangible and intangible results of the development process, i.e. drawings, models, prototypes. The elements of the object system are the subject and result of the operation system. (Albers & Meboldt, 2007)

The continuous definition and specification of a system of objectives as well as the quality of the defined objectives have an influence on the product success (Albers, Behrendt, et al., 2016, p. 543). The definition of a qualitative system of objectives, the establishment of an operating system and thus the successful implementation in the product are the core activities of product engineering (Albers & Meboldt, 2007). The described framework of a PEP model is presented in Figure 3.

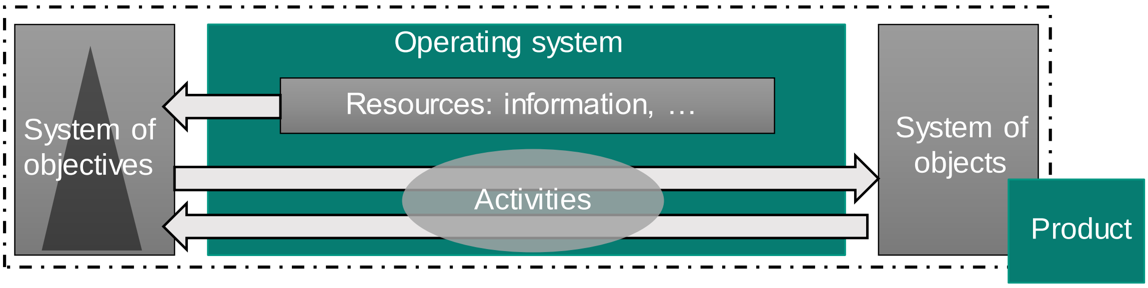


Figure 3: System model of PEP – adapted from Albers and Braun (2011)

The ZHO model was advanced by Albers et al. (Albers, Lohmeyer, et al., 2011), who used the model to describe the product developer in the center of an uncertain and iterative product development process. The advanced ZHO model is presented in Figure 4.

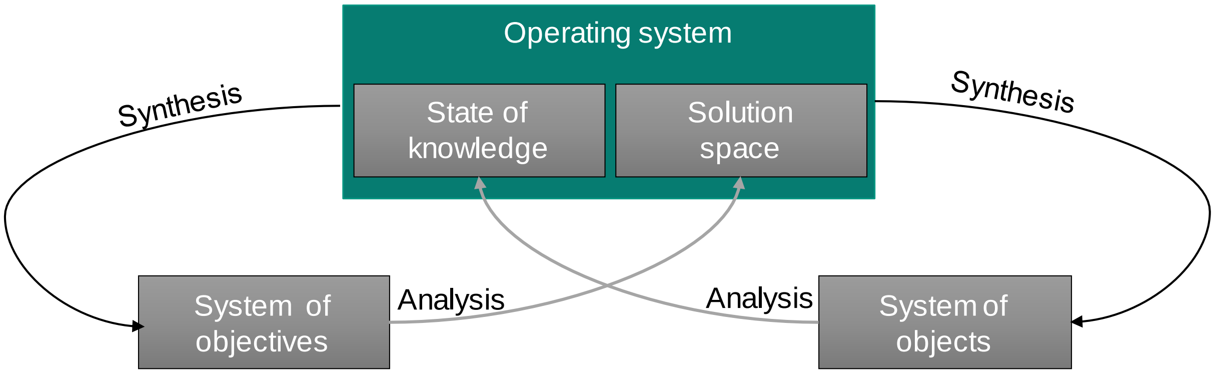


Figure 4: Advanced ZHO Model adapted from Albers et al. (2012)

iPeM – the integrated Product engineering Model

The integrated Product engineering Model (iPeM), according to Albers and Braun (2011), is a meta-model with a generic character from which individual models can be derived for each PEP. The iPeM supports process modelling and project management and contributes to the methodological support of the PEP. The central content of the iPeM is the operating system and the activities it contains. The activities of the operating system can be classified as 1) activities of product engineering and 2) activities of problem solving. The activities of product engineering are oriented towards the life cycle phases of a product and describe relevant aspects from a development perspective. The activities of problem solving, as indicated by the designation, comprise a problem-solving process and, together with activities of product engineering, constitute the activity matrix. This matrix remains unchanged along a PEP and thus serves as a consistent basis for a common concept and understanding model. Systematic and consistent implementation as well as coordination and control of all activities and processes is important for successful product development. (Albers & Braun, 2011) Figure 5 illustrates the iPeM – integrated Product engineering Model.

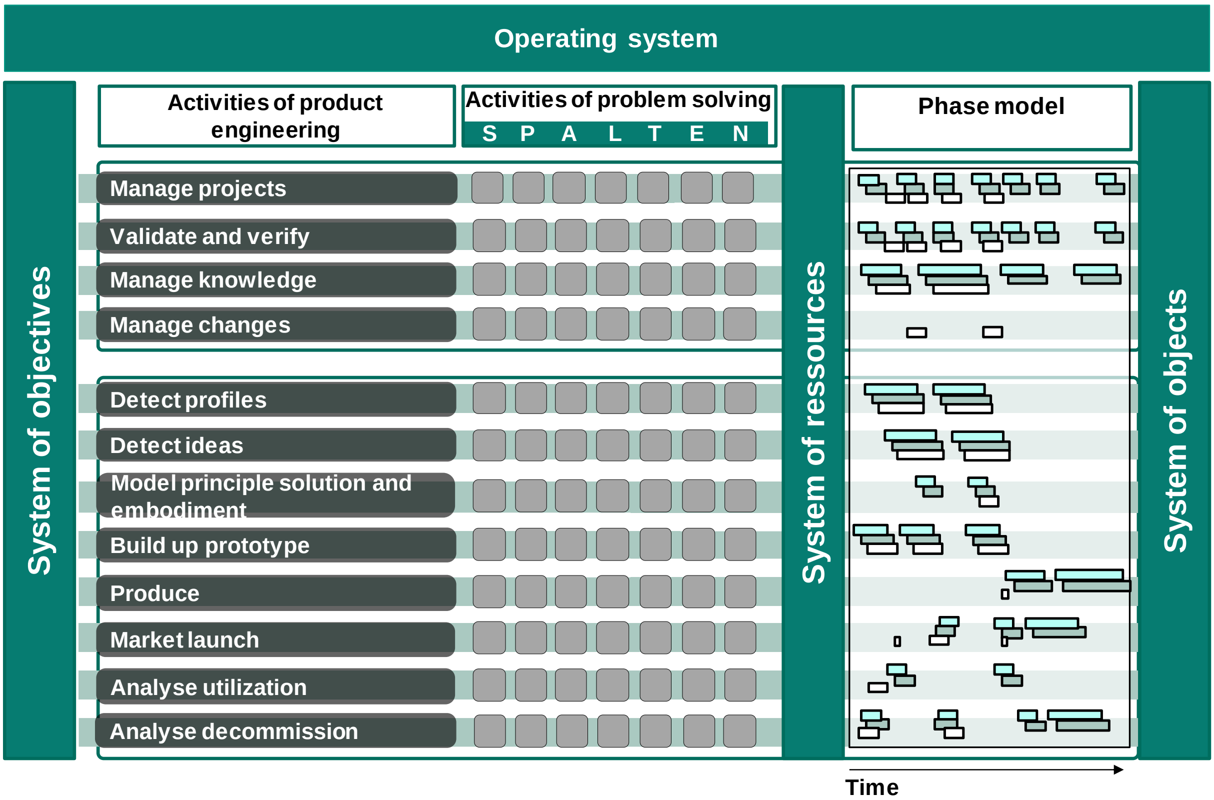


Figure 5: iPeM – integrated Product engineering Model adapted from Albers et al. (Albers, Reiss, et al., 2016)

The activities of product engineering consist of 12 activities in general. These activities are briefly described below according to Albers and Braun (2011) and Albers et al. (Albers, Reiss, et al., 2016).

Manage projects – a sequential activity in which object and target system are continuously compared during the entire PEP in terms of budgeting time, costs and other resources.

Validate and verify – the central activity in the PEP, serving not only to test the future product's physical properties in simulation or via prototype tests, but also to continuously compare the actual state achieved with the target state described in the target system.

Manage knowledge – the sequential activity that contains internal and external data, information and capabilities.

Manage change – the activity that involves the coordination of technical, economic and social changes.

Detect profiles – the activity that describes the step of assessing a product's market potential in terms of demand; customer wishes, the competitive situation and the enterprise's position are considered.

Detect ideas – the activity that involves the generation of initial solution-neutral ideas for products in response to market needs.

Model principle solution and embodiment – a stage in which product ideas are realized successively from abstract sketches and drafts to elaborated detailed drawings, CAD models, or production documents.

Build up prototype – the activity in which both physical and virtual prototypes at different levels of maturity are developed to validate and verify the product.

Produce – the activity containing all tasks needed to manufacture the product.

Market launch – the activity, often already anticipated during earlier PEP phases, to establish a sales network for the product.

Analyze utilization – the activity that serves as a source of information in early phases of product development whenever the future use of the product is anticipated and appropriate requirements for the product and process are derived from it.

Analyze decommission – the activity that includes the dismantling, recycling or final disposal of the product.

According to Albers and Meboldt (2007), **problem-solving activities** are referred to in iPeM using the German acronym SPALTEN, which denotes a cycle of problem-solving activities in a specific structure. Each letter stands for specific activity: **S** – situation analysis; **P** – problem containment; **A** – detection of alternative solutions; **L** – selection of solutions; **T** – analysis of consequences; **E** – deciding and implementing; and **N** – recapitulation and learning. (Albers & Meboldt, 2007) Altogether, the activities in this matrix comprise 84 fields corresponding to activities of product engineering activities.

A further part of the iPeM is a phase model, which is displayed on the right side in Figure 5. The phase model is the result of assigning certain time intervals to product engineering activities (Albers & Braun, 2011). The time schedules of product development, which occur before the activity model principle solution and embodiment, are referred to as the early phases of product development (Albers et al., 2017). Information acquisition, processing and evaluation takes place in early phases (Verworn, 2005, p. 20). According to Cooper and Kleinschmidt (1993), the success of a product is strongly determined by activities which are undertaken in the early phase of product development.

The method developed as part of this dissertation is integrated into the iPeM and focuses on three activities: (1) manage knowledge, (2) detect ideas and (3) model principle solution and embodiment. Therefore, further chapters on the state of the art are more strongly oriented towards the basics of the embodiment design process and the methodical approaches to support it.

2.1.2 Fundamentals and activities of the embodiment design process

Model principle solution and embodiment is among the important activities in the embodiment design process. According to VDI 2223 (2004), the embodiment design process is the sum of all activities in which the product developer determines the form characteristics of design elements. The embodiment design characteristics are determined by properties that describe the geometry (Verein Deutscher Ingenieure 2223, 2004, p. 11) and the features associated with the geometry as shape, dimensions, arrangement and number of the form design elements (Pahl & Beitz, 1997). Weber (2012) has a similar view and states that features assigned to embodiment design can be defined by characteristics such as component structure, shape, dimensions, materials, surface parameters and the spatial arrangement of the components. These design characteristics can be directly influenced by the product developer. (Weber, 2012, p. 31)

Analysis and synthesis are important activities in the embodiment design process. An analysis activity denotes an action aimed at understanding an existing system with result recognition, and a synthesis activity refers to an action aimed at creating a system that does not yet exist (Lohmeyer, 2013, p. 108). Analysis activities are essential for the successful development of new products, because during the analysis, important findings for new solutions can be identified (Birkhofer et al., 1980; Hacker, 2002). According to Pahl et al. (2007, pp. 75–76), synthesis is understood as information processing by forming connections and by linking elements and thus creating new combined effects. A successful analysis of existing products is important in order to create a sufficient information base for the synthesis. Therefore, analysis and synthesis activities form cycles in which the degree of the maturity of the development is continuously increased by the completed test and learning cycles. This maturation leads to the acquisition of case-related knowledge and thus to the development of a sufficient solution. (Lohmeyer, 2013, p. 113)

In order to support the embodiment design process methodically, various approaches exist in the literature. The Verein Deutscher Ingenieure (1997) has developed a "methodology for developing and designing technical systems and products," published in the VDI Richtlinie 2221. The guideline consists of seven work steps that, depending on the task, can be executed one after the other or iteratively. The guideline focuses on new product development and therefore mainly offers methods to support synthesis activities. The VDI 2221 was reworked and updated in 2019 as a “Design of technical products and systems Model of product design.” This reworked version presents and describes eight main product development activities 1) clarifying and itemizing the problem or task, 2) determination of functions and their structures, 3) searching for solution principles and their solutions, 4) assessing and selecting the solution concept, 5) subdivision into models – interface definitions, 6) designing the modules, 7) integrating the product as a whole and 8) assurance of the fulfilment of the requirements. In addition to these activities, other supporting elements are also mentioned as important, these include knowledge management and “Design for X.” (Verein Deutscher Ingenieure 2221, 2019b) Knowledge management is, according to VDI 5610, “the organising of all processes identifying, creating, recording, distributing and applying information, findings and experiences” (Verein Deutscher Ingenieure 5610, 2009). “Design for X,” according to Hubka (1984), is a “knowledge system that includes organized information concerning how individual properties of technical systems can be achieved during the design process.”

A Contact, Channel and Channel approach (C&C²-A) is a method that supports both analysis and synthesis activities in product engineering. The main target of the C&C²-A is to promote the understanding of technical systems and to support improvements of design solutions to achieve the defined design goals. The C&C²-A approach offers the possibility of describing technical systems in such a way that the shape can be assigned to each function. (Albers & Wintergerst, 2014) The C&C²-A consists of basic elements, which Matthiesen (2002) defines as working surface pairs (WSP), channel and support structures (CSS), and connectors (C) and defines as follows:

Working Surface Pairs (WSP) are set up when two arbitrarily shaped surfaces of solid bodies or generalized interfaces of liquids, gases or fields get into contact and are involved in the exchange of energy, substance and / or information. (Matthiesen, 2002)

Channel and Support Structures (CSS) are volumes of solid bodies, liquids, gases, or field-permeated spaces that connect exactly two pairs of surfaces and allow the conduction of matter, energy, and / or information between them. (Matthiesen, 2002)

Connectors (C) integrate the properties, which are relevant to the effect and are located outside the design area, into the system view. They are an abstraction of the systems environment, which is relevant to the description of the function under consideration. (Matthiesen, 2002)

According to Albers and Wintergerst (2014), together, these elements form a so-called Wirk-Net, which describes the energy, material and information flows in the system and within its system environment. Functions are the interactions between the WSP and the CSS connecting them. Connectors are used to integrate the technical system into the system environment and to capture interactions. (Albers & Wintergerst, 2014) The C&C²-A approach combines abstract functions with concrete geometry, thus making it possible to understand and to evaluate the design. The system functionality can be described by splitting up the design problem into smaller elements. (Albers et al., 2008)

C&C²-A model-based representations have been proven to aid in knowledge transfer in various applications. The integration of the C&C²-A into design guidelines for supporting the visualization of correlations can have a promising potential. However, it should be carefully examined when the application of C&C²-A brings added value, as the processing and description of information is associated with an increased effort.

2.2 FRPs as innovative materials in lightweight design

Fiber-reinforced plastics (FRPs) belong to a subgroup of composite materials and consist of no less than two components: a plastic matrix and reinforcing fibers (Karger-Kocsis, 2014, p. 31). Fiber-reinforced plastic is an important lightweight material that has been increasingly deployed in recent years in various industries. The combination of low density and high rigidity makes this material interesting for many applications in which lightweight design and design freedom are important considerations (AVK – Industrievereinigung Verstärkte Kunststoffe e. V., 2013, pp. 33–36). The properties of FRP can be tailored by various combination options, such as the choice of fiber material, fiber length, fiber volume content, fiber orientation or the properties of the resin system (Uddin, 2013, pp. 178–179). The adjustable composition of the properties enables tailor-made application of FRP, but also requires tailor-made engineering and production processes (AVK – Industrievereinigung Verstärkte Kunststoffe e. V., 2013, p. 33) taking into account the underlying composition of the material properties.

2.2.1 Important basics and terms

The matrix serves as a protection of fibers against external environmental influences, while also fixing them in a certain position, introducing forces into the fibers and taking overloads transversal to fiber orientation. The fibers in turn provide strength for the FRP composite through their mechanical properties in a longitudinal direction. (Schürmann, 2007, p. 13) The adhesion of the fibers in the matrix has an important influence on the resulting mechanical properties and long-term behaviors of the composite material (Drzal & Madhukar, 1993).

Matrix materials – Plastic matrices can be divided into three groups: thermosets, thermoplastics and elastomers (Schürmann, 2007, p. 83). In this work, only thermosets and thermoplastics are of importance and are therefore described below.

Thermosets – The most commonly used thermosets are reaction resins, such as unsaturated polyester resins (UP), vinyl ester resins (VE), epoxy resins (EH) and phenolic resins (PF) (Karger-Kocsis, 2014, p. 43). Thermosets are characterized by a high modulus of elasticity, a low creep tendency and a strong thermal and chemical resistance. Thermosets' dimensional stability is significantly more heat-resistant than that of thermoplastics. However, thermosets have a brittle behavior. The final shape must be formed during production, as subsequent shaping by heating is no longer possible. (Schürmann, 2007, pp. 84–85)

Thermoplastics – In contrast to thermosets, the melting process for thermoplastics can be repeated as often as required; this capability results in weldability advantages and more cost-effective recycling for thermoplastics. Thermoplastics' disadvantages are the tendency to creep at higher temperatures and a lower strength compared to thermosets. (Schürmann, 2007, pp. 85–86) Thermoplastics are characterized by a high resistance to delamination and a high residual compressive strength. The processing of thermoplastic materials is significantly faster than of thermosets. (Karger-Kocsis, 2014, p. 56)

Reinforcing fibers – The type of reinforcing fiber has a large influence on the properties of the composite material (Buschhoff et al., 2016). Such properties as stiffness, impact strength, environmental resistance and creep behavior can be specifically influenced by the appropriate selection of fiber material (Campbell, 2010, pp. 490–491).

Reinforcing fibers can be classified into four groups according to their materials and structures (Schürmann, 2007, p. 26):

- Organic fibers (e.g., carbon, nylon, aramid)
- Inorganic fibers (e.g., mineral, glass)
- Natural fibers (e.g., flax, wood)
- Metal fibers (e.g., steel, aluminum).

In addition, fibers can be divided according to their length as follows (Schürmann, 2007, p. 138):

- Short fibers with the length l = 0,1 – 1 mm
- Long fibers with the length l = 1 – 50 mm
- Endless fibers with the length l > 50mm.

Mechanical properties such as tensile strength can be positively influenced by appropriate fiber length (Yun Fu & Lauke, 1996). In this work only glass and carbon fibers are of importance and are therefore described below.

Glass fibers have solid tensile and compressive strength, as well as strong electrical and thermal insulation properties. Their other properties include a low moisture absorption, as well as high chemical and microbiological resistance. Due to the low stiffness, the glass fibers can be easily draped, which enables the production of complex parts. The surface quality can easily be detected due to their mostly transparent color, which makes quality control much easier with glass fibers compared to carbon fibers. Glass fibers' low tendency to creep also enables their function in both low and high temperatures. However, if glass fibers are subjected to higher temperatures for a longer period of time, their strength decreases. A decisive disadvantage of glass fibers is their low modulus of elasticity. (Schürmann, 2007, pp. 28–33)

Glass fibers can be divided into different types, including E-type and S-type. Each type has specific properties that make it suitable for use in certain applications (Schürmann, 2007, pp. 29–34). S-type is characterized by a high tensile strength and stiffness while E-Type or electrical glass is highly electrically resistant. (Cameron & Rapp, 2001, pp. 3142–3146)

Carbon fibers – The disadvantages of glass fibers in terms of a low modulus of elasticity motivated scientists to search for an alternative material at the end of the 1950s (Schürmann, 2007, p. 35). With carbon fibers, composite materials can obtain a high strength and modulus of elasticity, low weight, and a high anisotropy.[3]

[3] Anisotropy means that material properties are directionally dependent

Furthermore, the anisotropy influences thermal expansion coefficients (Schürmann, 2007, p. 39). The carbon fibers reveal a negative coefficient of thermal expansion in the longitudinal direction. In contrast to other materials, this property does not lead to expansion, but rather to a slight contraction of material. (Eickenbusch & Krauss, 2013, p. 15) The temperature resistance of carbon fibers is exceptionally strong and is significantly better than that of glass fibers. In addition to their valuable mechanical properties, carbon fibers are characterized by a high abrasion and corrosion resistance; they are conductive electrically and thermally. Owing to the properties mentioned, this reinforcement type is widely used in a variety of areas in which weight and mechanical strength are of great importance. However, carbon fibers also have some negative aspects, including their brittle fracture behavior, lower fiber-parallel compressive strength compared to tensile strength and high production cost. Furthermore, due to the opaqueness of the fiber, checking whether the carbon fibers are sufficiently impregnated with matrix resin is more difficult than with glass fibers. (Schürmann, 2007, pp. 39–42)

Carbon fibers can also be divided into different types according to their properties; these include HT (high-tenacity) fibers, HM (high-modulus) fibers, UHM (ultra-high modulus) fibers and others (Schürmann, 2007, p. 41). The differences between the mechanical properties of carbon and glass fiber types are presented in Table 1.

Table 1: Mechanical properties of the different fiber types referring to Karger-Kocsis (2014, p. 32)

		Tension			Compression	
		Modul [GPa]	Strength [MPa]	Breaking elongation [%]	Strength [MPa]	Density [g/cm³]
Glass	E-Type	80	3500	4	-	2,54
	S-Type	90	4500	5,7	1100	2,46
Carbon	HT	240	3750	1,6	2900	1,78
	HM	400	2450	0,7	1160	1,85
	UHM	540	1850	0,4	1100	2

Semi-finished material – The most well-known semi-finished materials are semi-finished fibers and pre-impregnated semi-finished materials, also known as “prepregs.” The former is a dry semi-finished material that only contains reinforcing fibers. A prepreg is a wet semi-finished material pre-impregnated with a resin system. Dry semi-finished fibers consist of fiber filaments of a certain length. (Flemming et al., 1996, p. 2) There are different types of dry semi-finished fibers, which vary across their realizations of fiber structures and resulting load-bearing structures. Some of these types are described hereafter.

Dry semi-finished structures – Endless filaments in a parallel arrangement are called rovings (Flemming et al., 1996, p. 2). **Rovings** belong to the one-dimensional reinforcing structures, which means that the reinforcing is mainly in one preferred direction (Cherif, 2016, p. 27). **Fleeces,** or non-woven fabrics, include fiber structures such as continuous filaments or short fiber yarns, which are formed into a sheet or bonded by any process (International Organization for Standardization (ISO) 9092:2011, 2011). **Mats** consists of bundles of spun threads and therefore have a coarser structure than a fleece. Mats can be reinforced with continuous or chopped fibers (Schürmann, 2007, pp. 64–66). Figure 6 displays an example of mats with chopped and endless fibers.

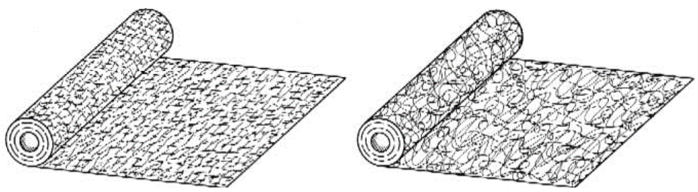


Figure 6: Example of mats with chopped and endless fibers adapted from Schürmann (2007, p. 64)

Woven fabrics consist of two fiber directions oriented at right angles to each other (Deutsches Institut für Normung (DIN) 60000, 1969). There are multiple different types of weave patterns, each of which has a different influence on the fabric's sliding strength (Henning et al., 2011, pp. 355–356). The most common bindings are plain, twill, and atlas, displayed in Figure 7 below.

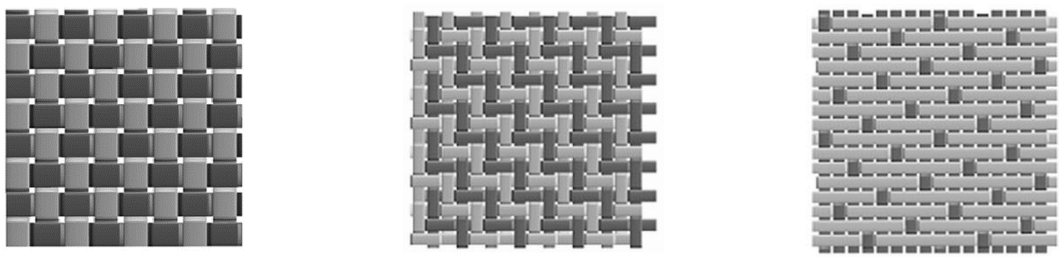
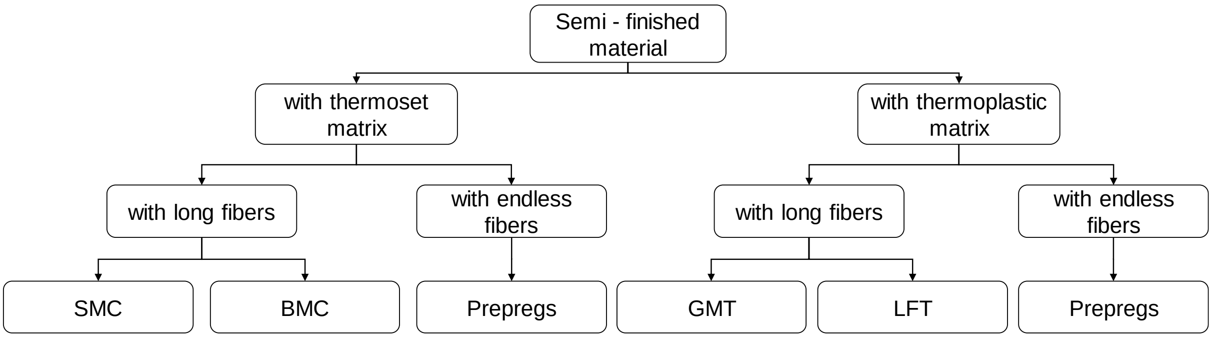


Figure 7: Weave pattern – plain (left), twill (middle), atlas (right) adapted from Henning et al. (2011, p. 355)

Pre-impregnated semi-finished materials (prepregs) – Prepregs are prefabricated with a reinforcement structure of continuous or discontinuous fibers that is combined with a thermosetting or thermoplastic matrix material (Diestel & Hausding, 2011, p. 381). Figure 8 classifies prepregs according to matrix material and fiber length.

This work focuses on two types of prepregs: continuous and discontinuous fibers, both of which are pre-impregnated within a thermosetting matrix material. The IRTG project abbreviates these two prepregs types as CoFRP, for continuous fiber reinforced polymers, and DicoFRP, for discontinuous fiber reinforced polymers.



Abbreviations
SMC – Sheet molding compound
BMC – Bulk molding compound
GMT – Glass mat reinforced thermoplastics
LFT – Long fiber reinforced thermoplastics

Figure 8: Classification of pre-impregnated semi-finished materials according to matrix material and fiber length in Schürmann (2007, p. 138)[4]

The sheet molding compound (SMC) is a DicoFRP and can consist of either glass or carbon fiber fleeces embedded in thermoset reaction resins (AVK – Industrievereinigung Verstärkte Kunststoffe e. V., 2013, p. 245). The fiber's length can vary between 25 and 50 mm, and the typical fiber volume content lies between 25 and 30% of weight but can also be adjusted up to 60% (Schürmann, 2007, p. 139). An SMC can be divided into three types according to the used fiber reinforcement: unaligned long fibers (SMC-R), aligned long fibers (SMC-D) and aligned endless fibers (SMC-C) (Jutte, 1979). The latter two have higher unidirectional strength compared to SMC-R (Schwartz, 2002, p. 793). Figure 9 illustrates these SMC types below.

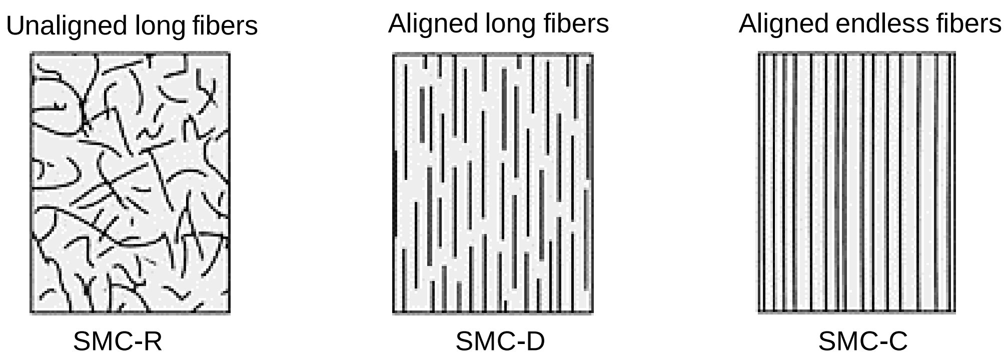


Figure 9: Designation of various SMC types adapted from Bonten (2016, p. 336)

[4] Text is translated from German to English

A **bulk molding compound (BMC)** is a fiber reinforced thermosetting material consisting of fibers with a length between 6 and 25 mm and a typical fiber content in the range of 15 to 30 % (Schürmann, 2007, p. 139). **Glass mat reinforced thermoplastics (GMT)** and **long fiber thermoplastics (LFT)** both consist of thermoplastic resin. This resin is reinforced for GMTs with glass fiber mats and for LFTs with long fibers. (Schürmann, 2007, pp. 151–156)

2.2.2 Challenging aspects associated with FRPs

As briefly mentioned in Section 2.2, FRPs properties can be tailored by the selection of matrix material and fiber reinforcement. Challenges associated with FRPs can therefore vary depending on material compilation. In this section, some challenges that are generally related to design and manufacturing with SMC materials are described.

One of the challenges is due to anisotropic properties (Klein et al., 2014; Puri, 1999). Anisotropy means that the material properties are directionally dependent (Schürmann, 2007, p. 17). These direction-dependent properties are determined by the orientation profile of fibers, (Roos & Maile, 2015, p. 306) which is directly related to the mold filling process (Davis et al., 2003, p. 49). Predicting the influence of processing parameters on the final fiber orientation poses a challenge for product developers when designing components (Li et al., 2017). The potential of anisotropy can only be fully exploited if its advantages, such as its high specific stiffness and strength in the fiber direction or property-related thermal expansion, are considered and used advantageously (Puri, 1999). Two flow phenomena can be differentiated during the mold filling process: shear and strain flows (Specker et al., 1990, p. 97). Shear flows prevail at the edges and align the fibers in the direction of the flow, while strain flows usually dominate in the middle and orient the fibers in a vertical direction against the flow direction (Schüle et al., 2008, pp. 219–220). The manufacturing process and parameters, the flow geometry in the tool, and the material's rheological properties can all greatly influence the fiber orientation (Schoßig, 2011, p. 7). The matrix's rheological properties are determined by the matrix's viscosity, fiber volume content, fiber-matrix adhesion and fiber length (Karger-Kocsis, 1989). The viscosity describes the material's flowability and can additionally influence the possible adjustment of the fibers during the flow process (D. H. Chang, 2007, pp. 545–546). Viscosity is not a constant variable and can be influenced by temperature and time (Beaumont, 2012, p. 20). The interactions of process parameters such as temperature, closing speed and cavity allocation must all be optimally adjusted for the respective material system and its properties.

A further challenging aspect is the strong influence of the manufacturing process on the resulting mechanical properties as well as quality of the molded parts (Davis et al., 2003, p. 49). In addition to fiber orientation, other important component properties are influenced during the manufacturing process. The investigations by Schmachtenberg et al. (2005) reveal the relationship between process parameters and the strength of the fiber matrix separation effect in SMC material. This effect results from the flow velocity difference between the fibers and a matrix, caused by the interaction of various factors such as fiber volume content, fiber aspect ratio,[5] viscosity and mold coverage. Another factor influencing the fiber separation effect is the initial mold coverage or the space required for the cutting package in the mold, which is illustrated in Figure 10. The fiber–matrix separation leads to surface defects and mechanical weak points. (Schmachtenberg et al., 2005)

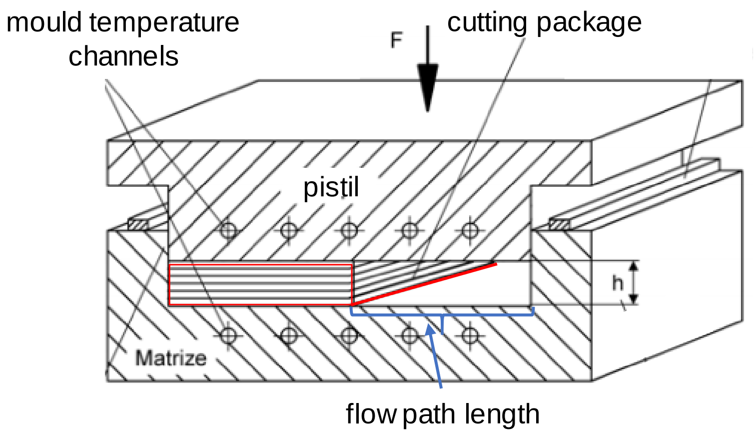


Figure 10: Initial mold coverage (in red color) adapted from Schmachtenberg et al. (2005)

Möbius et al. (2013) investigated the influence of fiber aspect ratio, fiber volume content, initial mold coverage and viscosity of the matrix material on the occurrence of the fiber–matrix separation effect in SMC material. Their experiments reveal that as the fiber aspect ratio rises, the fiber–matrix separation increases due to the larger mechanical interlocking. The reason for the larger mechanical interlocking effect is that in a higher fiber aspect ratio, the fibers are entrained more slowly by the matrix system than in a lower fiber aspect ratio. (Möbius et al., 2013)

Skrodolies and Michaeli (2006) investigated the influence of process parameters such as mold temperature, cavity allocation, air pressure, and closing speed on pore formation[6] in SMC material. The investigations reveal that more pores occur at low mold temperatures, which is caused by reduction of the air pressure in the cavity. In the experiment, the number of pores decreases due to an increase in the mold temperature. Low cavity occupancy (approximately 30%) leads to fewer pores due to the rising flow path and flow time. These two factors favor a low material viscosity, which in turn favor a lower rate of pores. (Skrodolies & Michaeli, 2006)

[5] Fiber aspect ratio - the fibers' length divided by its diameter

[6] Porosity is defined as gas inclusions in the form of cavities in pressed components

In addition to the material's rheological properties and manufacturing parameters, a component's design also can promote or reduce possible quality defects. Wall thickness transitions between thick walls in thin-walled areas cannot always be avoided by design. The investigations by Schmachtenberg et al. (2005) reveal that slow closing speeds (1 mm/s) lead to more distinctly low-fiber areas at the edge of the thickness transition area in comparison with higher closing speeds (5mm/s), as displayed in Figure 11. The material's flow velocity during the thickness transition caused by the press's closing speed results in this effect. (Schmachtenberg et al., 2005)

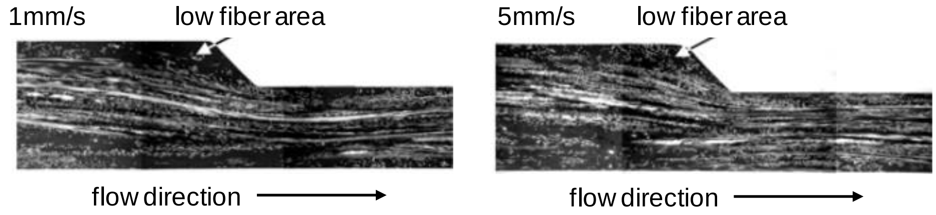


Figure 11: Influence of closing speed on fiber filling at the transition from thick-walled to thin-walled areas adapted from Schmachtenberg et al. (2005)

Schmachtenberg et al. (2005) detected a reproducible ejection of the fibers in the thickness transition flows from thin-walled to thick-walled areas. According to Schmachtenberg et al., this resulting ejection of the fibers is the result of the long delay at the transition behind the thickness step, as illustrated in Figure 12. This effect is not present at low closing speeds. In both cases, however, the matrix islands without fibers can be observed immediately after the thickness transition. (Schmachtenberg et al., 2005)

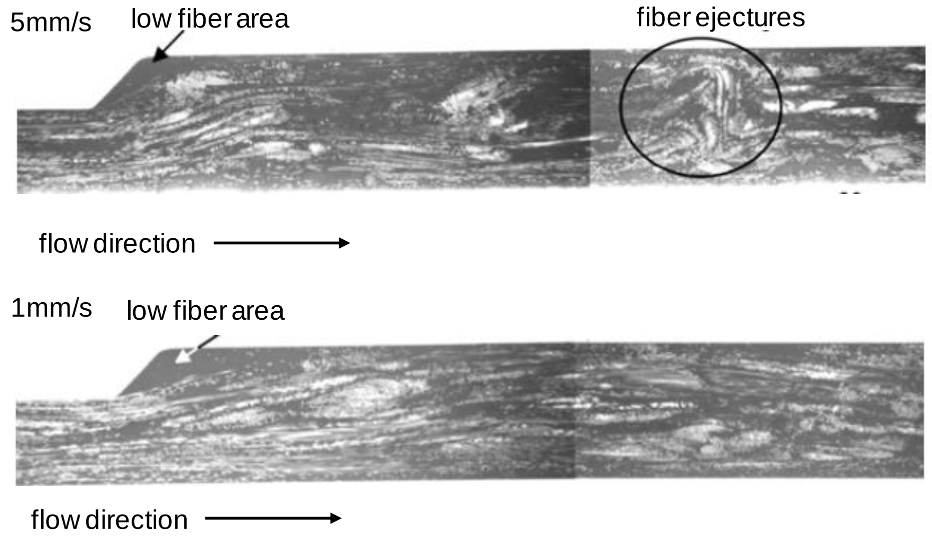


Figure 12: Influence of closing speed on fiber filling at the transition from thin-walled to thick-walled areas adapted from Schmachtenberg et al. (2005)

Specker et al. (1990) identified the influences on the quality of rib strength and interrelationships among the manufacturing parameters, the material properties and the rib geometry. As displayed in Figure 13, a high run-in resistance delays the material flow into the rib, which can lead to low fiber contents or fiber damage. The running-in resistance during rib-filling depends on the inlet radii, the ratio of plate thickness to rib thickness and the rib's inclination angle. A rib with a round run-in and a rib with a sharp-edged run-in are examined and, in the latter case, unfavorable fiber orientations occurred due to the shearing of the material at the rib base during transverse flow. (Specker et al., 1990, pp. 83–95)

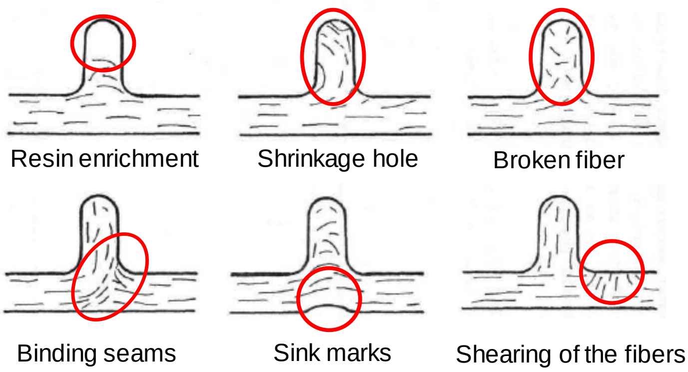


Figure 13: Fiber content and fiber orientation inhomogeneities in the rib area adapted from Specker et al. (1990, p. 86)

According to Specker et al. (1990), the pressure level at the rib base influences the rib filling and is altered by the tool's closing speed and temperature, the flow front position relative to the rib and the rib's geometry. Sharp edges at the rib inlet and low rib thickness increase the pressure level, which leads to unfavorable fiber orientations. The rib's filling time and the subsequent flow processes influence the fiber's orientation, content and damage. Earlier rib filling can cause the fibers to shear if they are transverse to the direction of flow. A rib filling that occurs too late leads to a poor rib connection. The molding's flowability can increase the rib connection and is determined by material parameters such as the matrix system, fiber structure, fiber content, fiber geometry, filler content and quality, as well as the temperature in the flow process. (Specker et al., 1990, pp. 95–101)

According to Hohberg et al. (2017), process simulation to predict resulting fiber orientation presents a special challenge, especially in the combination of long and continuous fiber reinforced thermosets. The commercial simulation programs that are currently available primarily consider shear-rate-dependent viscosity models, which leads to different results across simulations and experiments. The transfer of the results from the process simulation into the structure simulation represents the next issue. The process simulation has a different calculation grid, and the results can therefore not be integrated into an Abaqus[7] environment without a mapping step. (Hohberg et al., 2017)

2.2.3 Summary

The challenging aspect in product development with SMC materials lies in the manifold interactions among the material, design and manufacturing parameters. The material compilation determines the properties, which, in turn, can be positively or negatively influenced by process parameters during production. In addition, the material's properties must be considered when designing the component geometry. The process parameters must be adjusted according to the component's design to ensure homogeneous filling, appropriate fiber orientation and the avoidance of quality defects. However, changing some parameters to avoid or address certain effects can lead to an undesirable influence on other properties. For example, the high closing speed is well-suited to avoiding a fiber-matrix separation effect, but it also leads to the ejection of fibers and thus to weak points in the component during thickness transitions.

2.3 Design guidelines

Design guidelines[8], are well-known, according to the VDI 2223 (Verein Deutscher Ingenieure 2223, 2004, p. 66), as instructions for the expedient embodiment design of technical products and contain condensed, documented experiences of successful, proven solutions and procedures in earlier design tasks. Design guidelines are of great importance for both inexperienced and experienced product developers for familiarizing themselves with a new topic. The support is provided through concrete recommendations on the design's weak points and the provision of suitable suggestions for improvement. By following design guidelines, ideas for solutions to embodiment design issues can be found and faulty design solutions can be identified or avoided in advance. (Verein Deutscher Ingenieure 2223, 2004, pp. 66–67)

Design guidelines can be accessed in various sources on various topics and materials and are a widespread form of documentation of relevant engineering experiences. (Butenko & Albers, 2018)

This chapter analyzes published design guidelines for FRP materials in traditional and digital literature. The analyses focus on the content of published design guidelines, their structure, and their representation form. Furthermore, some examples of design guidelines for unreinforced thermoplastics and for metals are presented and compared with design guidelines for fiber reinforced plastics.

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[7] Abaqus is a software for finite element analysis

[8] In different literature sources design guidelines are sometimes called design rules or design recommendations.

The analysis of the design guidelines was performed manually with the support of the QDA Miner[9] data-mining tool, which enabled relevant information to be quickly identified and important search-relevant text passages to be found. Information sources included selected technical books in the field of product engineering with FRP, submitted publications at the International Conference on Composite Materials and scientific papers from the Journal of Plastics Technology.

2.3.1 Overview of design guidelines for FRPs

In 1995, the design manual (Fiberline Composites A/S, 1995) was released to facilitate the design and construction of well-functioning structures using composite profiles from the Danish Fiberline Composites A/S. The design specifications mainly focus on the E-glass roving reinforced Fiberline profiles manufactured with the pultrusion process. The Fiberline Design Manual is only applicable for structures that are built with Fiberline profiles. In 2002, the contents were updated and published in the form of a second edition. Figure 14 illustrates an example of design guideline in Fiberline Composites.

Point loading of profiles, for example, I-, U-, and L-profiles, as well as square tubes.

The types of loads shown in Figure are not appropriate for composite materials and should be avoided, unless they have been proven by analysis.

Therefore, Fiberline recommends the use of a washer diameter of 2.5*d.

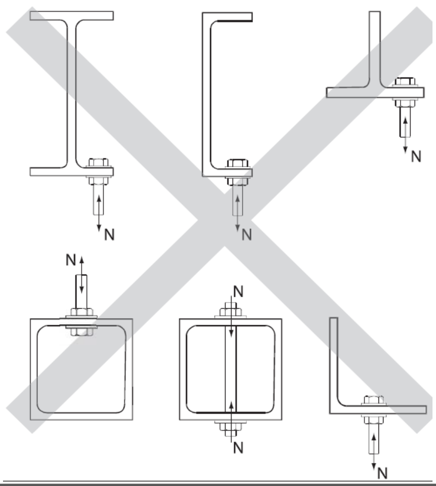


Figure 14: An example of a design guideline adapted from Fiberline Composites (2002)

Information is documented in text, images and formulas on 326 pages and can be used to make concrete calculations taking different stresses into account. It covers information related to chemical resistance, recycling and the fire properties of profiles.

The European Structural Polymeric Composites Group (EUROCOMP) (Clarke & Halcrow, 1996) represents the practical “Design Code for the Construction Industry” with the aim of enabling designers to use a broad range of polymer composites for structural applications. It particularly focuses on the use of glass fiber reinforced plastics in building design and civil engineering. Only the requirements for resistance,

[9] QDA-Miner is a commercial qualitative data analysis software.

serviceability and durability of composite structures are considered. First, the general recommendations on selecting a polymer resin, reinforced fiber material and type (for example mat, woven fabric), and different reinforcement elements, such as core, foam and honeycomb are given in the form of advice. Then, information on different types of material deformation such as creep, rupture and stress corrosion is described, as are their affecting factors and design considerations. It presents general guidance in term of designing for explosions, impacts, fires and chemical attacks in the form of short text with regard to fundamental requirements, performance criteria and design methods. Finally, the criteria about selecting an appropriate joining technique and a design of mechanical, bonded and combined connections are provided. In the case of mechanical joining techniques, the focus is on the bolted, riveted, clamped, threaded, contact and strap joints, as well as embedded fasteners. For bonded connections, the emphasis lies on adhesively bonded, laminated, molded, bonded insert and cast-in joints. In case of combined connections, the bonded-bolted and bonded-riveted joints are considered. The recommendations include a list of criteria that must be considered, as well as general design rules and relevant failure modes. As displayed in a sample in Figure 15, the recommendations are mainly recorded in text form and cover 672 pages.

Ideally the laminate of the part to be joined should be of balanced symmetrical section with fibre orientations distributed through the thickness of the laminate. Preferably there should be 25% of the fibres in the 0° direction, 25% in the 90° direction and 50% in the ±45° direction. In any case, there should be at least 12.5% of plies in each of the four directions 0°, +45°, −45°, and 90°, the 0° direction being parallel to the load.

In any one connection, there should be not less than two fasteners in a line in the loading direction and all the fasteners in the connection should be of the same diameter.

Figure 15: An example of a design guideline adapted from EUROCOMP (Clarke & Halcrow, 1996, pp. 138–139)

Wernli (1998) gives general information for fiber reinforced thermosets that accounts for various manufacturing processes. The author emphasizes the ribs’ design, edge structures, draft angles, radii, wall thicknesses and recommendations for the force transmission. As demonstrated in the sample in Figure 16, this description is done in the form of brief text with figures and is more limited to the general facts.[10] In case of ribs, the information indicates whether ribs can be fitted on both sides (the shape and back sides) and what shape (wave form, etc.) is possible, and even whether they can be used at all. Minimum and maximum values are given for the draft angle. Radii either

[10] According to Butenko and Albers (2019, p. 278)

“should always be as large as possible” or their possible minimum values are given. The wall thickness usually indicates whether the wall should be uniform everywhere or whether different wall thicknesses are possible.

Reinforcement ribs can be installed on both sides. Care must be taken to keep the radii to the surfaces as small as possible in order to prevent excessive marking on the opposite side.

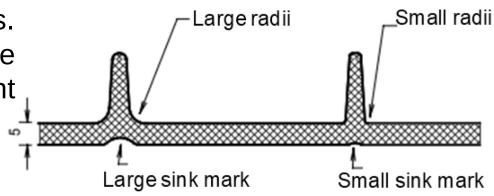


Figure 16: An example of a design guideline for SMC adapted from Wernli (1998)[11]

Davis et al. (2003) provide some guidelines for compression molded parts and focus mainly on manufacturability, structural integrity and aesthetics issues. Recommendation topics include 1) designing wall thickness to avoid different degrees of shrinkage and stress concentrations, 2) designing the corner/part radius to avoid solidification problems and to ensure proper filling with material, 3) designing ribs to avoid sink marks and flow anomalies, 4) designing the boss gusset to improve the overall torsional and bending stiffness and 5) designing hole placement for a structural and non-structural part. As demonstrated in the sample in Figure 17, the explanations are given with great details. In addition to textual explanations, various graphical representations are used to clarify described issues. Furthermore, design alternatives and visualizations of problem cases that occur with non-recommended designs are shown.

One of the most important guidelines when designing a plastic component for any manufacturing process is maintaining a uniform wall thickness in the part. Varying wall thickness creates regions with different degrees of shrinkage, structural performance and stress concentration. When a change in thickness is required, gradual transitions are recommended. Figure demonstrates how the thickness or position of the wall should change. Gradual change with no thick region is preferred. Abrupt changes in wall thickness can also affect how material flows through the mold cavity. During mold filling the resin will tend to flow easier into thicker regions than in thinner regions. This may give undesirable mold filling patterns, which could lead to weld or knit lines, gas entrapment, or less than optimal fiber orientation. One should remember that in compression molding the cavity’s thickness is changing throughout the molding processes.

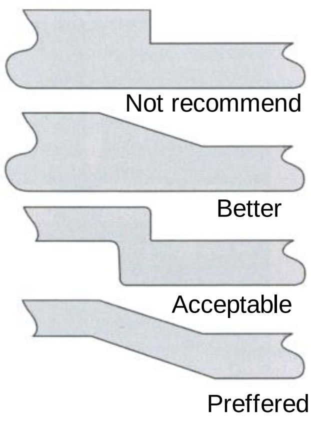
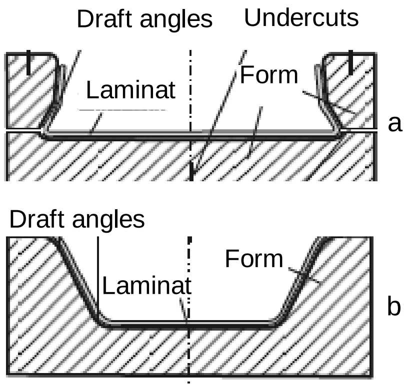


Figure 17: An example of a design guideline adapted from Davis et al. (2003, p. 113)

[11] The text is translated from German to English

Schürmann (2007) provides information about designing FRP laminates. The focus is on avoiding warpage and handling transverse forces, as well as tensile and flexural loads. Additionally, details regarding proper demolding, avoiding resin accumulation and air pockets and achieving surface quality without sink marks are given. The author also presents detailed information and numerous examples on force introduction through the loop, bolt and adhesive connection. Contents refer generally to FRP laminates. A number of design rules can also be implied in text across different chapters. The recommendations can usually be seen in the form of text and figures with sufficient explanations, as demonstrated in the sample in Figure 18.[12]

Composite fibre components are usually produced in negative molds. Firstly, undercuts must be avoided. Secondly, it is essential to provide draft angles on all sides. This applies in particular to thick-walled, rigid components. Thin-walled structures can be bent easily and just peel it out of the mold. On this and on a careful treatment If the mold is not treated with release agents, the component remains locally adhered to the mold and is damaged during forcible demolding.



Design to choice, if undercuts in the manufacturing tool are unavoidable.

Figure 18: An example of a design guideline adapted from Schürmann (2007, p. 624)[13]

The European Alliance for SMC/BMC (2007) presents design considerations for SMC and BMC materials and provide information in the form of plain text and illustrations with favorable and unfavorable designs that include brief explanations. The content includes recommendations on the design of ribs by A-class and non-A class surfaces, details about rib thicknesses, wall thickness, radii and draft angles. Special rules are provided for the design of bosses to reduce the risk of cracking, inserts to prevent torque retention, the design of drill openings and punches and designs for adhesive bonding. Figure 19 illustrates an example of a design recommendation in the European Alliance for SMC/BMC.[14]

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[12] According Butenko and Albers (2019, p. 278)
[13] The text is translated from German to English
[14] According to Butenko and Albers (2019, p. 278)

Keep wall thicknesses constant to avoid thin to thick sections along material flow paths and at the end of the flow - so as not to impair excellent surface quality and isotropic properties.

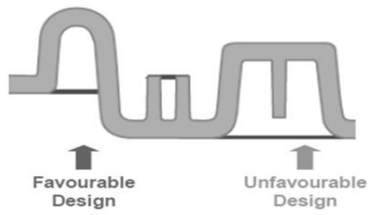


Figure 19: An example of a design recommendation adapted from the European Alliance for SMC/BMC (2007, p. 18)

The Department of Defense Handbook (2012) presents information in the form of general lessons learned for FRP materials in the form of a table with two columns. The first column contains the so-called lesson and explains the essential information in one to two sentences. The second column provides brief explanations as to why the information is important. The lessons learned are grouped into 13 main topics and contain information on different subjects such as sandwich design, bolted/bonded joints, joining to metal or composite material, fabrication and assembly, quality control and more. A total of 164 lessons on 17 pages are mainly documented in text-based form as exemplified in Figure 20.[15]

Lesson	**Reason or consequence**
For highly loaded bonded joints a cocured, multiple step, double sided lap is preferred.	Very efficient joint design.
Where possible, 45° plies (primary load direction) should be placed adjacent to the bondline; 0° plies are also acceptable. 90° plies should never be placed adjacent to the bondline unless it is also the primary load direction.	Minimizes the distance between the bondline and the plies that carry the load. Prevents failure of surface ply by “rolling log" mechanism.

Figure 20: An example of a lesson learned adapted from Department of Defense Handbook (Composite Materials Handbook-17, 2012, pp. 675–676)

Industrievereinigung Verstärkte Kunststoffe e. V. (AVK) (2013) contains recommendations on designing with SMC, LFT and GMT materials. The recommendations refer to the design of wall thickness and wall thickness jumps, the design of ribs on visible and invisible surfaces, and the specifications of radii and draft angles for SMC material. The information is provided mainly in the form of text and illustrations, as exemplified in the sample in Figure 21. There are significantly fewer explanations for the design considerations for GMT and LFT materials compared to SMC material. The objectives of some recommendations are not directly obvious since

[15] According to Butenko and Albers (2019, p. 278)

the textual explanation is not always given, as illustrated in Figure 22. Information in some design recommendations differs in its level of detail.[16]

When designing the radii of the rib connection, it must be decided whether good surfaces or optimum strengths are important. The surface improves as the radius decreases, while the transverse strength of the rib decreases.

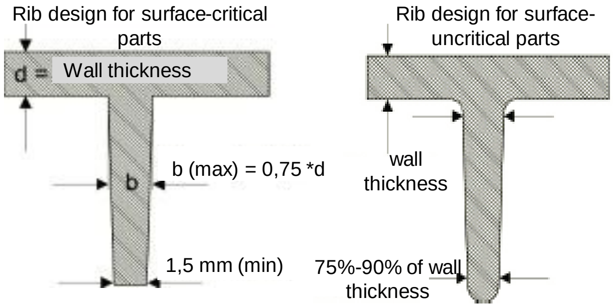


Figure 21: An example of a design guideline for SMC adapted from AVK (AVK – Industrievereinigung Verstärkte Kunststoffe e. V., 2013, p. 420)[17]

Edge reinforcements in compression molding and extrusion.

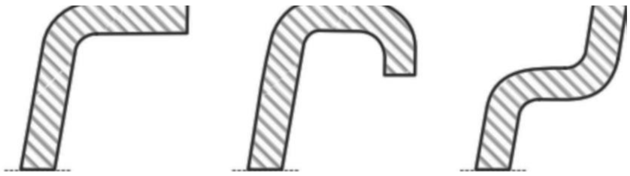


Figure 22: An example of a design guideline for LFT adapted from AVK (AVK – Industrievereinigung Verstärkte Kunststoffe e. V., 2013, p. 435)[18]

The Verein Deutscher Ingeniere (2014) provides design considerations for different fiber orientations in the design of beam elements, surface, shell-shaped and carrier-shaped elements as well as for wavy and tubular rods. The recommendations cover various objectives, such as avoiding warpage, expansion differences and buckling, as well as increasing torsional and bending stiffness. Some of the guidelines consider different acting forces and provide special recommendations for favorable fiber orientation. Additionally, design advice for force transmission via bonding, loops and friction is provided. As demonstrated by the example in Figure 23, all recommendations are given for CoFRP materials and are provided in the form of text and figures.[19]

[16] According to Butenko and Albers (2019, p. 278)
[17] The text is translated from German to English
[18] The text is translated from German to English
[19] According to Butenko and Albers (2019, p. 278)

Parallel fiber composites are to be used for these elements. Reduction of the differences in elongation can be achieved by a transverse reinforcement of fabric layers.

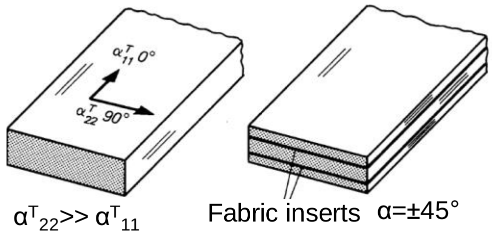


Figure 23: An example of a design guideline adapted from VDI (Verein Deutscher Ingenieure, 2014, p. 8)[20]

Drechsler and Bockelmann (2016, p. 890) provide design principles for FRP materials based on the guidelines of the R&G Faserverbundkunststoffe GmbH (2009). The principles are displayed in a table with a short description and a design principle illustrating the unfavorable and optimized solutions, as displayed in Figure 24. Recommendations on following design characteristics, such as wall thickness, radii, draft angles and the design of bonding connections are given.

Provide as uniform wall thicknesses in the component as possible in order to avoid resin accumulation and local differences in the fibre volume content and to enable a uniform force flow.

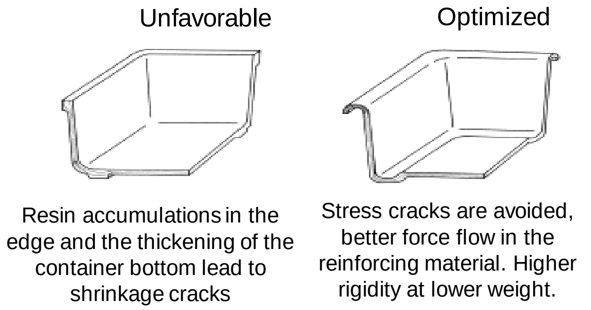


Figure 24: An example of a design guidelines adapted from Drechsler and Bockelmann (2016, p. 890)[21]

2.3.2 Design guidelines for unreinforced thermoplastic materials and metals

DuPont Engineering Polymers (2000) provides general design principles for DuPont Engineering thermoplastic resins. Considerations regarding following topics are addressed: the importance of uniform wall thickness, design solutions for the wall thickness transitions, design of draft and knock-out pins, fillets, radii, bosses, ribbing, holes, coring, threads, undercuts and molded-in inserts. As exemplified in Figure 25, design guidelines are presented in the form of short text and figures illustrating strong and poor design solutions.

[20] The text is translated from German to English

[21] The text is translated from German to English

Where different wall thicknesses cannot be avoided, the designer should effect a gradual transition from one thickness to another as abrupt changes tend to increase the stress. Further, if possible, the mold should be gated at the heavier section to insure proper packing.

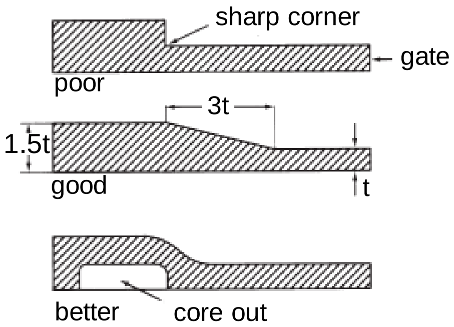


Figure 25: An example of a design guideline adapted from DuPont Engineering Polymers (2000, p. 7)

Lanxess Energizing Chemistry (2007) provides a design guide to assist the design and manufacture of products made from the Lanxess line of thermoplastic engineering resins. The recommendations are available on topics such as the design of ribs, corners, bosses and thickness transitions, as well as gussets, undercuts, molded-in threads, holes and cores. The guidelines are provided in the form of text with detailed explanations and images; an example of a rib design recommendation is presented in Figure 26.

Generally, taller ribs provide greater support. To avoid mold filling, venting, and ejection problems, standard rules of thumb limit rib height to approximately three times the rib-base thickness. Because of the required draft for ejection, the tops of tall ribs may become too thin to fill easily. Additionally, very tall ribs are prone to buckling under load. If you encounter one of these conditions, consider designing two or more shorter, thinner ribs to provide the same support with improved moldability (see figure 2-13). Maintain enough space between ribs for adequate mold cooling: for short ribs allow at least two times the wall thickness.

Figure 2-13

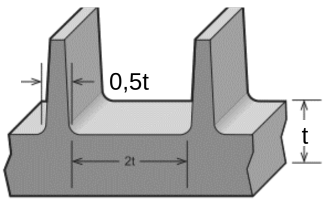


Figure 26: An example of a design guideline for unreinforced thermoplastics adapted from Lanxess Energizing Chemistry (2007)

Stratasys Direct Manufacturing (2015) provides guidelines for injection-molded thermoplastics parts in regard to the following topics: wall thickness design, coring, gussets, bosses, ribs, draft and texture, sharp corners and inserts. The recommendations are presented in the form of text with brief explanations and images showing a strong and poor design solution. Figure 27 illustrates an example of rib design recommendation to avoid sink marks.

Rib thickness should be less than wall thickness to minimize sinking effects. The recommended rib thickness should not exceed 60 percent of the nominal thickness. Plus, the rib should be attached with corner radii as generous as possible. The base radius should be a minimum of 0.25 X (T) thickness.

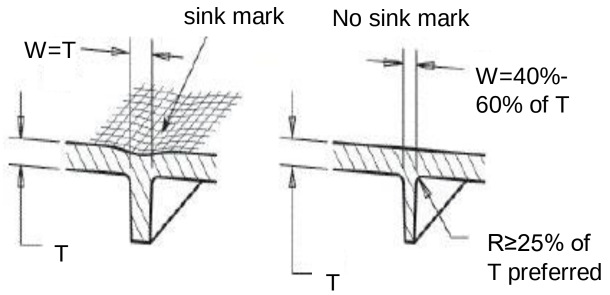


Figure 27: An example of a design guideline for unreinforced thermoplastics adapted from Stratasys Direct (2015, p. 4)

Verein Deutscher Giessereifachleute (2005) presents design recommendations for the design of cast components made of cast iron materials. Design guidelines regarding minimum wall thickness, transitions between walls and ribs, the connection between two sections of different wall thicknesses and the design of core elements, bosses and ribs are available. As demonstrated in Figure 28, guidelines are presented in the form of explanation texts and figures.

If it is not possible to achieve a constant transition due to design reasons, a stepwise transition between the two wall thicknesses can be used. If the ratio of smaller to larger thickness exceeds 2/3, a simple transition is sufficient; if the ratio is smaller than 2/3, a stepwise transition over a larger length is required. Sharp, inner edges must be avoided, as well as incorrectly designed transitions, which results in an accumulation of metal.

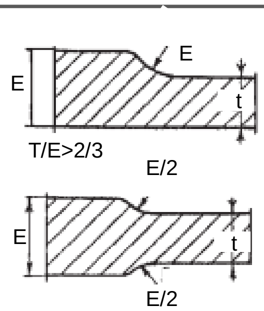


Figure 28: An example of a design guideline adapted from Verein Deutscher Giessereifachleute (2005, p. 112)[22]

Gerd and Reitter (2013) supply design considerations for the design of sheet metal structure beads. In total, there are about 55 brief text explanations with images demonstrating a poor and a good design solution. Figure 29 illustrates an example of these text and image explanations.

[22] The text is translated from German to English

The distribution and design of the clamping bearings is important with regard to the overall stiffness behavior. The clamping bearings should be evenly distributed over the circumference

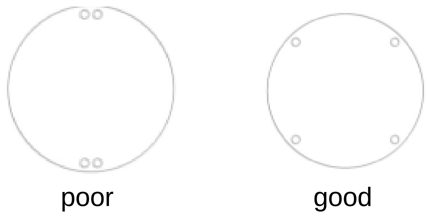


Figure 29: An example of a design guideline for sheet metals adapted from Gerd and Reitter (2013)[23]

Böge and Böge (2017) presents design guidelines on adhesive joints. As displayed in Figure 30, this documentation form does not differ from previously presented design guideline examples.

A construction suitable for bonding should follow the following design guidelines: Butt-joints can not be used because the adhesive surface is too small. A shaft connection is possible, but expensive to produce.

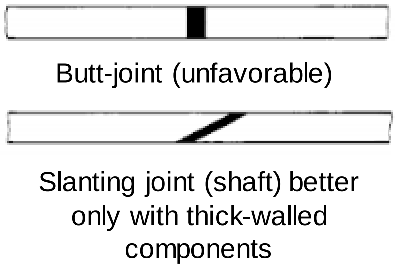


Figure 30: An example of a design guideline for bonding connections adapted from Böge and Böge (2017, p. 755)[24]

2.3.3 Comparison and analysis of design guidelines for FRP materials

As the provided examples reveal, the guidelines for FRP, non-reinforced plastics and metals hardly differ in terms of presentation. For the most part, the design guidelines consist of a text part and part with a graphical visualization; rarely do they include a text description alone. However, the text descriptions differ in their level of detail and structure. In some guidelines, the contents are described in more detail and provide not only the main statement, but also the consequences of non-compliance as well as concrete recommendations and additional explanations. This added information better supports the synthesis activities. Other examples are brief and contain only a short-described recommendation without detailing the consequences or simple background information. The figures in design guidelines often provide the difference between an ideal and a poor solution, or simply allow the reader to visualize possible alternative solution(s). For example, Figure 31 clearly compares four guidelines on the topic of uniform wall thickness.

[23] The text is translated from German to English

[24] The text is translated from German to English

1

One of the most important guidelines when designing a plastic component for any manufacturing process is maintaining **a uniform wall thickness in the part**. Varying wall thickness creates regions with different degrees of shrinkage, structural performance and stress concentration. When a change in thickness is required, gradual transitions are recommended.
Figure demonstrates how the thickness or position of the wall should change. Gradual change with no thick region is preferred. Abrupt changes in wall thickness can also affect how material flows through the mold cavity. During mold filling the resin will tend to flow easier into thicker regions than in thinner regions. This may give undesirable mold filling patterns, which could lead to weld or knit lines, gas entrapment, or less than optimal fiber orientation. One should remember that in compression molding the cavity's thickness is changing throughout the molding processes.

Not recommend Better Acceptable Preffered

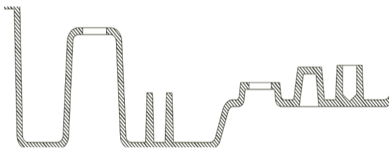
2

The aim should be to achieve as **uniform a wall thickness as possible** over the entire component. Wall thicknesses from 1.2 mm have proven themselves in pressing technology. Smaller wall thicknesses are possible, but usually problematic.

Favorable design Unfavourable design

3

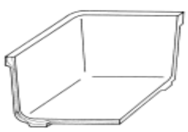
Keep wall thicknesses constant to avoid thin to thick sections along material flow paths and at the end of the flow - so as not to impair excellent surface quality and isotropic properties.



4

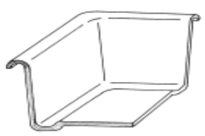
Provide as **uniform wall thicknesses** in the component as possible in order to avoid resin accumulation and local differences in the fibre volume content and to enable a uniform force flow.

Unfavorable



Resin accumulations in the edge and the thickening of the container bottom lead to shrinkage cracks

Optimized



Stress cracks are avoided, better force flow in the reinforcing material. Higher rigidity at lower weight.

Figure 31: Comparison among four design guidelines for FRPs for the example of topic wall thickness adapted from (1) Davis et al. (2003, p. 113), (2) the European Alliance for SMC/BMC, (2007, p. 18), (3) AVK – Industrievereinigung Verstärkte Kunststoffe e. V. (2013, p. 419),[25] and (4) Drechsler & Bockelmann (2016, p. 890)[26]

[25] The text is translated from German to English
[26] The text is translated from German to English

The first guideline contains considerably more detailed information on the subject compared to the others. All four guidelines contain a main statement in the first sentence that explain the importance of keeping wall thickness uniform throughout the component. However, in the second sentence, the most significant differences between the four examples occur. The first guideline provides information on the consequences of the uneven wall thicknesses, so that the reader immediately understands the added value of the guideline and why it is important to follow it. Next, the first guideline provides a recommendation with detailed explanations of the visualized solutions. However, such information is completely missing in the second and third examples. In the fourth example, the consequences are briefly mentioned and a short explanation of both the unfavorable and optimized solutions is given. The visualization of solutions is simple in all four examples.

When reading the first three design guidelines in the figure above, the question arises of whether these recommendations are suitable for FRP, because none of them explicitly address important details regarding fiber volume content and its relation to wall thickness. Drechsler and Bockelmann (2016, p. 891) mention the fiber volume content in the fourth example and provide detailed explanations outside the recommendation, as displayed in Figure 32.

…wall thickness must be designed in conjunction with the number of layers and the desired fiber volume content, so that often no predefined value can be assumed as for metals. If local changes in **wall thickness** are to be realized, the number of layers can be reduced or increased locally step by step. This enables the component to be stocked with as constant a fiber volume content as possible. To avoid local stress increases, neither a change in wall thickness without appropriate adjustment nor a sharp transition should be selected. The different fiber orientation of adjacent layers makes it possible to significantly increase the damage tolerance of the laminate, as this stops crack growth at an early stage.

Figure 32: Continuation of the fourth design recommendation in text in Drechsler and Bockelmann (2016, p. 891)

Section 2.2.2 presents various effects at the transition from thin-walled to thick-walled areas and vice versa. Figure 11 and Figure 12 demonstrated that low-fiber areas or fiber ejections can occur during production and that such areas present the component's weak points. However, these points are only addressed partly in the design guidelines in Figure 31.

Figure 33 displays three examples of recommendations for designing ribs with SMC material to avoid sink marks. The text in all three examples is brief and refers to design elements that influence the potential occurrence of sink marks. The first example names three design elements: draft angle, radii and rib thickness. However, the other two examples only refer to the radii as a design element with a decisive influence. The second example contains general content both in text and in the figure. The first and third recommendations largely contain the same information and complement each other in terms of different additional information.

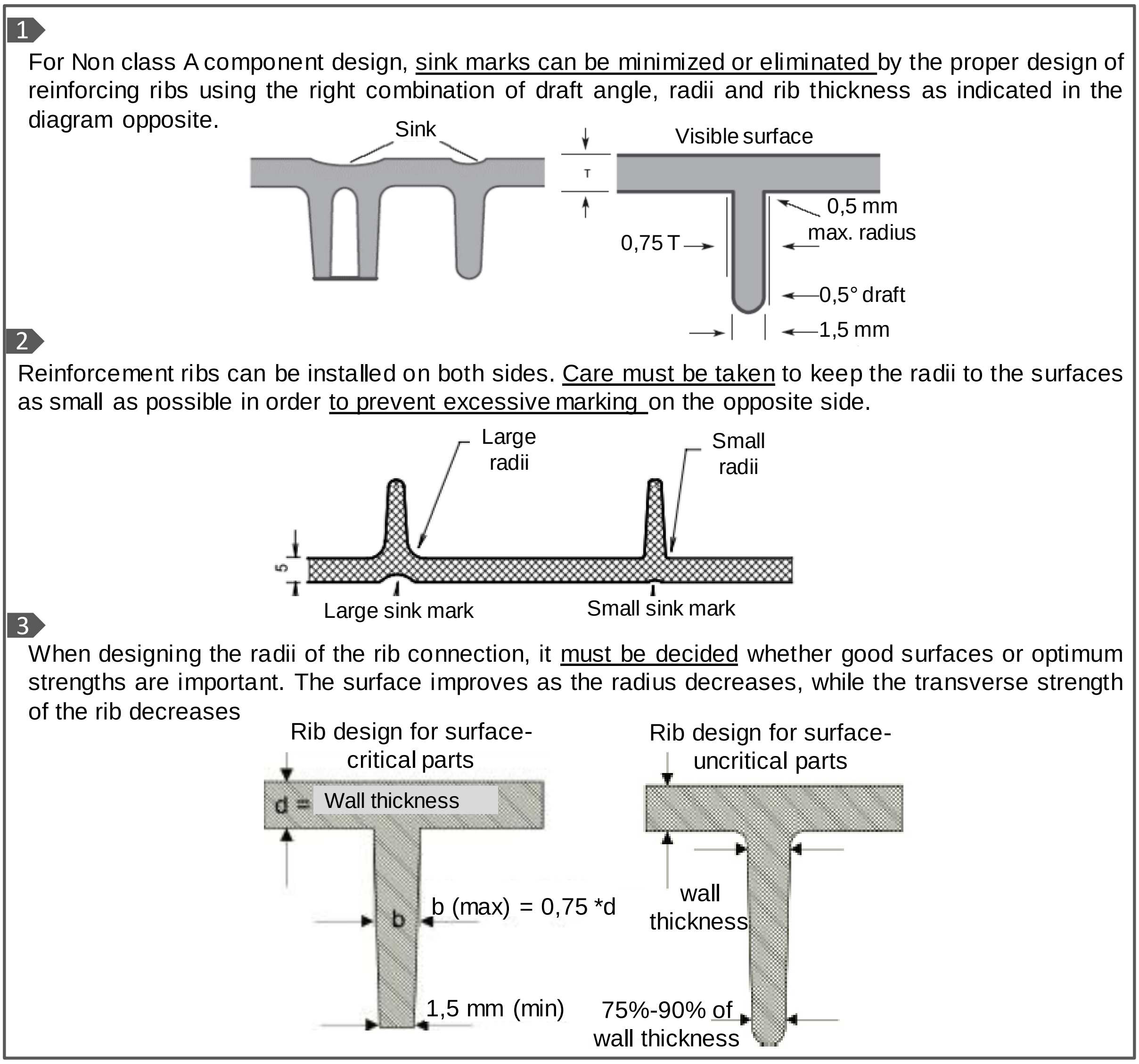


Figure 33: Comparison between three design guidelines for SMC materials on example of a rib design to avoid sink marks (1) European Alliance for SMC/BMC (2007, p. 22), (2) Wernli (1998),[27] (3) AVK – Industrievereinigung Verstärkte Kunststoffe e. V. (2013, p. 420)[28]

All three design guidelines lack information on the factors that can lead to sink marks when using SMC material, which makes it difficult to synthesize and transfer knowledge to other similar situations. Furthermore, as the test results with SMC materials by Specker et al. (1990) reveal, the sharp-edged inlet radii have a negative influence on the fiber orientations inside the ribs due to the shearing of the material at

[27] The text is translated from German to English
[28] The text is translated from German to English

the rib base during transverse flow. This point is not explicitly addressed in any of the three examples. Sheet molding compound material systems can be developed individually according to the requirements and can, for example, contain carbon fibers instead of glass fibers (European Alliance for SMC/BMC, 2007) and have a differing fiber volume content and fiber length (Schürmann, 2007, p. 138). None of the three examples address the question of the extent to which such recommendations can also be applied to modified SMC material systems. When designing ribs, objectives such as increased stiffness or weight reduction are usually pursued. The occurrence of sink marks is an effect that the designer must consider during the design, but not as a primary goal. For example, in Figure 34, the increasing value of stiffness and weight for unreinforced plastics is calculated in AlliedSignal Plastics (1996) based on the ratio of rib height to wall thickness. The question of how much this information can change when using a SMC or other FRP material remains unanswered.

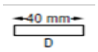
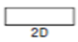
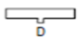
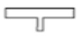
Weight and stiffness of a ribbed section with 6 mm nominal wall thickness and 50 mm rib spacing at different rib heights					
case	form	rib dimensions	rib height / wall thickness	percentage weight increasing	percentage stiffness increasing
0		n.a.	n.a.	n.a.	n.a.
1		n.a.	n.a.	100%	700%
2		2,5 mm B x 2,5 mm H	1:2	3,12%	21%
3		2,5 mm B x 5 mm H	1:1	6,25%	77%
4		2,5 mm B x 10 mm H	2:1	12,5%	350%
5		2,5 mm B x 15 mm H	3:1	19,0%	927%
6		2,5 mm B x 20 mm H	4:1	25,0%	1900%
7		2,5 mm B x 25 mm H	5:1	31,0%	3353%
D =Thickness =5 mm					

Figure 34: Increase in stiffness and weight based on the ratio of the rib height to the wall thickness for unreinforced plastics in AlliedSignal Plastic (1996, p. 17)

2.3.4 Conclusion

The “presentation form”[29] of contents in the design guidelines for FRP materials does not differ significantly from the design guidelines for unreinforced plastics or metals.

[29] As presentation form, visualization type selected for information documentation such as: text, figures, formulas, is meant

Usually, the content consists of a description in the form of text and a visualization in the form of illustration(s). (Butenko & Albers, 2018) The content of most design guidelines is rather short and contains a primary message, a general or concrete recommendation, and a brief mention of consequences in the case of a poor solution. However, the guidelines will not usually explain all the effects that can lead to a poor outcome. Synthesis activities and knowledge transfer to other situations, at least for designers with little experience in this field, are difficult when these design guideline descriptions lack essential context. The detailed information, which addresses the consequences of a poor design solution and additionally explains how the negative effects arise, promotes a more universal understanding. This understanding is a basis for synthesis and knowledge transfer. If the analysis process is performed poorly due to missing or misinterpreted information, an incorrect solution may be the result of the synthesis. Therefore, guidelines should support both analysis and synthesis activities to improve their applicability and added value. By demonstrating the interrelationships, guidelines can help product developers to transfer knowledge to their own products.

The majority of recommendations do not relate to the challenges in the design of products with FRPs. The guidelines hardly consider embodiment design in connection with manufacturing and material influences, both of which are important when designing with FRP materials. As stated, some of the guidelines are text-based and do not contain any figures. However, graphical representations can provide different types and amounts of information that allow engineers to process information faster and understand the design concept clearer than with solely text (Hannah et al., 2012).

2.4 Decision support in product engineering

“The early phase of product generation engineering is a phase that begins with the initiation of a project and ends with an evaluated technical solution that finally covers the initial target system with regard to its essential elements” (Albers et al., 2017). Decisions in the early phases of product engineering are particularly important and have a large influence on the design development cost (Tan et al., 2017a). The later defects are discovered in the product life cycle, the higher the corrective measures’ costs (Brüggemann & Bremer, 2015, p. 29). According to study by Tan et al. (2017b), early design decisions account for an 86% cost impact of all design decisions. Therefore, especially in these early phases of product engineering, suitable methods and tools are important to support product developers’ decision making.

Decision support by means of multi-criteria decision-making methods has become increasingly important in recent years (Bruno & Genovese, 2018). The following sub-chapters contain basic information about multi-criteria decision analysis (MCDA) methods. Important terms, the main development steps, and the most commonly used methods, as well as recommendations for their selection, are briefly introduced. Peer-reviewed publications dealing with the review of MCDA methods were analyzed to obtain a comprehensive overview of the current status in this area. Seven publications that examined a total of 1,325 articles were selected, and they have contributed to the discovery of further relevant articles. Trends and new developments in the field of MCDA approaches in the period from 1980 to 2016 could thus be taken into account. Table 2 contains brief data regarding these publications, and it includes their respective titles, the time frames that were analyzed, the number of papers and the main focus.

Table 2: Peer-reviewed publications in the field of MCDA

Peer-reviewed publication	Time frame	Number of papers	Focus
A review of multi-criteria decision-making methods for infrastructure management (Kabir et al., 2014)	1980-2012	300	Trends and new developments in the field of MCDA methods
Multi-criteria decision analysis for nature conservation: A review of 20 years of applications (Adem Esmail & Geneletti, 2017)	1990-2009	86	Providing recommendations for better MCDA application
A systematic review of multi-criteria decision-making applications in reverse logistics (Rezaei, 2015)	1990-2014	80	Review of most-used MCDA methods in the field of reverse logistics
Multi-criteria decision analysis in environmental sciences: Ten years of applications and trends (Huang et al., 2011)	2000-2009	312	Trends by MCDA methods and influence of multiple methods on decision analysis
A review of multi-criteria decision-making techniques for supplier evaluation and selection (Agarwal et al., 2011)	2000-2011	68	Review of various MCDM methodologies reported in the literature
Structuring problems for multi-criteria decision analysis in practice: A literature review of method combinations (Marttunen et al., 2017)	2000-2015	333	Review of problem-structuring methods (PSMs) and their combination with MCDA methods.
A critical review of multi-criteria decision making in protected areas (Castro & Urios, 2016)	2000-2016	164	In-depth review of MCDM methods

2.4.1 Definition of important terms

Multi-criteria decision analysis is a generic term for a collection of systematic approaches developed to support decision-making processes by systematically comparing the pros and cons of different alternative solutions against a set of explicitly defined criteria (Beinat & Nijkamp, 1998; Geneletti & Ferretti, 2015; Linkov & Moberg, 2012). Based on the first part of the definition – "MCDA is a generic term for a collection of systematic approach" – MCDA can generally be divided into two main classes: (Hwang & Yoon, 1981, p. 3; Kabir et al., 2014) multi-objective decision making (MODM) and multi-attributive decision making (MADM), in which both are the main terms to which other categories of methods are assigned. The majority of these methods are understood in the definition as a collection of systematic approaches.

The next part of the definition – "systematically comparing the pros and cons of different alternative solutions against a set of explicitly defined criteria" – requires some basic terms such as criteria and attributes to be introduced. According to Hwang and Masud (1979, p. 13), "**Criteria** are standards of judgment or rules to test acceptability." Malczewski (1999, p. 707) slightly expands this definition to the following: "a criterion is a standard of judgment or rule on the basis of which alternative decisions can be evaluated and ordered according to their desirability." In the MCDA understanding, a criterion is a generic term that indicates both attribute (in the case of MADM) and objective (in the case of MODM) approaches (Hwang & Masud, 1979, p. 13; Malczewski, 1999, p. 709). The use of criteria helps indicate the general class of concerned problems (Hwang & Masud, 1979, p. 13) and differentiate between alternatives (Sabaei et al., 2015). Hwang and Masud (1979, p. 13) have defined attributes as "the characteristics, qualities, or performance parameters of alternatives."

2.4.2 The MADM and MODM approaches

The aim of MADM approaches is to evaluate alternatives with regard to the fulfillment of objectives. A solution space is already known, in contrast to MODM approaches, and it consists of a predetermined number of alternatives. (Triantaphyllou et al., 1998; Tzeng & Huang, 2011, pp. 1–2) In MODM approaches, the number of possible solutions is not predetermined, and the aim is to design the "best" alternative by considering various interactions within design constraints in order to achieve defined objectives (N.-B. Chang & Pires, 2015, p. 250). Multi-objective decision making contains an infinite number of possible solution elements, referred to as continuous solution space (Rohr, 2004, p. 32). Multi-attributive decision making includes further sub-classes of methods, and various designations of the sub-classes under MADM are used. Vincke (1989)[30] differentiated the sub-classes as 1) the multi-attributive utility theory (MAUT), 2) outranking and 3) interactive methods. Roy (1996) classified MADM methods as 1) unique synthesis criterion approaches, eliminating any incomparability, 2) outranking synthesis approaches, accepting incomparability, and 3) interactive local judgment approaches, with trial–error interaction. Jyh-Rong (2013) divided MADM into

[30] According to Yan and Manoj (2014)

two broad sub-classes: 1) MAUT and 2) outranking methods. Hwang and Masud (1979) classified MADM into three sub-classes: 1) a priori preference articulation, 2) a progressive preference articulation (interactive method) and 3) a posteriori articulation of preferences.

The unique synthesizing criterion approach and the MAUT use a single-criterion function for the comparison of alternatives. The outranking methods involve building binary relations to outline the decision maker's preferences on alternatives. The interactive methods combine calculation steps with information on the decision maker's preferences. (Guarnieri & Hatakeyama, 2011) The priori preference articulation means that subjective information is first elicited from the decision maker and then utilized to find a preferred solution. The progressive preference articulation uses an interaction with decision makers to find a better solution and the progressive revelation of preferences to create a resulting sequence of solutions. In the posteriori articulation of preferences, alternative solutions are first generated and then provided to the decision maker for the selection. (Buchanan, 1985, pp. 27–45)

2.4.3 Main development steps

The development of an MCDA method consists of four main stages. These stages are named differently in some sources; however, they generally have the same meaning. In this work, each stage's description is listed according to Guitouni and Martel (1998):

- Stage 1: Structuring the decision problem
- Stage 2: Articulating and modelling the preferences
- Stage 3: Aggregating the alternative preferences
- Stage 4: Making recommendations.

Stage 1 – Structuring a decision problem. According to Guitouni and Martel (1998), when making decisions, various, often conflicting aspects should be taken into account, so that a decision is "no longer an optimal but rather satisfactory one." Many authors agreed that decision making requires a clear definition of objectives (El Amine et al., 2014; Jyh-Rong, 2013; Rohr, 2004, p. 21). Therefore, the focus is first on the understanding of a decision problem, its structuring and clarifying decision-makers objectives (Marsh et al., 2016). Problem structuring methods (PSMs) are increasingly integrated into MCDA approaches, with the purposes of promoting a structured discussion and supporting problem owners to consider the situation from other perspectives (Marttunen et al., 2017).

Identification of objectives: After understanding a decision problem, the identification of objectives takes place. Different approaches are suggested for this purpose, such as an examination of literature, casual empiricism (generating of objectives by observing relevant decision makers), conducting an analytic study (Keeney & Raiffa, 1976, p. 35).[31] Keeney (2007, p. 13) suggested further devices that involve a range of different questions that make it easier for stakeholders to identify possible objectives by answering them, as illustrated in Figure 35.

Devices to help with identifying objectives	
Wish list	Create a wish list to be achieved by problem solving
Alternatives	Identify perfect & terrible alternative and articulate what is good and bad about each;
Consequences	Identify the possible consequences
Goal and Constraints	Identify the aspirations relating the stated goals and corresponding limitations
Different perspectives	View the objectives from different perspectives (competitors, customers, other interest groups)
Strategic values	Determine of ultimate values that can be presented in a mission statement, vision or strategic plan
Generic values	Determine of customers, employees and stakeholder's values
Why do you care?	Define why each stated value is important
What do you mean?	Specify the meaning of each stated value more precisely

Figure 35: Devices to identify objectives according to Keeney (2007, p. 13)

Buede (1986) extended the methods for developing a hierarchy of objectives of Manheim and Hall (1967) and described them as a top-down (objective-driven) and a bottom-up (alternative-driven) approach. The top-down approach is recommended if a decision maker is not sure about available alternatives and can only recognize a part of possible solutions related to a problem context. In the bottom-up approach, possible alternative solutions are already predefined, and the identification of objectives is based on the analysis of the major differences between them.

The quality of a decision depends on the selection of alternatives (Keeney, 1992, p. 22). Therefore, a number of alternatives that are important for solving a decision problem are required. All alternatives need a well-defined description with decision-relevant criteria. This is a prerequisite to enable a comparison among alternatives. Where the defined decision-relevant criteria for alternatives are not applicable, then either alternatives should be reconsidered or new criteria for the description should be created. (Geldermann & Lerche, 2014, p. 5)

[31] Based on MacCrimmon (1969)

Formulation of criteria: By means of criteria, a systematic assessment of how each individual alternative contributes to the achievement of objectives takes place (Adem Esmail & Geneletti, 2017). The criteria can be defined within a **top-down** or **bottom-up** approach. In the top-down approach, criteria are defined based on an analysis of subordinate goals, and in the bottom-up approach, they are defined based on alternative solutions. Alternatives are analyzed regarding their strengths and weaknesses, and as a result, criteria are derived on the basis of identified differences. (Marsh et al., 2016)

Both approaches can lead to different results; therefore, a careful choice is important (Morton & Fasolo, 2009). Whereas the top-down approach leads to general criteria, applying the bottom-up approach results in definition of specific criteria (Marsh et al., 2016). Other options for identifying criteria can be the involvement of a decision-making team or analysis of relevant secondary information sources (Dodgson et al., 2009, p. 33), such as documents describing previous solutions or studies of stakeholder's priorities (Marsh et al., 2016). Regardless of the approach chosen, determined criteria should describe a complete decision-making problem and associated goals (Geldermann & Lerche, 2014, p. 25).

The formulated criteria should also meet certain requirements. According to Dodgson et al. (2009, pp. 35–39), the resulted criteria should be complete, operational, independent, non-redundant and non-overlapping. A brief description of these individual requirements is provided in Figure 36. The additional requirements, such as: comprehensive, concise and understandable are mentioned in Wang et al. (2009) and Keeney (1992) and depicted in Figure 37.

Requirements on criteria	
Complete	Should capture all relevant factors for the decision
Operational	Clearly defined in terms of objective or subjective scales
Independent	Reflect the performance of alternatives from different aspects
Non-redundant	Absence of unimportant criteria without any impact on the result
Non-overlap	Clear definition of criteria to avoid double counting and as result too much weight

Figure 36: Requirements on criteria[32]

[32] Author's own representation based on Dodgson et al. (2009, pp. 35–39)

Requirements on criteria	
Comprehensive	Reflect the essential characteristic and the whole performance
Concise	Concise with objectives and alternatives of decision maker
Understandable	Describe clear the consequences

Figure 37: Additional requirements on criteria[33]

Multi-criteria decision analysis is an iterative process. Based on the knowledge gained, the previous steps (identification of alternative solutions or formulation of goals) should be critically analyzed and, if necessary, corrected. For example, the identification of alternative solutions can lead to the adaptation of objectives, and the formulation of criteria can lead to the adaptation of alternative solutions, which, in turn, can have an influence on the defined objectives. (Geldermann & Lerche, 2014, pp. 15–16)

Stage 2 – Articulating and modeling the preferences. The main objectives of stage 2 are to identify scales that represent preferences for alternative solutions and to weight them according to their relative importance for a decision-making problem. Therefore, preferences provide information about the degree of positive or negative attitude of the decision maker towards the consequences of the alternatives. (Geldermann & Lerche, 2014, p. 28)

A preference exists if, for example, alternative (a) is preferred over alternative (b) (a > b) (Rohr, 2004, p. 26). A general distinction is made between two types of preferences: value data (preference on alternative solutions) and weights (preferences on criteria) (Geldermann & Lerche, 2014, p. 28). The scoring on alternative solutions provides information about the performance with regard to a criterion defined in the previous stage (Adem Esmail & Geneletti, 2017), and it demonstrates how important this criterion is for an entire decision-making problem (Geldermann & Lerche, 2014, p. 28). There are different methods for preference articulation, and each can have a significant influence on decision-making results (Chen, 2006, p. 15; Guitouni & Martel, 1998). Therefore, different factors should be considered by selecting the appropriate preference expression.

According to El Amine et al. (2014), it is important to be aware that preference expression is:

- Adapted to the information type
- Comfortable for a decision maker to use
- Applicable to a decision situation.

[33] Author's own representation based on Wang et al. (2009) and Kenney (1992)

Marsh et al. (2016) proposed two additional recommendations for selection:

- Consideration for whether the scoring or rating of alternative solutions is required
- Consideration for the required level of precision – the precision of scoring methods depends on scoring properties.

The values of the judgment can be in ordinal, nominal, interval, ratio, and absolute scales (Rohr, 2004, p. 24). The last three scales belong to the cardinal scale. The description, possible applications, and examples of each scale are illustrated in Figure 38.

Scale	Description	Applicability	Example
Ordinal	• a rankings: "larger", "smaller", "more", "less", "stronger", "weaker" between two different characteristic values; • the distances between the individual values cannot be quantified; • no arithmetic mean may be calculated	• frequency; • chronological order	grades at school
Nominal	• a comparison is only possible to decide whether the characteristic are equal or different; • only for qualitative characteristics; • the values cannot be sorted by size, in the sense of "is greater than" or "better than".	• frequency	gender
Interval	• objectively justifying of the distance size between two values; • statements on the amount of differences between two classes; • this scale has no zero point.	• frequency; • chronological order; • distance	temperature in C°
Ratio	• objectively justifying of the distance size between two values; • statements on the amount of differences between two classes; • this scale has zero point.	• frequency; • chronological order; • distance; • natural zero point	age
Absolute	• in addition to a natural zero point, the absolute scale also has a natural unit of measurement. • values can be interpreted directly	• frequency	number of members

Figure 38: Scale types description[34]

The aim of the weighting is to gather stakeholders' preferences among the defined criteria (Marsh et al., 2016). The weighting of the criteria is an important task, as it influences the final result (Zardari et al., 2015, p. 35). The resulting weights generally provide information on the relative importance of the criterion (Jyh-Rong, 2013; Malczewski, 1999). There are various weighting methods in the literature, not all of them are described and listed in following. Wang et al. (2009) classify weighting methods into three categories: subjective weighting, objective weighting and their combination – integrative weighting. The first type, subjective weighting, is based on

[34] Author's own representation based on the scale types description in Sedlmeier and Renkewitz (2018, pp. 71–77)

the preferences of the decision makers. Second, objective weighting calculates the weighting using objective information in a decision matrix through mathematical models. This type of weighting neglects the subjective information from a decision maker. The third type, integrated weighting, determines the weights of criteria using a combination of a decision maker's subjective preferences and objective decision matrix information. (J.-J. Wang et al., 2009)

Subjective weighting includes a number of different methods, such as direct rating, the ranking method, the point allocation method, the simple multi-attribute rating technique (SMART), the ratio method, a trade-off, a pairwise comparison, the swing weighting method, and the revised SIMOS (Roszkowska, 2013; J.-J. Wang et al., 2009).

By contrast, objective methods include the entropy method, the standard deviation method, the criteria importance through intercriteria correlation (CRITIC) method, the maximizing deviation method, the statistical variance procedure, the mean weight, and the ideal point method (Roszkowska, 2013; Zardari et al., 2015, pp. 32–33). Brief descriptions of some subjective and objective weighting methods are presented in Figure 39 and Figure 40. The number of criteria and the grade of uniqueness between them are crucial factors for selecting the most appropriate weighting method (Zardari et al., 2015, p. 36).

Subjective methods	Description
Direct rating	- straightforward method for assigning values to criteria - similar to scales used on a Likert-scale questionnaire - the numbers 1–5, 1–7 or 1–10 are used to indicate importance
Ranking method	- criteria are ranked in order from most important to least important - the rank position is weighted and then normalized by the sum of all weights
Point allocation	- allocating of numbers to describe the criteria weights by dividing 100 points among the criteria
Paarwise comparison	- comparison of each criterion against every other criterion in pairs - ordering of criteria
Ratio weighting method	- ranking the relevant criteria according to their importance - the least important criterion is assigned a weight of 10 and all others are judged as multiples of 10 - the resulting raw weights are normalized to sum to one
Swing method	- ranking from an alternative with the worst outcomes on all criteria - changing one criterion from worst to the best and given the most preffered swing 100 points
SMART	- calculation of an overall value of a given alternative as the total sum of the performance score of each criterion multiplied with the weight of that criterion. - rank the importance of criteria from worst levels to best levels
Trade-off weighting method	- compromise between two criteria when an ideal combination of the two is not attainable - pair comparisons and defining of an exchange rate
Revised SIMOS	- playing card to each criterion - rank the cards from the least important to the most important

Figure 39: Descriptions of some subjective methods[35]

[35] Author's own representation based on Zardari et al. (2015, pp. 25–67)

Objective methods	Description
Entropy method	- measure of uncertainty in the information formulated using probability theory - calculating of weights using information matrix
Standard deviation method	- similar to Entropy method - determines the weights of criteria in terms of their standard deviation
CRITIC method	- correlation analysis to detect contrasts between criteria
Mean weight	- deriving the weights by using equation wj=1/n, where n is number of criteria - assumpion that criteria are of equal importance
Statistical Variance Procedure	- calculating weights by statistical variance of information
Maximizing deviation method	- assigning a larger weight for the criterion with a larger deviation value among alternatives
Ideal point method	- ordering of criteria based on their separation from the ideal point - the closest alternative to the ideal point is the best one

Figure 40: Descriptions of some objective methods[36]

Stage 3 – Multiple-Criteria Aggregation Procedure (MCAP). The aim of the third stage is to aggregate the results of a criteria assessment and weighting for the overall performance of the individual alternatives. Different aggregation methods apply different rules (families of aggregation methods) for the calculation of the overall performance. (Adem Esmail & Geneletti, 2017)

The selection of an aggregation method depends on the decision problematic, (Marsh et al., 2016) scale type, type of solution space (continuous or discrete), kind of uncertainty and type of dependency among the criteria (Stamelos et al., 1999)[37]. According to Roy (1996), the decision problematic can be categorized as 1) the description problematic, 2) the choice problematic, 3) the sorting problematic and 4) the ranking problematic. An explanation of each decision problematic is provided in Figure 41.

Decision problematic	
Description problematic	Providing an appropriate set of actions and a suitable family of criteria, without making any recommendation
Choice problematic	Reducing the number of actions to find a single alternative or a possible smaller subset
Sorting problematic	Assigning each action a category related with the feasibility and the possibility of the implementation
Ranking problematic	Complete or partial preording of the alternatives

Figure 41: Decision problematic[38]

[36] Author's own representation based on Zardari et al. (2015, pp. 25–67)
[37] Based on Vincke (1992)
[38] Author's own representation based on Roy (1996)

The selection of an MCAP method is a critical issue because each method may yield different results for the same problem (Guitouni & Martel, 1998; Triantaphyllou & Lin, 1996; Zanakis et al., 1998). The literature includes various studies dealing with the development of some aids and recommendations to support the selection of the appropriate MCAP method. Laaribi et al. (1996) proposed a typological tree for the selection of the appropriate MCAP method, as displayed in Figure 42. The methods are divided into different categories, which differ slightly in detail for discrete MADM and continuous MODM methods. The following categories are included for a differentiation of MADM methods (Laaribi et al., 1996):

- Nature of information (deterministic, non-deterministic)
- Level of information (cardinal, non-cardinal)
- Type of decision problem (choice, sorting, ranking)
- Type of evaluation (absolute, relative)
- Type of inter-criteria information (known, partially known, unknown).

In the case of MODM methods, the categorization is based on (Laaribi et al., 1996):

- Nature of information (deterministic, non-deterministic)
- Type of approach (interactive, non-interactive)
- Type of non-determinism (stochastic, non-stochastic)
- Nature of non-stochastic (fuzzy, possibility)
- Type of information (explicit, implicit)
- Type of preference incorporation (no preference, a priori, a posteriori).

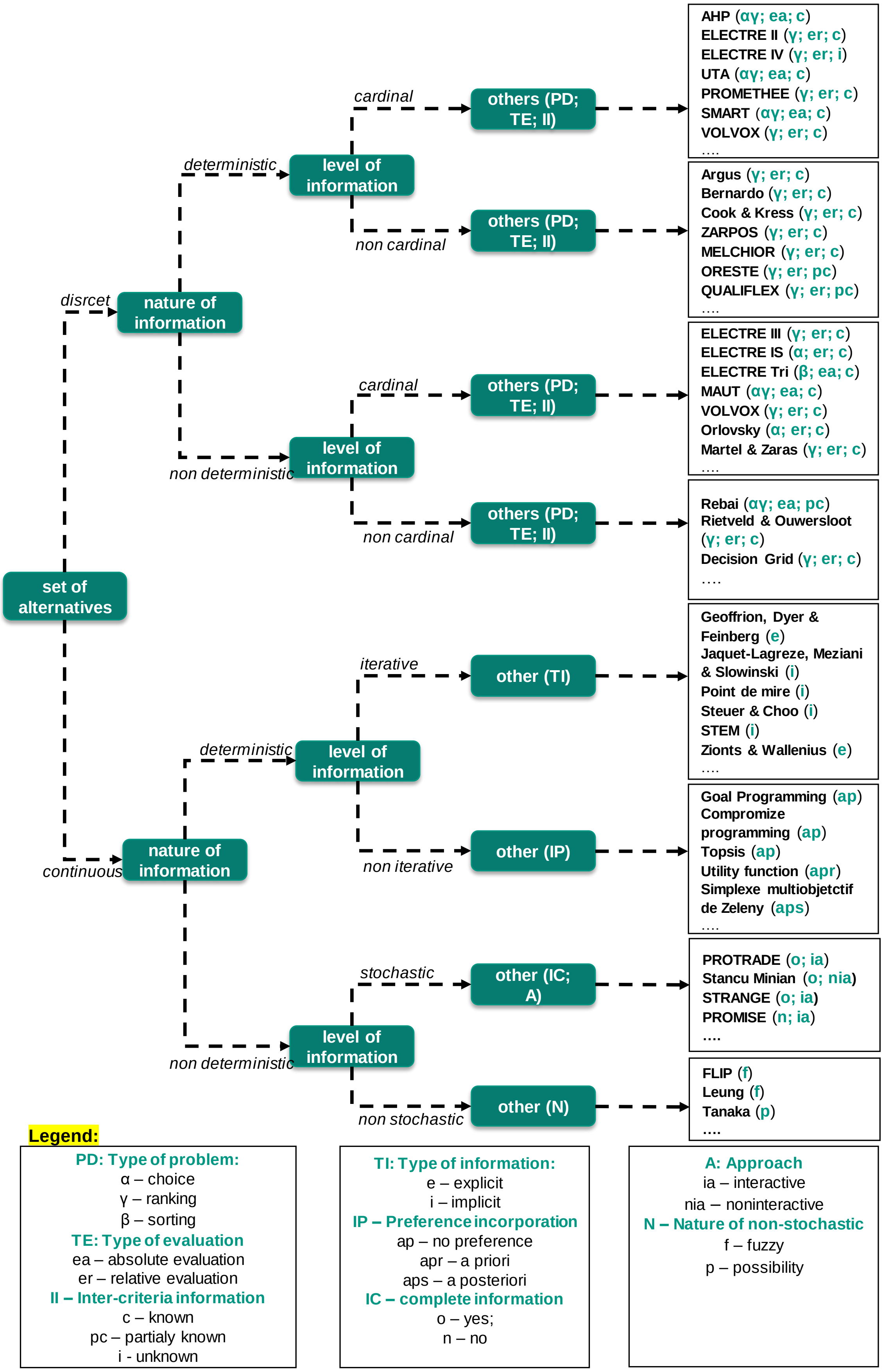


Figure 42: Classification of MCAP as a typological tree adapted from Laaribi et al. (1996)

Based on this typological tree, Guitouni and Martel (1998) developed some guidelines for the selection of appropriate MCAP methods. The most important recommendations are provided with regard to five points, which are illustrated in Figure 43.

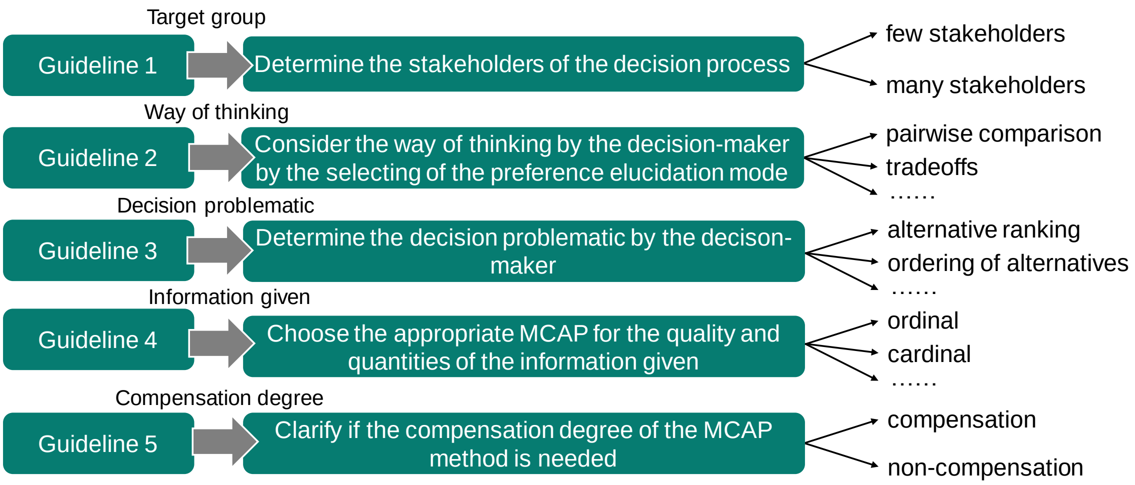


Figure 43: Guidelines for selecting an MCDA approach[39]

The first recommendation is to determine the number of stakeholders. The second one suggests considering a decision maker's way of thinking by their selection of a preference elucidation mode. The preference expression mode can have a major influence on decision-making results; therefore, a decision maker should feel familiar when handling it. The third recommendation involves determining a decision problematic, while the fourth and fifth recommendations concern the selection of an appropriate MCAP method. (Guitouni & Martel, 1998)

A choice thus depends on whether the information has an ordinal, a cardinal, an interval or a ratio scale type (Domshlak et al., 2011). Furthermore, the distinction between the certainty and uncertainty of the decision situation should be taken into account. According to Malczewski (1999, p. 100), three types of uncertainty exist, namely, deterministic, probabilistic and fuzzy. The term "deterministic decision making" is used when a decision maker knows the decision environment perfectly. However, in practice, decisions usually involve some aspects that are unpredictable or difficult to predict, which form part of probabilistic and fuzzy decision-making problems. A key difference between these two lies in the nature of uncertainty. Probabilistic uncertainty is associated with limited information about a decision situation, whereas fuzzy uncertainty is associated with a vagueness concerning the description of the semantic meaning of statements. (Malczewski, 2006)

[39] Author's own representation based on Guitouni and Martel (1998)

A further influence factor on the selection of an appropriate MCAP method is whether a compensation degree of the MCAP method is needed. This compensation is an aggregation of all criteria in a clear value, where the poor performance of some alternative solutions with regard to certain criteria is compensated for by the optimal performance with regard to others. A decision maker should agree with the results of the compensation. (Guitouni & Martel, 1998)

2.5 Knowledge Management in Decision Support Systems

According to VDI 5610 (Verein Deutscher Ingenieure 5610, 2009), knowledge management is “the organising of all processes identifying, creating, recording, distributing and applying information, findings and experiences.” Nowadays the term “knowledge” is often mixed up in its meaning with the terms “data” or “information,” although they differ in their definitions (Warth, 2012, p. 7). These terms are introduced briefly in Section 2.5.1, as they are often used in further chapters. Afterwards, the basics of decision support methods and existing knowledge management approaches to support product development by providing embodiment design information are briefly described.

2.5.1 Data, Information, Knowledge

Data is a sequence of characters (letters, numbers, symbols) without their own meaning or indications of their usability. Data turns first into **information** when it is put into a certain context. In order to transform information into **knowledge**, an individual must network it in a purposeful way and incorporate it into his or her experiential context (North, 2016, p. 37). According to North (2016, p. 37), “knowledge is based on individual experiences, is context-specific and bound to people.”

Knowledge always refers to earlier experiences or actions and thus enables new situations to be viewed and understood in a retrospective manner. It is knowledge that enables people to recognize familiar patterns and establish connections between the current situation and past events. (Schmidhuber, 2010, p. 193)

Based on the definition of knowledge, it follows that knowledge cannot be stored in the form of documents (Schmidhuber, 2010, p. 193) and that “knowledge database” is not a proper term for databases, which contain information as partial areas of knowledge (North, 2016, p. 37). As Larry Prusak[40] stated, “One cannot manage knowledge […] but one can create an environment in which knowledge prospers.” (Schütt, 2003)

[40] Larry Prusak was founder and Executive Director of IBM Institute for Knowledge Management (IKM)

2.5.2 Decision Support System

According to Power (2002, p. 1), “decision support systems (DSS) are interactive computer-based systems that help people use computer communications, data, documents, knowledge, and models to solve problems and make decisions.” Ariav and Ginzberg (1985),[41] identify three main components of a DSS: database management, management of models, and user interface management (dialogue management), as visualized in Figure 44.

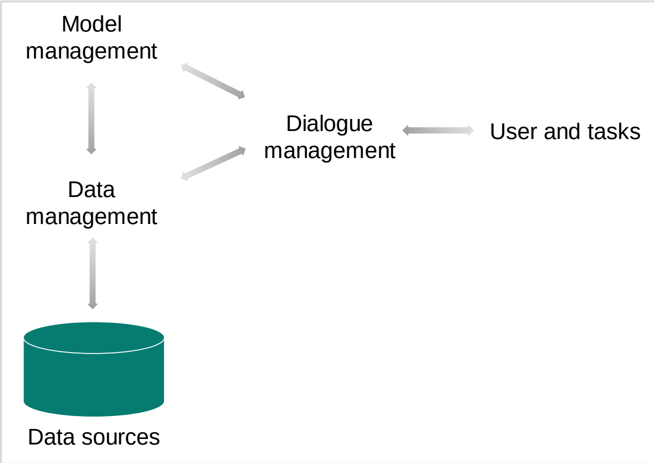


Figure 44: DSS components adapted from Ariav and Ginzberg (1985)

The storage and retrieval of DSS data is carried out in the database using database management. Dialogue management is important for providing communication between users and DSS and to ensure easy access to the DSS. With the aid of model management, decision models can be represented, and data can be analyzed and processed on the basis of these models (Shen, 1987), meaning that the MCDA methods described in Section 2.4 play a central role.

Five types of DSS systems can be differentiated: communication-driven DSS, data-driven DSS, document-driven DSS, knowledge-driven DSS and model-driven DSS (Marin, 2008; Power & Sharda, 2007). **Communication-driven DSS** is used to support persons working on a shared task (Marin, 2008; Power, 2000) by connecting decision-makers and creating an environmental for the exchange of information (Bhargava & Power, 2001). **Data-driven DSS** uses collected structured internal company or external data to fit the decision maker’s needs. **Document-driven DSS** is applied when to retrieve information in a variety of electronic formats and find documents using a specific set of search terms. **Knowledge-driven DSS** uses problem-solving expertise in the form of information, facts and rules to provide recommendations in a particular domain of knowledge. Finally, **model-driven DSS** is used to support decision makers

[41] Based on Bonczek et al. (1982) and Sprague & Carlson (1982)

in analyzing a situation by evaluating the data and parameters provided. (Marin, 2008; Power, 2000)

2.5.3 Decision-support and knowledge-management tools

This section provides a brief overview about currently existing decision support methods for product development with FRPs.

Nezamian and Setunge (2014) developed a guideline and recommended procedures for using FRP composites in the rehabilitation of concrete bridge structures that relies on the life-cycle cost analysis. A multi-criteria decision-making model that covers goals, constraints and decision variables is used. The focus is mainly on the evaluation of alternatives using a whole life-cycle cost analysis. Industry is only involved in the validation of the MCAD model developed, and user interface management is not discussed.

Al-Oqla et al. (2016) developed a decision-making model to evaluate and select the appropriate non-woven natural reinforcement fiber-/polypropylene-based composites for interior parts in the automotive industry. The analytical hierarchy process (AHP), one of the MADM methods, is applied to assess alternatives (materials) taking into account various evaluation criteria.

Sapuan et al. (2011) presented the decision support model for material selection for an automotive dashboard panel. The AHP method is used to assess various types of natural fiber composites regarding defined criteria. The focus lies on the development of the decision model. Other aspects such as demands of future users or user interface management are not discussed.

Premkumar et al. (2014) presented a semantic knowledge management system for laminated composites. In focus are mechanisms for the capturing, reusing and sharing of information using an ontology for knowledge model creation. The emphasis is on the software-technical implementation of the knowledge management system with a special ontology-based tool.

For other, non-fiber-reinforced materials, further approaches were identified that deal with supporting decision-making through providing design guidelines. Watson et al. (1996) developed a meta-methodology, that provides a basis for evaluating DFX guidelines, depending on design tasks and on a phase of design process. The goal of the meta-methodology is to form a ranking order that allows the product developers to consider the design rules with strongest influence on the actual situation.

Rehman and Yan (2005) developed a PROCONDES system to support design engineers at a conceptual design stage. Decision support for the selection of conceptual design solutions is based on the consideration of functional requirements and showing ideal and problematic life cycle consequences. The approach is presented using the example of a case study for a sheet metal component concept design.

Kratzer et al. (2009) developed an agent-based system ProKon to support design engineers during the embodiment design phase. The system focuses on the design of a transverse compression bandage and takes into account a part of relevant design guidelines. The main objective is to check a design solution in a CAD-Tool for any inconsistency and suggestion of possible improvements in case of faulty design.

Bauer (2009) introduced a tool to search relevant DFX guidelines according to product requirements. Guidelines are classified according to an appropriate means-purpose relationship. The specification of objectives determines which product characteristic can be fulfilled and which DFX guidelines are relevant.

Albers et al. (2009) developed a wiki-based knowledge management system to support design engineers in the field of microtechnology by providing design patterns. Design patterns are means that represent information about solutions in a generic and abstract way. The authors also suggest a concrete structure for the representation of microtechnology information to support a proper balance between information content and clarity. The suggestion for the structure contains following captures: 1) name of design pattern, 2) context about where and what way the problem occurs, 3) description of problem, 4) description of solution, 5) description of positive and negative consequences, 6) information about related patterns, 7) examples of successful application of patterns and 8) references.

Albers et al. (Albers, Schmalenbach, et al., 2011) developed an ontology-based ceramic-design information system (K-KIS) for the representation and retrieval of the ceramic specific embodiment design knowledge generated within the interdisciplinary research project CRC 483.[42] The focus lies on internal use for the storing, reusing and sharing of generated information. The search for information took place as a free text search or as a category search. Furthermore, the pre-defined multifilter enabled search results to be restricted by selecting additional information in the form of attributes. However, slight changes in the ontologies structure required the redesign of the database system because of the software restrictions. (Schmalenbach, 2013, p. 145)

Albers et al. (Albers, Reiß, et al., 2015) developed an application for mobile devices (Inno-Fox) within the framework of a BMBF-funded project IN² – “from INformation to Innovation.” The aim of Inno-Fox is to support product developers in their search for suitable methods by providing situation-specific recommendations. Inno-Fox contains a collection of methods for support product development. All methods are described in

[42] CRC 483 – “High performance sliding and friction systems based on advanced ceramics”

the form of standardized method profiles with a predefined structure. The method recommendation is provided by means of an interactive access part, which in turn is based on iPeM. Utility analysis is used to calculate the suitability of methods according to the user situation.

2.6 Conclusion

Product engineering is a knowledge-intensive process (Albers, Lohmeyer, et al., 2010), accessing the right information at the right time has become increasingly important (Jackson, 2018) and requires suitable knowledge-management approaches. The common expression “if only we knew what we know” (Davenport & Prisak, 1998) still applies to many manufacturing companies today. The proper reuse of engineering knowledge offers major benefits; however, it requires effort not only in the introduction, continuous maintenance and further development of appropriate methods of decision support, but also in ensuring that the documented information is of a high quality and relevance.

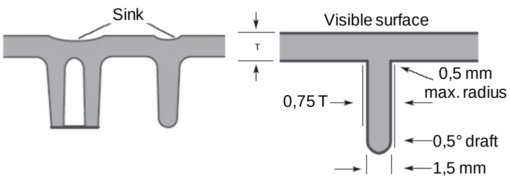
The challenges in developing products with FRP are significantly greater than with conventional materials (Lopez-Anido & Naik, 2000) and place high demands on product developers and development processes. Since each PEP is individual, and the requirements change often, it is important to support design engineers during their engineering activities (Albers, 2010). Despite the increasing use of computers, product developers still play a central role in product development and contribute with their experience and knowledge, as well as with social skills, to a development project’s success (Ponn & Lindemann, 2011, p. 10).

Design guidelines are widely used as a way of documenting the findings and experiences related to embodiment design. The results of the analysis of the state of the art have shown that the content of most design guidelines is rather short and mostly insufficiently supports the analysis and synthesis activities, which are important for product development. Furthermore, a search for design guidelines is time-consuming, as the required information is spread over several books and publications. (Butenko & Albers, 2018)

The majority of recommendations that were found do not relate to the challenges in the design of products with FRPs. The guidelines hardly consider embodiment design in connection with manufacturing and material influences, both of which are important when designing with FRP materials. Figure 45 visualized a comparison between an example of a theoretical design guideline and an example of a real fiber-reinforced system. It is evident, that current design guidelines are simplifications of problems and are usually described abstractly to support easy understanding. However, reality has a clear problem definition and requires concrete information. Design guidelines in their current form are highly limited with respect to their transferability to real application cases. However, documenting all information from a real application can lead to information overload. The challenge is to find a way to support knowledge transfer without sacrificing important information and without overwhelming the product developer with an information overload.

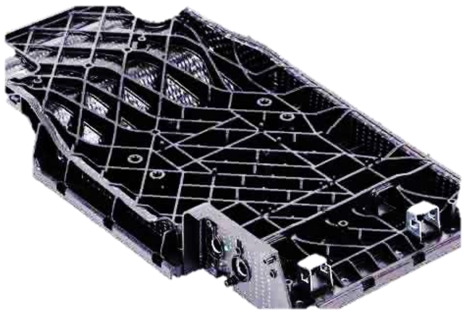
Current Design Guidelines

For Non class A component design, sink marks can be minimized or eliminated by the proper design of reinforcing ribs using the right combination of draft angle, radii and rib thickness as indicated in the diagram below.



Reality

Rear seat system of an off-road vehicle



Current design guidelines:

- are **simplifications** of problems and
- are usually described **abstract** for **easy understanding**

Current design guidelines **hardly** consider **embodiment design in connection with**

- manufacturing restrictions
- manufacturing effects
- …

- **Highly limited** transferring to real application cases

BUT

Reality requires:

- a **clear problem definition**
- **concrete** information

Reality requires:

- consideration of the **relevant manufacturing and material influences** on the design solution

- **Documenting** all information from a real application can lead to **information overload**

Figure 45: Reality vs. current design guidelines: Why current design guidelines are insufficient for knowledge transfer[43]

[43] An example of the design guideline presenting rib design is adapted from the European Alliance for SMC/BMS (2007, p. 22). The image of the rear seat system of an off-road vehicle reinforced with endless fibers is adapted from (Kunststoff Magazin, 2018).

3 Research methodology

This chapter presents the methodology applied in this thesis. The chapter begins with the formulation of the work's research hypotheses and research questions, and then outlines the study's objectives before describing the methodological approach applied.

3.1 Research hypotheses and research questions

The following three research hypotheses were examined in this work:

Research hypothesis I:

> Existing design guidelines for FRPs found in the literature do not support knowledge transfer sufficiently for practical applications in industry.

Research hypothesis II:

> The use of development guides, formulation rules and quality checklist can support the creating of sound design guidelines for FRPs and increase the quality of documentation.

Research hypothesis III:

> Introducing a knowledge-based decision support for searching through large amounts of data and identifying information that is relevant to a given situation can allow solutions to be found more efficiently.

For each research hypothesis, multiple research questions were established. These questions guided the investigations undertaken in the current study and their answers served to confirm or refute the above hypotheses.

Related to **research hypothesis I**, the following research questions were formulated.

Research question I:

> How do industry representatives assess the practicability of published design guidelines for FRPs?

Research question II:

> From the industry's point of view, what information must be included in FRP design guidelines in order to properly support the design process?

With respect to **research hypothesis II**, three further research questions were defined.

Research question III:

Which form of information representation used in design guidelines (text-based representations, text represention s with images of ideal and poor solutions, or text representation with C&C²-based images of ideal and poor solutions) is best suited to support knowledge transfer?

Research question IV:

What are the differences between experienced and inexperienced product developers' assessments of the suitability of information for knowledge transfer?

Research question V:

How can the target-oriented documentation of information in design guidelines be methodically supported?

Finally, **research hypothesis III** was examined via the following research questions.

Research question VI:

How should design guidelines for FRPs be conceived so that situation-relevant embodiment design characteristics from different design guidelines can be dynamically compiled into a single design guideline?

Research question VII:

How can decision-support tools be used to identify PEP situations and facilitate the creation and communication of situation-specific design guidelines?

Research question VIII:

How efficient is using a knowledge-based decision-support method to search for and identify situation-relevant design guidelines in comparison to searching without such a method?

3.2 Objectives

The main objective of this work is to develop a practical approach that aids product developers in the early phases of product development during embodiment designing with FRP materials. The work aims, on the one hand, to promote knowledge transfer by improving the documentation practices used in current design guidelines. On the other hand, the thesis seeks to support product developers ability to determine the relevant embodiment characteristics for a particular product or situation by facilitating the search for design guidelines containing relevant information.

In order to accomplish the objective of improving knowledge transfer, it was necessary to determine what members of the target group[44] require regarding subject areas for design guidelines, including the content and form of presentation they require. Different ways of presenting information in design guidelines – including text-based representations, and illustrations of ideal and poor design solutions – needed to be evaluated in terms of their suitability for knowledge transfer and their acceptability among the target group. In addition, it was essential to create formulation rules for the drafting of design guidelines and quality check points for evaluating the guidelines themselves. Both formulation rules and quality checkpoints were to be regarded as a means of assisting product developers and not as an obligation the developers must follow. Product developers with different experience in the field of FRPs are also to be supported through the supplying of relevant situation-related information. The developed approach should be evaluated by the target group to ensure that knowledge transfer had indeed been improved in comparison to the approach currently used, and that the implementation of intelligent support for the identification and implementation of relevant design guidelines had increased efficiency. The present work takes into account all components of a DSS,[45] concentrating mainly on those components concerned with methodical development and less on those related to software-based implementation.

3.3 Research approach

The present work was carried out according to the design research methodology (DRM) as developed by Blessing and Chakrabarti (2009). The DRM is a methodological approach characterized by a set of supporting methods and guidelines that aim to improve the efficiency and effectiveness of a research project. The DRM divides the research process into the four following stages: the research clarification stage; a first descriptive study stage; the prescriptive study stage; and a second

[44] Industry representatives who are employed in the field of FRP and are directly or indirectly involved in the product development

[45] Decision Support System

descriptive study stage. (Blessing & Chakrabarti, 2009) These four stages are depicted in Figure 46.

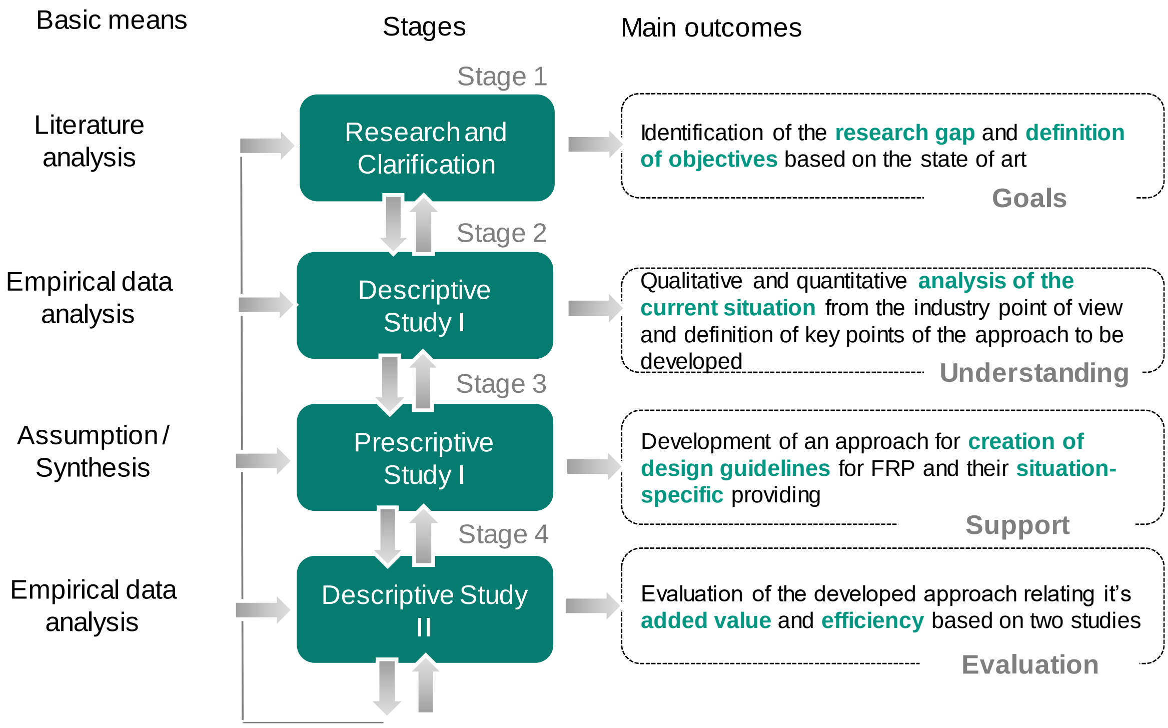


Figure 46: Design research methodology referring to Blessing and Chakrabarti (2009)[46]

In the research clarification stage, a comprehensive literature analysis is carried in order to gain insight into the research topic and thereby identify potential research gaps. On the basis of the identified research gaps, research hypotheses, research questions and concrete research objectives are formulated, the latter of which comprise the most important outcome of this stage.

The subsequent stage is comprised of qualitative and quantitative studies. In the first descriptive study in the present work, industry representatives were asked to evaluate the quality of knowledge transfer and the applicability of existing design guidelines for FRPs. By clarifying the advantages and disadvantages of the current design guidelines, this process allowed the principle challenges currently facing product development with FRPs to be established. It also helped to gather the information necessary to meet these challenges, ultimately permitting a deep understanding of the underlying research area. In this stage, data was collected by means of semi-structured interviews. This form of interview is an appropriately empirical, qualitative method for information gathering, as, compared to fully-structured interviews, semi-structured interviews offer the researcher the chance to introduce new ideas or variations in the interview that allow more in-depth information to be obtained (Harrell

[46] Main outcomes are modified according to outcomes in this thesis

& Bradley, 2009, p. 27). In the next part of this stage, a quantitative study involving data from a larger number of industry representatives was carried out to validate the results of the interview study. A structured online-based questionnaire was used to collect data for this purpose. This method of data collection is cost-effective and, therefore, suitable for questioning a large sample (Atteslander, 2008, p. 147; Bortz & Döring, 2006, p. 252). Software used for the execution of online survey allowed the survey to be designed and structured with a branching logic, whereby different response scenarios could be covered.

The findings from the literature analysis and initial descriptive studies are examined in the next step by performing further investigation experiments and studies. In the first study, different forms of information representation (text-based, illustration-based, model-based) were compared in case studies in which industrial representatives evaluated the suitability of each form for better transfer of information. In the second study, the usefulness of current design guidelines in real applications was examined using the example of the demonstrator developed within the IRTG project. The demonstrator clearly represents the research results that have resulted from the application of the selected design guidelines for SMC material. In the third study, methodological aids to support the creation of design were developed and their usability investigated.

On the basis of insight gained in the performed studies, an approach was then developed to improve information transfer per design guidelines and an approach to support product developers in their search for relevant information by providing situation-specific design guidelines. A development process model that systematically describes the development processes involved in the approach and their necessary steps was created to facilitate the approach’s implementation. Within the process model, measures were also established for the model’s continuous improvement through the use of verification and validation points and associated optimization cycles.

In the descriptive study II, the developed knowledge-based decision support system was evaluated in terms of its added value and efficiency based on two studies.

4 Industry survey on design guidelines

This chapter presents the procedure and the results of the qualitative and quantitative surveys with industry representatives. The aim was to assess the existing design guidelines for FRPs with regard to the knowledge transfer and practical suitability from the user's point of view. First, the methodological approach for the planning and conducting of the qualitative, semi-structured interviews is described. Afterwards, the important results are provided. Finally, the concept for a fully structured online questionnaire based on the findings of the interviews and the important results are presented.

4.1 Semi-structured interviews – Methodological approach

An important step in the development of semi-structured interviews is the creation of the interview guide, which contains a written list of general questions to be covered in the interview study. This serves as an orientation, so that non-essential aspects of the research questions are overlooked. Following the interview guide in the semi-structured interviews is important and recommend to obtain comparable qualitative data. (Russel, 2006, p. 212)[47]

The interview guide consists of five main categories:

1) Participant-related data
2) Use of design guidelines
3) Challenges associated with FRPs in product development phases
4) Desired content in design guidelines to meet mentioned challenges
5) Requirements on design guidelines.

The first draft, published in Butenko et al. (2017), contains two further categories,[48] which are summarized in the category "use of design guidelines" due to their similarity during an analysis of the interview results.

Each of these five categories are assigned specific topics and related questions, as depicted in Figure 47. In the first category, the capturing of participant-related data, such as industry, department, activities of PEP, and experience in the field of FRPs, is important for understanding and categorizing the information gained during the course of the interviews.

[47] According to (Butenko et al., 2017)

[48] (1) The advantages and disadvantages of the current design guidelines and (2) situations and tasks where design guidelines are usually used/needed

The second category refers to the questions regarding the application/non-application of design guidelines, the reasons for this, as well as the advantages and disadvantages of current design guidelines from the industry's point of view. The answers to those questions help one understand which positive aspects of the design guidelines are appreciated by industry representatives and which aspects urgently need to be improved.

The third category deals with questions about challenges in the PEP with FRPs. The information on these questions helps one to understand which topics are currently challenging and why. This also provides a sufficient basis for comparing the needs of the industry with the topics currently covered in the existing design guidelines in the literature.

The next category deals with questions about the required content in the design guidelines and their level of detail to ensure the necessary support. Since participants with different levels of experience in the field of FRPs are involved in the study, these questions allow the differences in needs between experienced and less experienced participants to be identified.

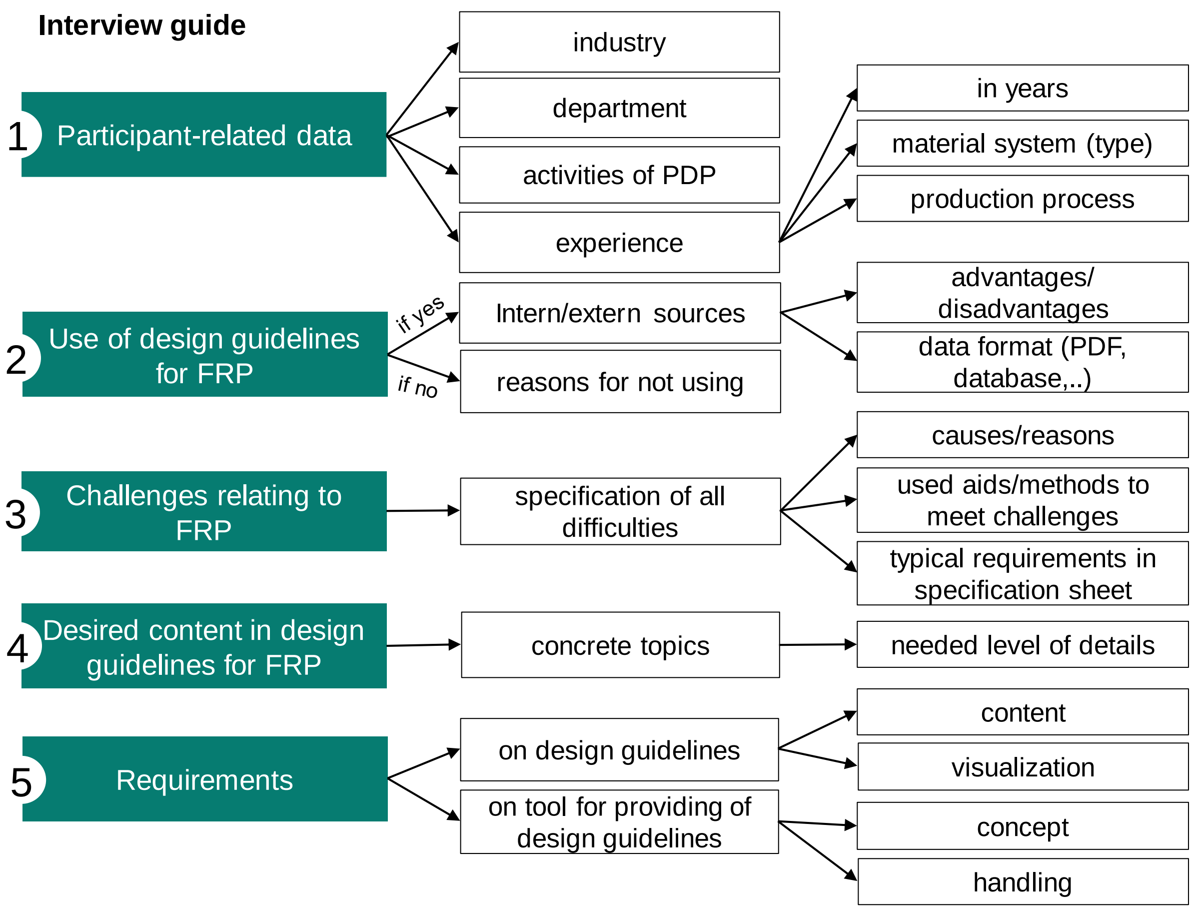


Figure 47: Structure of the interview guide

The last category contains questions about the requirements for design guidelines and the tool for their administration and provision. With regard to the guidelines, the focus is on identifying the requirements for describing the content and form of visualization. The requirements for the tool include the handling, navigation, search and management of information. Approximately 30 questions were prepared for these five categories. Figure 48 presents an excerpt from the questions in the interview guide, with the topics on the left-hand side and the sample questions on the right.

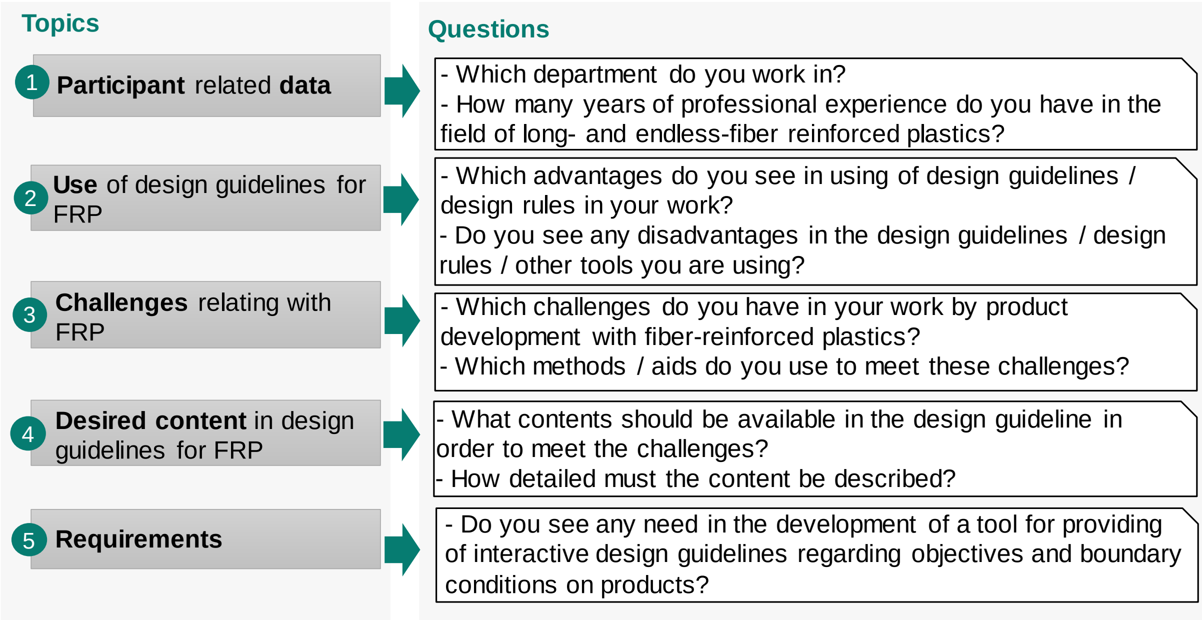


Figure 48: Interview guide with questions – based on Butenko et al. (2017)

Another, no less important aspect in qualitative research in order to obtain valid findings is the representativeness of the persons interviewed in a sampling. A distinction can be made among three types of sampling: convenience sampling, selective sampling (also known as judgment sampling) and theoretical sampling (Marshall, 1996).

The convenience sampling is one of the least rigorous techniques (Marshall, 1996), and in it, the sample is selected on the basis of participants accessibility (Given, 2008, p. 124). In the case of selective sampling, certain characteristics of the sample are determined before the start of the qualitative study based on the questions under investigation, theoretical knowledge of the research area and other available studies (Marshall, 1996). In theoretical sampling, a precise idea of the size and characteristics of the sample is formed iteratively during the research process and a decision as to which information should be collected as next is made based on continuously collected data (Glaser & Strauss, 1967, pp. 45–49).

The selective sampling method is chosen for the interview study, as the investigations are based on concrete questions, which allow the definition of certain criteria for the selection of participants in order to obtain a representative part of the target group. Attention is paid to the selection of participants, as they have an important impact on the results of the study.

Participants with varying experience in the field of FRPs and who are active in fields related to the embodiment design were identified. Of 74 industry representatives invited to participate in the interview study, 16 agreed. The emphasis in finding participants was to ensure that both inexperienced and experienced product developers participated, so that needs could be assessed from different perspectives. The contact request was made by e-mail, and the background for the interview study and the IRTG project aims were briefly described.

The interviews were conducted in person and on the phone and each lasted between 45 and 60 minutes. (Butenko et al., 2017) First, the background of the interview study was briefly presented to clearly inform the interviewees about the goals. The basic terms were then clarified to ensure a common understanding. In addition, permission was obtained to record the interview. Recording ensures better concentration, as no notes need to be taken during the conversation.

For the analysis of the interviews, the deductive and inductive method of category formation according to Mayring (2000) was selected. The aim of the **category system** is to define those aspects that appear relevant for the analysis and which are to be filtered out of the transcribed interview text. In this context, a category is an identifier to which text passages are assigned. (Kuckartz, 2010)

First, categories were defined deductively based on the questions asked in the interview study. The information that could not be associated with any of the defined categories was assigned to the remaining category. In the next step, new categories were created inductively on the basis of the analysis performed.[49] The combined application of deductive and inductive methods for the analysis of qualitative data is frequently used (Stamann et al., 2016).

Figure 49 summarizes all described steps taken to collect the data from the interviews.

[49] According to Butenko et al. (2017)

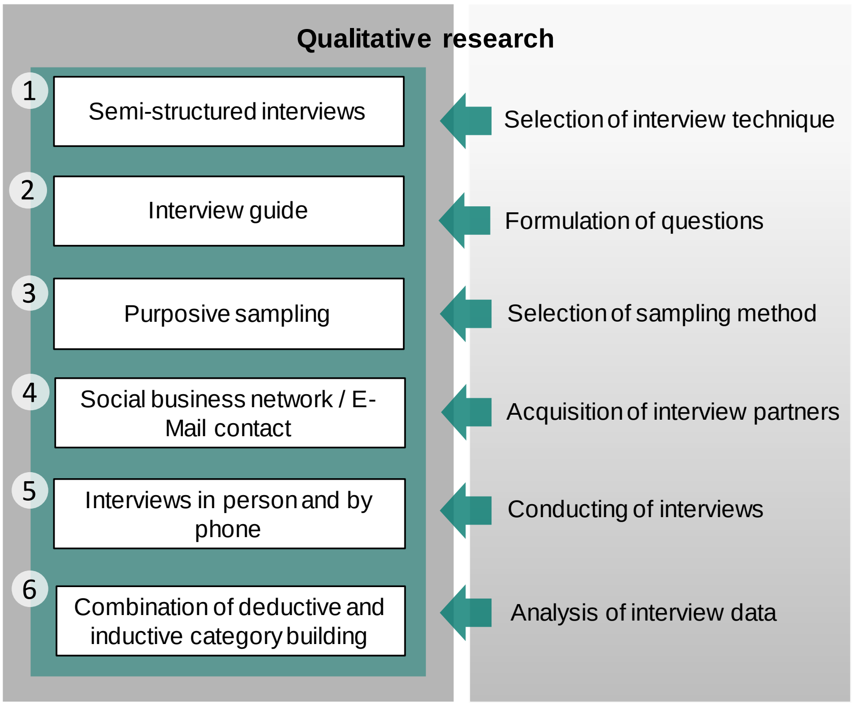


Figure 49: Methodological approach – qualitative study

4.2 Semi-structured interviews – Main results

4.2.1 Participants backgrounds

Six of participants are from North America and the remainder are from Germany. Most of the participants in the interview study are employed in the automotive industry, while the others are from the aerospace, plant engineering, wind power plant and engineering consulting industries. (Butenko et al., 2017)

The interviewed persons were also active in different areas, from material characterization and validation to design and manufacturing. Figure 50 presents the participants' backgrounds based on the results published in Butenko et al. (2017). The dark green square clearly marks the assignment of participants to the corresponding industrial fields.

	Industry				
Thereof active in the …	Automotive industry	Plant engineering	Wind power plant	Aerospace industry	Engineering consulting
Construction of body elements (design and calculation)	▲				
Development / design of interior trims for vehicles	▲				
Design of component modules	▲				
Development/design of heavy-duty cranes			▲		
Development of aircraft components				▲	
Development of components for the automotive and aerospace industries	▲			▲	
Production of components for the automotive industry (from concept to finished product)	▲				
Production of door modules	▲				
Development of manufacturing technology	▲				
Technology manager in an automobile association	▲				
Validation engineers (crash simulation)				▲	
Materials engineer in the research				▲	
Material characterization and validation				▲	
Engineering consulting from idea to concept					▲
Technology manager for plant development		▲			

Figure 50: Participants' activity fields based on Butenko et al. (2017)[50]

The interviewed persons had different levels of experience with FRPs, ranging from one year to more than 16 years. As can be recognized in Figure 51, most of participants had between 3–5 and 6–10 years of experience.

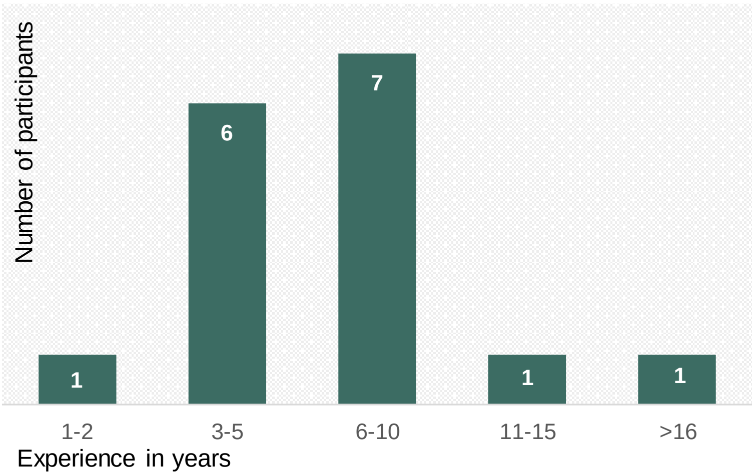


Figure 51: Level of experience with FRPs

[50] The activities of the participants are listed more detailed in comparison to the publication in Butenko et al. (2017)

The participants had experience with different material systems. All 16 interviewees mentioned experience with carbon fiber-reinforced plastics (CFRPs), while eight cited experience with glass fiber-reinforced plastics (GFRPs), and only two had experience with nature fiber-reinforced plastics (NFRPs) and aramid fiber-reinforced plastics (AFRPs).

4.2.2 Use/non-use of design guidelines for FRPs

Half of the participants confirmed, and another half abandoned, the use of design guidelines (Butenko et al., 2017). Those who confirmed were active in design and production, and their reasons for using design guidelines were internal specifications of companies and, more efficient design and workflows by avoiding or minimizing documented processing errors. Company-internal design guidelines were mentioned as more practical and useful than those in the literature.

"At our company, the design guidelines look like this: In the beginning, there is a text that tells you what it is all about. Then, there are some pictures of how such a component could look. The part for the design is only 'naked numbers', that is, mathematical relationships, for example the choice of a suitable rib thickness as a function of the plate thickness." (Butenko et al., 2017)[51]

Design guidelines in the literature were described as less helpful on the following grounds:

Information is useful for the basics, but not for real applications:

*"*Design guidelines are not application oriented*."* (Butenko et al., 2017)[52]

"Many design guidelines are not clear; the necessary data should be summarized at the end of each chapter, so that the employee can quickly obtain the necessary information."[53]

Specific contents are mostly not available:

"Searching for a load case is often without success." (Butenko et al., 2017)[54]

Searching for the necessary information takes too long:

"Nobody wants to read a multi-page document." (Butenko et al., 2017)[55]

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[51] Statement of one participant in the interview study, documented in Wilwer 2016 p. 69 (co-supervised bachelor thesis). The evaluation of the interview results conducted in Germany was partly carried out within the framework of the co-supervised bachelor thesis.

[52] Statement of one participant in the interview study

[53] Statement of one participant in the interview study

[54] Statement of one participant in the interview study

[55] Statement of one participant in the interview study

The guidelines do not correspond to the current state of the art:

"The existence of certain design guidelines is unknown, and care is sometimes neglected, so that many of the initial design guidelines do not meet the required standard." (Butenko & Albers, 2018)[56]

However, company-internal guidelines also had some disadvantages from the perspective of the participants (Butenko et al., 2017):

Not detailed enough and confusing:

"Due to the fact that we don't have any internal regulations how the information is to be documented, this leads to a lack of certain information at certain places."[57]

The search for the suitable information takes too long:

"In our department internal design guidelines are documented in PowerPoint format. Each is responsible for documenting important information gained from projects. Meanwhile, such PowerPoints consist of hundreds of slides, which make the overview difficult."[58]

Participants who abandoned the use of design guidelines were employed in the fields of crash simulation, research and consulting. The reasons for this abandonment were their respective fields of activity. Those who were not actively involved in the design of components stated that there are no design guidelines to use, while the participant from a simulation department stated that he does not need them, since his focus is on the optimization of components.[59] Furthermore, participants in the research field stated that they are working above the state of the art and that their research serves rather as input for the development of design guidelines. At another company, no use of the design guidelines was possible, as most cases have never existed due to individualized customer requirements. However, design guidelines are seen here as quite meaningful, "especially when cases keep recurring, it makes sense not to start all over again to work through the necessary analysis."[60]

Although only half of the participants said they are using design guidelines; 15 out of the 16 participants generally found the use of design guidelines to be helpful if those guidelines meet certain quality criteria. At this point, participants mentioned that the use of such design guidelines could reduce the frequency of faults in design and thus save time needed for revisions.

[56] Statement of one participant in the interview study
[57] Statement of one participant in the interview study
[58] Statement of one participant in the interview study
[59] Documented in Wilwer 2016, p. 69 (co-supervised bachelor thesis)
[60] Statement of one participant in the interview study

4.2.3 Current challenges relating to FRPs

Another question discussed in the interviews relates to current challenges[61] in the development of products made of FRPs from the perspective of various participants. These challenges are described individually below.

1. Stability of manufacturing processes and their influence on the quality

The stability (precision) of manufacturing processes was a frequently mentioned challenge in handling FRPs. This challenge includes compliance with the required component quality under the same process conditions. The reason is that unpredictable, local differences in the component can occur during a manufacturing process due to the fluid mechanics and the associated fiber matrix interaction during the process. Both problems are subject to a high inspection effort for highly loaded structures.[62]

"This is probably the largest challenge in the world-wide industry, because it is challenging to make 2–3 identical components. Imagine that you have to make 100,000 a year. Quality becomes a major challenge, and this is definitely a major bottle neck."[63]

2. Increased effort in the field of quality assurance

The test effort is another, significant cost factor that must be considered when using composites. Fast and reliable quality assurance is important, especially for FRP materials, but challenging with respect to the automation and integration of quality assurance procedures directly into production.[64]

"Depending on the component, we may have to make a 100% test.[65] There is a need for non-destructive, efficient quality assurance approaches in order to determine the number of components that are not of the required quality."[66]

3. Selection of proper manufacturing process and parameters

This topic is also indicated as highly relevant and challenging due to the influence of manufacturing processes on different aspects such as quality of finished parts and

[61] Challenges are briefly mentioned in (Butenko et al., 2017)
[62] Interview results, documented in Wilwer 2016, p. 66 (co-supervised bachelor thesis)
[63] Statement of one participant in the interview study
[64] Brief summary based on the statements of the participants in the interview study
[65] Documented in Wilwer 2016, p. 66 (co-supervised bachelor thesis)
[66] Statement of one participant in the interview study

costs. The selection of a manufacturing process depends on the requirements for the component, the production size and the properties of the material.[67]

“We have many meetings to discuss this topic. This topic is critical because the manufacture process dictates the price, the volume needed for production and material selection. Unfortunately, all these aspects are not independent; they all influence each other.”[68]

4. Selection of appropriate post-processing and its parameters

The post-processing of FRP components is the next relevant topic. The challenge here is to select suitable procedures and their process parameters to avoid delamination, edge damage or poor quality of the finished surfaces.[69]

“Different factors influence the quality of post-processing and must always be considered. When milling, for example, the correct tool with suitable helix angle and coating and corresponding parameters such as cutting speed, feed rate and milling direction should be selected depending on the selected material and layer structure. If you have selected inappropriate parameters, this can lead to a loss of quality.”[70]

5. Prediction of the adjusted fiber orientation during the manufacturing process

“There is no sufficient working simulation tool on the market. Determining fiber orientation beforehand is not yet state of the art. It is only possible to design a component/tool by experience. Flow simulations are unfortunately only 90–95% correct. For the remaining 5%, we need component tests or experiential knowledge."[71]

Calculations to predict fiber orientation are significantly more complex than by isotropic materials. The determination of fiber orientation is important, as it has a significant influence on the properties of the resulting component.[72]

6. Draping simulation of components

The final fiber orientation occurs during the drapability of the components from two-dimensional into three-dimensional structures, and it determines possible component geometries. The draping properties of the semi-finished products determine the

[67] Brief summary based on the statements of the participants in the interview study
[68] Statement of one participant in the interview study
[69] Brief summary based on the statements of the participants in the interview study
[70] Statement of one participant in the interview study
[71] Statement of one participant in the interview study, documented in Wilwer 2016 p. 67 (co-supervised bachelor thesis)
[72] Brief summary based on the statements of the participants in the interview study

possible component geometries. Furthermore, the quality of the results influences the accuracy of the prediction of the local fiber architecture for the given geometry in order to obtain the required load-bearing capacities of the components.[73]

“There are already commercially available simulation tools with models for the draping simulation of woven fabric prepregs, but another prepreg technique such as multiaxial fabric has a much more complex draping behavior. There is a lack of appropriate simulation models and processes for these semi-finished materials.”[74]

7. Crash and impact behavior

The crash and impact behavior of FRPs proves to be another challenging topic because of the material’s anisotropy. The simulation of the impact behavior requires generally valid material models to be available, and the determination of these material models is correspondingly complex and requires additional real tests. The quality of the material models in turn influences the meaningfulness of simulation results. Due to the complex anisotropic behavior and failure mechanisms depending on the type of reinforcement, modeling the material behavior, selecting a suitable modeling approach and interpreting the simulation results are challenging tasks.[75]

“The challenge is that we don’t know what we are modeling. In other words, what we think we are modeling is different from the result. So that gap is permanent here.”[76]

“There are different material models; however, these can almost never be adopted, as otherwise realistic results cannot be achieved. The development of such models is very time consuming and requires real attempts. If material parameters or fiber reinforcement change, the material model should be adapted accordingly. Another point is that too complex material models lead to increasing computing times and thus make a simulation uneconomical.”[77]

8. Limits of knowledge in the field of FRPs

The limits of knowledge in the field of FRPs and the associated wariness are relevant points in the use of a fiber composite. Product developers are not always aware of the possibilities offered by FRPs and the limitations to which they are subject.[78]

[73] Brief summary based on the statements of the participants in the interview study
[74] Statement of one participant in the interview study
[75] Brief summary based on the statements of the participants in the interview study
[76] Statement of one participant in the interview study
[77] Statement of one participant in the interview study
[78] Brief summary based on the statements of the participants in the interview study

"In the case of a problem solution, people rely on proven solutions, if one has gained experience with a certain material or production process, then the next time, they use that material and the experiences connected with it again. Many product developers simply don't have the time to familiarize themselves with the new topic."[79]

9. Material selection

Material selection is challenging in the case of FRPs, as the composition of the matrix, fiber material, length and arrangement have a significant influence on the properties. In addition, the production process of fibers, a matrix or a semi-finished product has a further significant influence on the properties.[80]

"The properties change depending on the mix and on the manufacturing process, and people don't realize it. If you give the material to the supplier and say you want the same component with this layout, you will receive back two components that look the same but have totally different properties."[81]

10. Scattering in the material properties

The disordered microstructure in long-fiber-reinforced polymers leads to local scattering in the material properties. (Butenko et al., 2017) Uncertainties in material properties lead to the selection of a sufficiently high safety factor and the oversizing of the components. As a result, the potential for lightweight construction is not fully exploited.[82]

"The prediction of material behavior difficult, especially with flat components and joining technology. Layer construction, layer arrangement et cetera have considerable effects on the component behavior."[83]

11. Imprecise material characterization

Material characterization plays an essential role in the simulation-aided design of the molding process. Failure criteria are important for a correct description of the material characteristics because they form the specific stress conditions that lead to a failure of the material. The characterization of the failure criteria requires robust experimental and analytical tools.[84]

[79] Statement of one participant in the interview study
[80] Brief summary based on the statements of the participants in the interview study
[81] Statement of one participant in the interview study
[82] Brief summary based on the statements of the participants in the interview study
[83] Statement of one participant in the interview study
[84] Brief summary based on the statements of the participants in the interview study

“One of the major challenges is the correct description and understanding of the behavior of fiber-reinforced structures; there is a lack of approaches to characterize especially hybrid composites in a reliable way.”[85]

12. Optimal utilization of anisotropic behavior

Fiber material and their orientation, content and length have an important influence on the resulting properties. To utilize anisotropic behavior in the most effective way, these factors must be taken into account in the embodiment design phase. However, this requires, on the one hand, the precise characterization of the material properties and, on the other hand, the suitable process parameters to ensure that, in reality, those properties are obtained in the finished component.[86]

“The determination of the fiber orientation that occurs during manufacturing is challenging. Often, components are substituted together without actually taking the fiber orientation into account.”[87]

13. Load-compliant design of stiffening elements

Load-compliant design was and remains a challenge in construction with FRPs. Products with customized properties are relevant to the optimal design and utilization of fiber orientation and are constantly being researched. Realistic simulation results of the behavior of components are very important to the accuracy of material characterization.[88]

“Correct material characteristic values are the most important for the design. Fiber orientation is extremely important for the design of components and it is therefore necessary to be clear how the load acts on the component (force application) in order to design the fiber orientation accordingly.”[89]

14. Production-compliant design

The consideration of manufacturing restrictions in the embodiment design is another point that is important to ensure the manufacturability of the components. Furthermore, the quality also depends on compliance with production restrictions. If radii are insufficient, rib geometry is incorrect or the wall thickness or another geometrical

[85] Statement of one participant in the interview study
[86] Brief summary based on the statements of the participants in the interview study
[87] Statement of one participant in the interview study
[88] Brief summary based on the statements of the participants in the interview study
[89] Statement of one participant in the interview study

aspect is not properly designed, the result can be warpage, poor surface quality or insufficient mold filling.[90]

"Again and again, mistakes are made in the embodiment design. This is because the manufacturing restrictions are not always taken into account or are not always known. Manufacturing restrictions vary depending on different production processes, materials and product requirements. Geometries that are possible with one material and manufacturing process cannot necessarily be achieved by same process but with other materials."[91]

15. Temperature and humidity effects in later application

Knowledge about environmental influences on the properties of FRPs plays an important role in the embodiment design and must be considered. The extraction of this information requires real investigations into prototypes.[92]

"Material aging caused due to environmental effects such as humidity and high temperature and has different effects depending on the occurrence of these effects. The definition of the correct period of use is difficult and must be based on failure criteria."[93]

16. Force load introduction via connection elements

In a force-locking force introduction, a preload loss can occur between the lowest and highest operating temperatures due to different coefficients of the thermal expansion of the joining partners.[94]

"The choice of the joining technique to be used has an influence on the choice of material and the manufacturing process. The reason for this is the possibility of the force introduction. It is important for a designer to know the advantages and disadvantages of a joining process and the design measures that this entails."[95]

17. Corrosion protection of metal inserts

The connection of CFRPs with metals is accompanied by the risk of electrochemical corrosion, which should be considered in the design stage. This corrosion is cause by the different electrical surface potentials between metals and CFRPs. The selection of

[90] Brief summary based on the statements of the participants in the interview study
[91] Statement of one participant in the interview study
[92] Brief summary based on the statements of the participants in the interview study
[93] Statement of one participant in the interview study
[94] Brief summary based on the statements of the participants in the interview study
[95] Statement of one participant in the interview study

the correct material combination or appropriate protection against corrosion is important. Another important subject is stress corrosion cracking, which is the main concern in composites and occurs due to the combination of a corrosive environmental stress and a mechanical stress.[96]

"Know how to handle the corrosion-promoting factors, if they occur at all, the consequences that this has for the component should not underestimated. These considerations should already be taken into account when selecting materials."[97]

18. Design for recycling

The recycling of FRPs has become increasingly important in recent years due to the worldwide increase in the use of these materials in various industries. Compared with other materials, FRPs are difficult to recycle because of their multiphase structure, which consists of at least three components: fibers, resin matrix and fillers. In addition, the FRP materials are often joined with other materials by adhesive or mechanical means, which makes recycling even more difficult.[98]

"The costs of the end-of-life stage of products should be considered in the early stage of product development; if this is left out, then the eventual costs will come to mind later, especially when legislation regarding recycling changes. Therefore, products should be developed taking into account their dismantling and possible reuse at the end of that application's life."[99]

4.2.4 Desired content according to determined challenges

Within the framework of a scientific discussion,[100] the challenges communicated by the interviewees are divided into three categories:[101]

- Material-related challenges
- Design and validation related challenges
- Production process-related challenges.

[96] Brief summary based on the statements of the participants in the interview study
[97] Statement of one participant in the interview study
[98] Brief summary based on the statements of the participants in the interview study
[99] Statement of one participant in the interview study
[100] Regular scientific discussions within the framework of the IRTG project
[101] Originally, topics were divided into four categories: design, simulation, production and material and published in (Butenko, Wilwer, et al., 2018). Design and simulation were merged in one category: "design and validation" as a result of analysis and evaluation of desired contents related to both categories.

The results of the survey revealed that not only embodiment design knowledge, but also general technical information is necessary for optimal support. The difference is that in the case of embodiment design knowledge, information that contains concrete design recommendations for the underlying objectives and boundary conditions is needed. Within the framework of general technical information, an overview of various possibilities is expected, such as the advantages and disadvantages of various structural reinforcements.

The interviews were conducted with German and North American industry representatives. Interestingly, the challenges and desired content in design guidelines differ minimally between the two sets of representatives. The difference was that some of the challenges described as current in Germany were seen not as current but as future challenges in North America.

The desired information in design guidelines and in general for all challenges is presented below in Table 3, Table 4 and Table 5. The following findings are based on the first drafts published in Butenko et al. (2017) and Butenko and Albers (2018).

Table 3: Desired content in the category – Material

Topic	Desired content
Imprecise material characterization	- Information on how the necessary material properties can be determined - Information about which test methods exist/are suitable for the determination of material properties
Scattering material properties	- Information about approaches for predicting the expected scattering in material properties - Information on the prediction of the component behavior based on the scattering material properties
Material model for structural simulation	<u>Support in the selection of material model</u>: - Information on criteria for selecting the right material model - Information on the advantages, disadvantages and applications of failure models <u>Support in the development of material model</u>: - Information on material properties (fiber materials and matrix materials) - Approaches for considering the process-dependent fiber orientation directly in the simulation - Information on the calculation of damage progression - Information on how to validate the material model

Table 4: Desired content in the category – Production process

Topic	Desired content
Stability of manufacturing processes and their influence on the quality	- Information on influences of manufacturing effects on the component properties - Information on suitable process parameters for a given material system to avoid production effects
Increase effort in the field of quality assurance	- Suitable methods for non-destructive quality assurance
Selection of proper manufacturing process and parameters	- Information on advantages/disadvantages of different manufacturing methods - Information on appropriate methods depending on material and product requirements
Selection of appropriate post-processing methods and their parameters	- Advantages and disadvantages of different post-processing methods - Appropriate post-processing methods as well as their process parameters depending on material system - Approaches against delamination for different procedures - Information on surface pre-treatment during coating (cleaning and influence of release agents) - Information on heat removal during machining

Table 5: Desired content in the category – Design and validation

Topic	Desired content
Optimal utilization of anisotropic behavior	- Information on behavior by creep and relaxation processes, maximum temperatures and maximum loads - Information on material properties - Information on appropriate process parameters to ensure the necessary properties
Material selection	- The influence of the visibility/invisibility of a component. (Particularly in the automotive sector, components with visible areas have the highest demands on the achievable surface quality) - Influences of the environment (increased humidity, low or high temperatures and electromagnetic radiation) - Necessary mechanical, chemical and thermal properties - Drapability of the material - Material cost - Load-dependent criteria (load cases and loading speeds) - Prescribed manufacturing process - Possible joining technology - Prescribed post-processing
Limits of knowledge in the field of FRPs	- Information about the possibilities and limitations of a material (material properties)
Load-compliant design	- Approaches to reinforcements of parts in visible areas (choice of appropriate stiffening and measures to avoid sink marks in case of ribs reinforcement) - Information on advantages/disadvantages of different reinforcements - Information on suitable reinforcement type depending on underlying requirements and boundary conditions - Information on material properties - Information on selecting safety factor
Production-compliant design	- Information about advantages/disadvantages of different manufacturing processes - Realizable geometries depending on manufacturing process

Table 5: Continuation

Topic	Desired content
	- Information on suitable process parameters depending on material system and component design - Information on suitable design type (such as integral and differential design) depending on requirements
Corrosion-resistant design	- Information on ideal corrosion protection - Information on the treatment of corrosion-inhibiting/ corrosion/promoting factors - Information on suitable material combinations
Force load introduction via connection elements	- Information about advantages and disadvantages of different joining technologies for load introduction - Information on suitable join partners/fasteners - Information on appropriate measures against creep behavior during preload - Information on necessary pretreatments
Humidity and temperature influences in later application	- Information on the influence of temperature on corrosion and electrical conductivity - Information on the mass increase by moisture absorption - Information on thermal distortion / thermal residual stress
Design for recycling	- Information on design for recycling - Information on design for re-use
Prediction of the crash and impact behavior	- Information on material characteristics - Information on appropriate failure models - Information on evaluation of results of crash simulation
Draping simulation of components	- Approaches for defining the optimal draping strategy - Information on influence factors on drapability - Information on appropriate material models

4.2.5 Requirements regarding design guidelines for FRPs

The participants saw the need to revise the existing concept of design guidelines. This need was confirmed both by those who actively use design guidelines and those who do not. (Butenko et al., 2017) The following requirements were expressed with regard to the following points:

Up-to-date contents:

"A design guideline should always reflect the current state of the art. Because of this fact, a digital catalogue would be recommended again, as updating it proves to be much easier than publishing a new book. In addition, regular updates can ensure that everyone who uses these design guidelines is always up to date."[102]

Transparent information regarding material properties:

"A digital catalog is a good way to deal with materials. The more detailed this is, the better it is for the user." "Information about matrix materials, exact descriptions, should be documented in an appendix to ensure a certain transparency and to not flood the user directly with information."[103]

Differentiation of the contents regarding the target group:

"An appendix with basic design principles, material properties is absolutely necessary if this catalog is also to be for beginners. However, such a catalog is probably mostly used by experts, so it is rather "nice to have", but not mandatory." "Less text and better more specific examples of what the solution may look like, what are the disadvantages if certain aspects are not taken into account."[104]

A standardized template for the documentation of the design guidelines:

"Knowledge is often passed on in such a way that an engineer who leaves the company has three months to document his knowledge. There are no templates used in our company. By specifying a structure for the design guidelines, it would be possible to make time management more efficient, that is, more information could be documented by the engineer."[105]

Clear objectives and application-oriented information:

"With a good design guideline, the designer should be able to design components without having to acquire additional knowledge of materials, production processes, et cetera."[106]

[102] Statement of one participant in the interview study
[103] Statement of one participant in the interview study
[104] Participant with 16 years of experience
[105] Statement of one participant in the interview study
[106] Statement of one participant, documented in Wilwer 2016, p. 68 (co-supervised bachelor thesis)

A uniform structure to ensure the comparability of possible alternative solutions:

“It must quickly become clear why solution A is better than solutions B and C in my situation.”[107]

Improvement of ideal versus poor examples:

“I think the presentation of the contents with good and bad examples is not bad; what can actually be improved is the informative value of the examples.”[108]

Transparency about the scope of design guidelines:

“It is not always clear how appropriate a design guideline is for my situation. Especially when the result is a search hit in 20 documents. I have to read every single one; somewhere in the text, it may say whether this guideline is suitable for my material or production process.”[109]

4.2.6 Requirements for the searching and providing design guidelines

The following requirements regarding the tool for the searching and providing design guidelines are based on Butenko, Wilwer et al. (2018):

Easy to find necessary information without extensive searching:

“Structure with material systems (SMC, LMT, BMC, [...]) at the beginning, because the material is mostly specified by the customer, then, allow the selection of whether it is a visible area or not a visible area, of which reinforcement elements are in focus – ribs, beads et cetera then of relevant objectives and relevant design guidelines as a result.”[110]

Access independent of location:

“At the customer's location, it should be possible to quickly find relevant design guidelines and to check the feasibility of certain ideas at an early stage.”[111]

Central control and monitoring:

“Central monitoring and management, otherwise everything becomes relatively confusing. The entries must be continuously checked for quality.”[112]

Information according to the user’s experience:

“This is a more nice-to-have requirement, but it would be advantageous if some intelligence could be guaranteed by providing search results. The beginner needs

[107] Statement of one participant in the interview study
[108] Statement of one participant in the interview study
[109] Statement of one participant in the interview study
[110] Statement of one participant in the interview study
[111] Statement of one participant in the interview study
[112] Statement of one participant in the interview study

different details than the more advanced user to apply the information. The more advanced user does not need a general introduction to the topic – he needs specific examples; the more the better."[113]

Intuitive operation:

"The more complex the operating of a system, the less the willingness to use it. Don't make things unnecessarily complex."[114]

Easy to update with little effort:

"Everyone must be able to update old information or enter new data; otherwise the acceptance among users decreases."[115]

4.3 Quantitative study – Methodological approach

The results of the interview study served as a basis for the development of the online questionnaire. The aim of the questionnaire is to confirm and expand the information gained in the interview study by including a larger number of participants and to provide answers to the following two research questions:

Research question I:

How do industry representatives assess the practicability of the published design guidelines for FRPs?

Research question II:

What information must be included in the design guidelines for FRPs in order to support the design process from the industry's point of view?

The approach used in the quantitative study and its relation to the qualitative study are presented in Figure 52.

The first draft of the survey was created in the framework of the co-supervised bachelor thesis[116] and implemented with the freeware LimeSurvey software.[117] LimeSurvey enables the easy and fast creation of online questionnaires with the advantages of the possibility to create flexible structures with "if → then" operations, the ability to export

[113] Statement of one participant in the interview study

[114] Statement of one participant in the interview study

[115] Statement of one participant in the interview study

[116] Wilwer 2016, (co-supervised bachelor thesis) – in the framework of the thesis, first draft of basic questions and structure was created

[117] The revision and extension of the survey took place as part of this dissertation. All members of the IRTG project were actively involved in the validation of the questionnaire and contributed to the success of the survey.

the collected data directly to the suitable format for further evaluations, location-independent execution and no accruing costs.

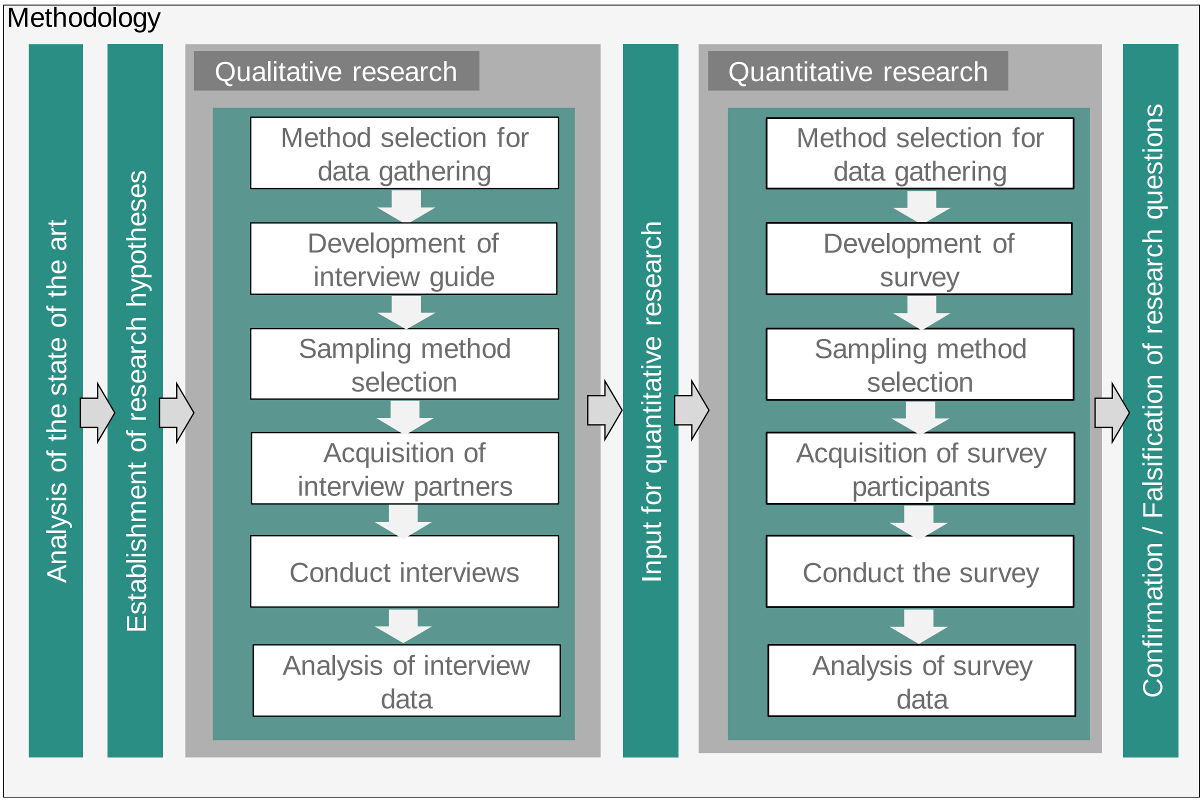


Figure 52: Qualitative and quantitative research – methodological approach

The questionnaire was designed interactively using “if → then” operations and consisted of both fixed questions that were always displayed and questions that were asked according to the answers given. In this way, the questionnaire was optimally adapted to the different study participants, which also reduced the probability of the study being discontinued prematurely due to irrelevant questions. However, the effort involved in the design of the study increased, since all possibilities had to be carefully thought through. The question design was chosen from general to specific, as information on general questions influenced the order of the questions provided. The survey started with the collection of participant-related information, including questions regarding industrial field, years of experience in dealing with FRPs, experience with certain material technologies, PEP activities in which the person is active in his or her current tasks and application/non-application of design guidelines and the reasons for this. The answers to these questions were formulated as single-choice and multiple-choice formats with prepared answer options. In addition, an "other" field was also provided as a free text format if the listed answer categories were not suitable. The reason these general questions were included to begin the survey was that the information collected enabled the analysis of the requirements for design guidelines collected in the specific part of the questionnaire. If the participants withdrew prematurely from the survey without entering those data, then it would have been difficult to analyze why certain contents are necessary in design guidelines. The structure of the first part of the survey is presented in Figure 53, with the subject areas highlighted in dark green and the examples of possible answer options in gray. White represents the categories with the free text answers.

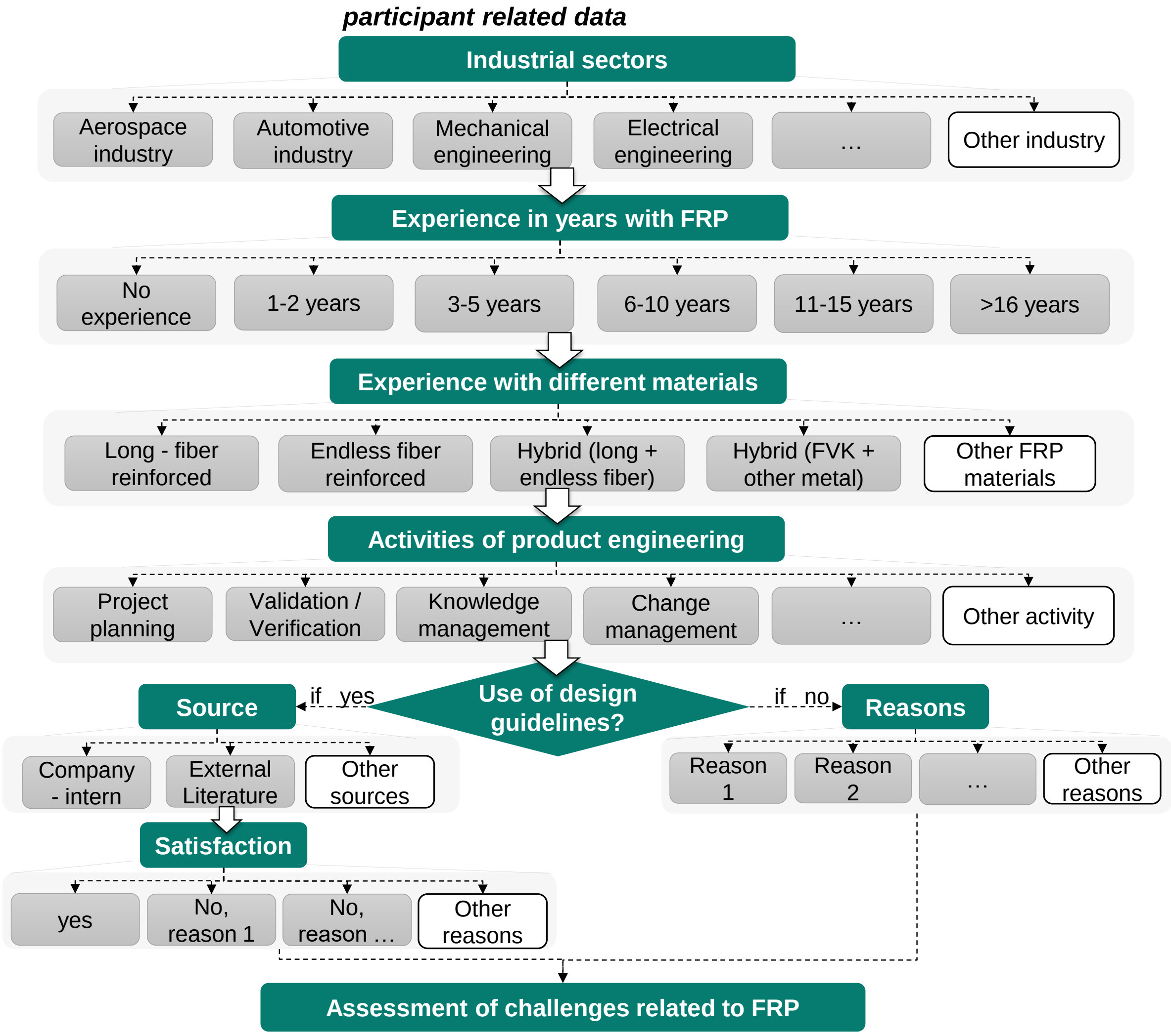


Figure 53: Structure of the first part of the survey[118]

After the general questions, specific questions were asked regarding the challenges related to embodiment design. All the challenging topics that emerged from the interview study were sorted into a number of clusters that summarized related topics. Each cluster always contained a main term and the related descriptive topics. These additional topics are referred to as "challenging characteristics" and clusters as "challenges." The challenges raised in the qualitative study are listed, and participants

[118] Author's own representation based on Wilwer 2016, pp. 84-88 (co-supervised bachelor thesis). The first draft of basic questions and structure was created in the framework of the bachelor thesis. The survey was revised and extended as part of this dissertation.

must assign them to the one of the four provided categories based on their situations and experiences.

These four categories are the following:

- The challenge is strongly relevant
- The challenge is moderately strong in relevance
- The challenge is of little relevance
- The challenge is not relevant.

Each category of relevance is clearly defined and described in the legend so that every participant shared a common understanding and could make an objective evaluation.

Moreover, an if-then operation is defined after each value assignment characteristic. If a challenge was selected as strongly relevant, then the next characteristics that describe the challenge were displayed. Each challenge has between three and eight describing characteristics listed as multiple-choice options, as visualized in Figure 54.

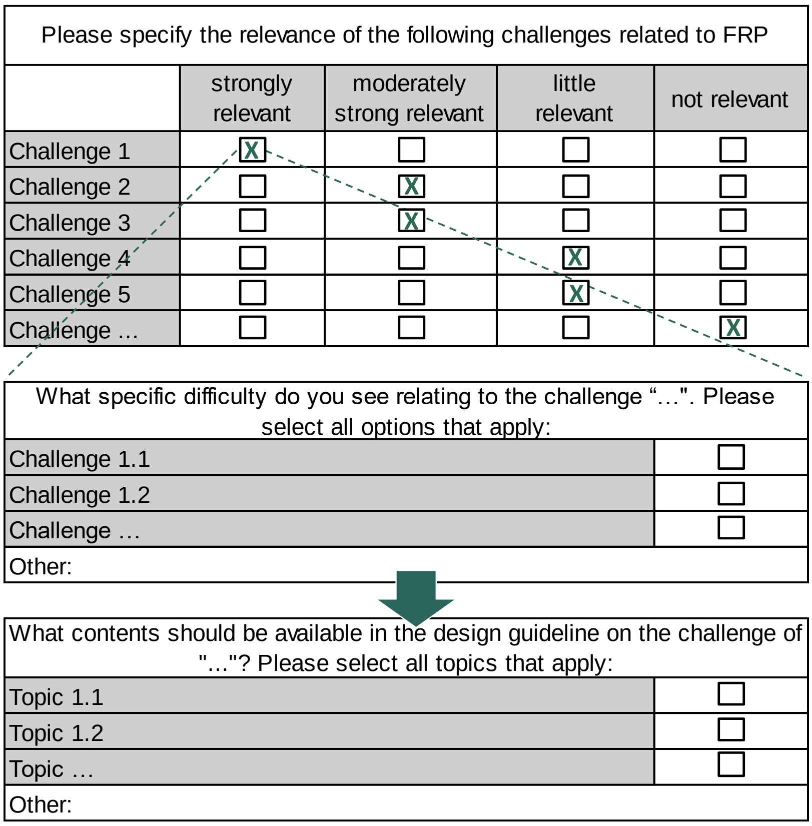


Figure 54: An example for the structure of the questionnaire

If participants assessed the challenges as lower than strongly relevant, then no further describing characteristics of the challenge were displayed. This was necessary to keep the processing of the survey at a reasonable level. The pre-test showed that 80% of participants rated between 7 and 10 challenges as highly relevant and moderately relevant. The questionnaire therefore took between 40 and 60 minutes. In order to reduce the likelihood that the survey would be terminated prematurely due to the effort and time required to process all questions, it was decided that additional questions would be asked only about the challenges and desired content in the assessments with the highest relevance.

Depending on the area from which a participant comes, either all or part of the characteristics can be relevant to him or her. This specification and the understanding of possible differences between the relevant properties of challenges are important for the development of design guidelines on the one hand and to verify the correct understanding associated with the collected challenges on the other. The answer option "other" can also be selected, so that further relevant characteristics from the participant’s point of view can be suggested. In the next step, the required topics in the design guideline are to be selected in relation to the specified challenge. If a challenge is assessed as having moderately, little or no relevance, then no further questions are displayed with regard to this challenge. Figure 55 presents an example of the statements converted from the interviews into a closed format.

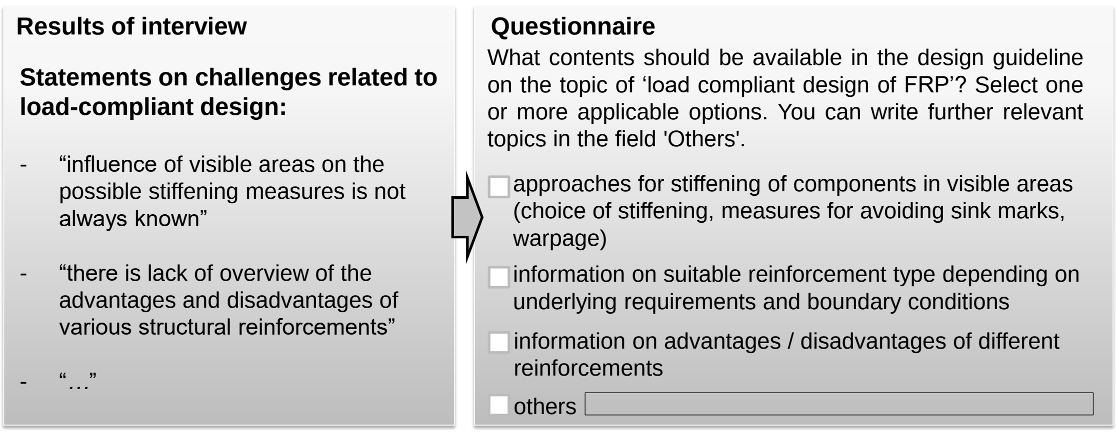


Figure 55: Using the interview results to develop a questionnaire with multiple-choice selection options

After all questions regarding challenges and required content were answered, the survey ended with four final questions about the following:

- The need for cost estimation
- An assessment of the need for interactive provision of information in design guidelines
- The size of the company
- Other comments and suggestions on the subject of design guidelines for FRPs.

These questions were asked at the end because if the study were to be abandoned prematurely, answers to these questions have no significant influence on the analysis of the most important results.

The question regarding cost support was formulated because two participants in the interview study mentioned these points as “nice to have.” The aim was to evaluate this need by increasing the number of participants and, if the need was confirmed, to promote the topic as an area for future development. The question about the size of the company belongs to the category of general information. This information may be relevant in the analysis of the results but is much less in comparison to the other person-related questions at the beginning of the survey. The second part of the survey is displayed in Figure 56.

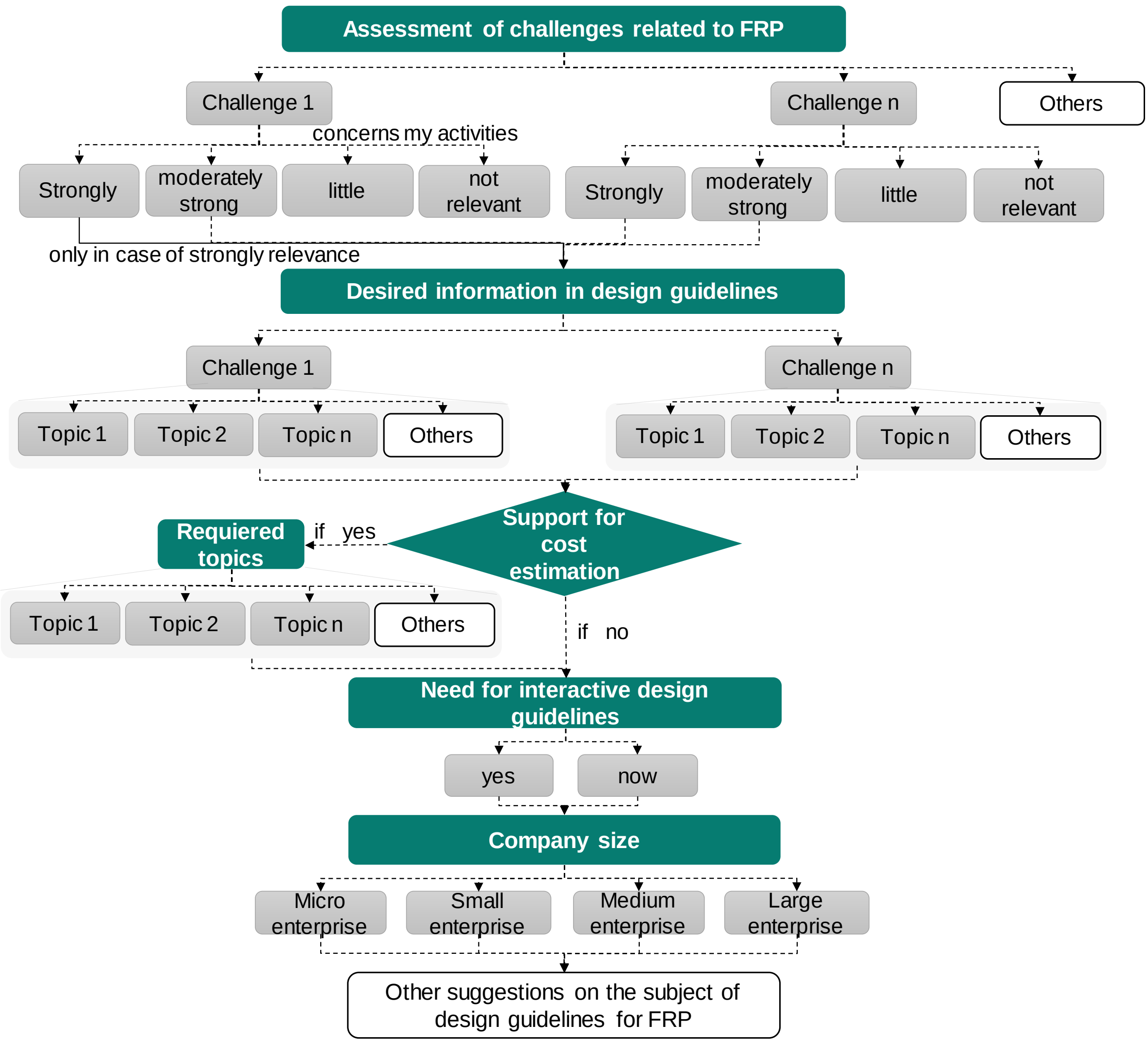


Figure 56: Second part of the survey[119]

The validation of the questionnaire with regard to the structure, quality and understanding of questions received a great deal of attention. All these points were validated in advance by IRTG members within the framework of two pre-test studies.

119 Author’s own representation based on Wilwer 2016, pp. 84-88 (co-supervised bachelor thesis). The first draft of basic questions and structure was created in the framework of the bachelor thesis. The survey was revised and extended as part of this dissertation.

Based on pre-test results, the order of some questions was changed, and more precise definition of questions was achieved.

The participant characteristics relevant to this study are similar to those described in the interview study. The potential questionnaire partners were acquired through the Xing and LinkedIn social business networks, through inquiries at exhibitions and through various associations such as the following:

- Carbon Composites e.V. (CCeV)
- VDMI Hybrid Lightweight Technologies
- Industrial Association fiber reinforced components (AVK)
- CFK Valley Stade e.V.
- Lightweight BW.

These associations represent the important target group for the survey, and they are among the most important players in the field of FRPs and lightweight technologies. The link to the survey with a necessary introduction was sent to the study participants by e-mail.

4.3.1 Main results – Participants

A total of 57 participants participated in the study. Most of them had between 3 and 5 years (30%) and between 11 and 15 years (25%) of experience in the field of FRPs. Furthermore, 19% of participants had 6–10 years and 18% had 1–2 years of experience. Only two participants, or 3.5%, indicated that they had no experience, and three participants (5%) had more than 20 years of experience. The participants in the survey have different levels of experience, which allows for the determination of requirements for the design guidelines from different perspectives. Figure 57 visualizes the number of participants and their experience.

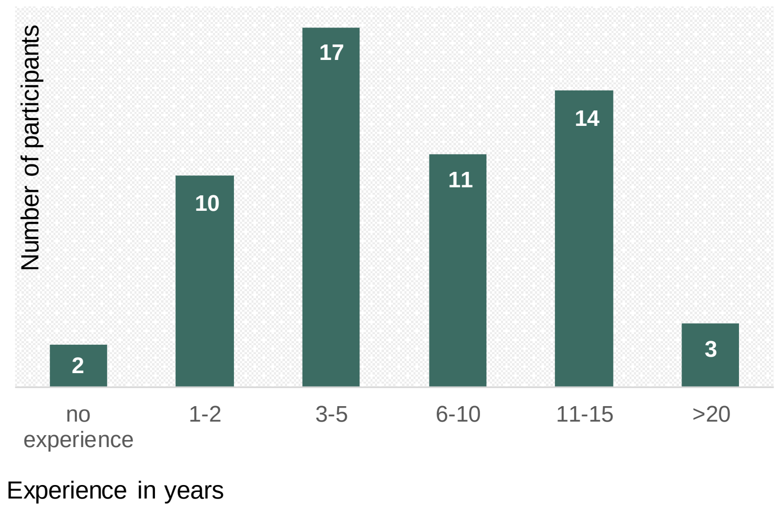


Figure 57: Experience and number of study participants

The study participants were from various industries, as depicted in Figure 58. Of the 57 participants, 21 were employed in the automotive industry, 15 in the aircraft industry, 8 in mechanical engineering, 3 in construction and the remaining 7 in other industries (such as materials supplier, shipbuilding or wind power). (Butenko, Wilwer, et al., 2018, p. 76)

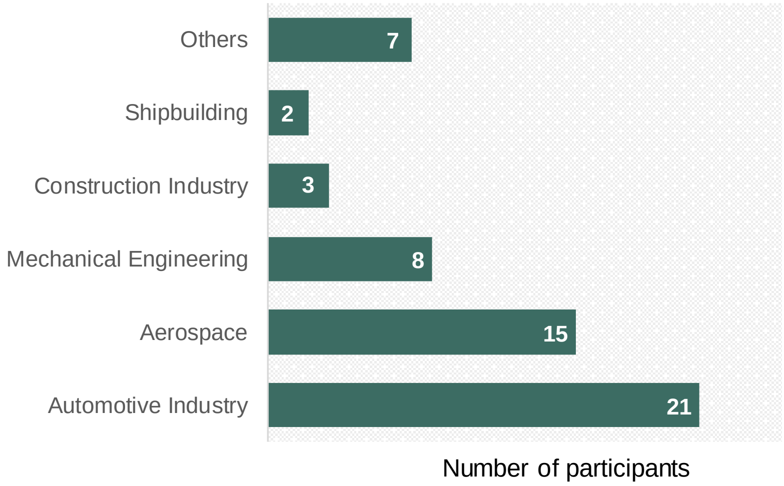


Figure 58: Industrial sectors of study participants

The majority of participants stated that they are employed in large companies. One-third of the participants indicated that they are employed in medium-sized enterprises, and the smallest part said that they are employed in small and micro enterprises. The distribution is visualized in Figure 59. To enable a clear assignment to a certain type of enterprise, all participants provided a clear description based on the definition of the Commission of the European Communities (2003).[120]

[120] According to Commission of the European Communities: micro enterprise: fewer than 10 persons employed; small enterprise: 10-49 employed persons; medium-sized enterprise: 50-249 employed persons; large enterprise: more than 250 employed persons.

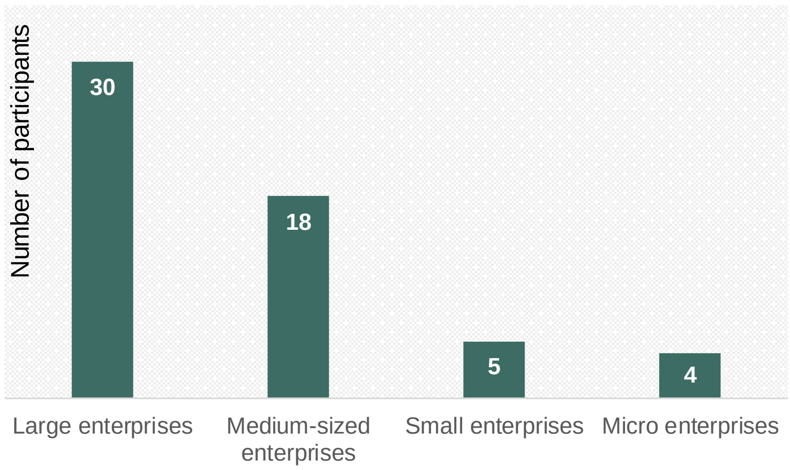


Figure 59: Company size of the employed participants

In addition to the size of the company, questions were also asked about the activity fields of the participants. A distinction was made among different categories, which are listed below with a brief definition.

Research and development	You are involved in the development of new approaches and ideas, and the planning, implementation, interpretation, calculation and testing of various research and development topics.
Planning	Part of your task is to clarify the requirements, the objectives, the product functions, the resources and the data required for a project. You take care of a product from the idea to the commissioning.
Design	You are involved in the creation of mechanical structures, design calculations, design drawings and CAD designs and their analysis, planning, implementation, control and documentation.
Validation / verification	You carry out calculations and simulations for technical-physical systems, evaluate real systems and optimize developments based on the data obtained.
Production	You are responsible for production processes, their planning, optimization and order execution. You care for products and ensure their quality.
Market launch	You are responsible for the market introduction of products.

As displayed in Figure 60, 39 participants stated that they are active in the field of research and development, five each in design and production and one in verification /validation. Two participants did not select any option and five indicated that they are active in other fields.

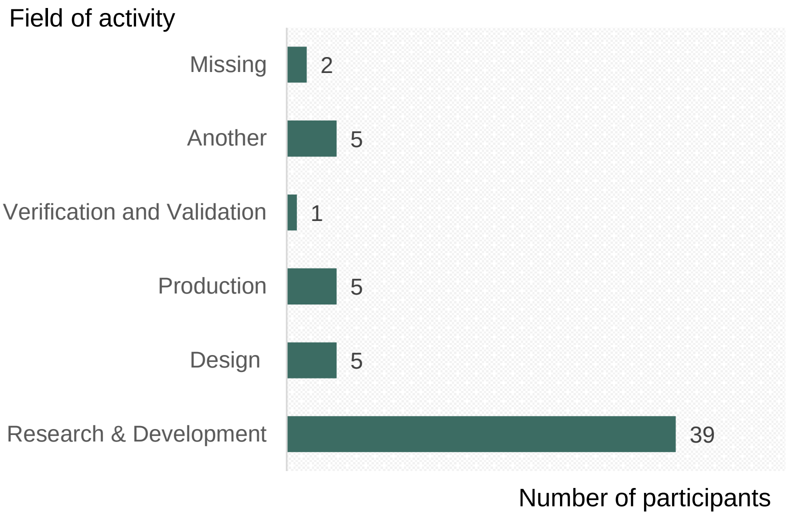


Figure 60: Field of activity of participants

4.3.2 Main results – Use of design guidelines

Of the 57 study participants, 24 stated that they do not use design guidelines in their daily work. Their reasons were, either their respective fields of activity or their dissatisfaction with the design guidelines themselves. Thirteen stated that they work in research and are therefore ahead of the state of the art. Another 13 indicated that no design guidelines are available for their specialization area, and nine claimed that design guidelines are usually not suitable for their application cases. The remaining statements for the non-use of design guidelines refer to unclear contents, a lack of detail in contents and the long time required to conduct an information search. (Butenko, Wilwer, et al., 2018)

Table 6 lists the number of entries and the percentage distribution related to the different reasons for not using design guidelines. A multiple selection of the listed answer options for not using design guidelines was possible, and the number of entries is therefore higher than the number of participants involved in this question.

Table 6: Reasons for not using design guidelines for FRPs – based on (Butenko, Wilwer, et al., 2018)

I do not use any design guidelines because ….	Number of entries	in %
… I am above the state of the art	13	28%
… there are no design guidelines for my area of specialization	13	28%
… design guidelines are usually not suitable for the application	9	20%
… design guidelines are not detailed enough	4	9%
… design guidelines are confusing	4	9%
… searching for appropriate design guidelines is time consuming	3	6%
Total	46	100%

Thirty-three participants indicated that they use design guidelines in their daily work. Apart from two participants, the rest (31) confirmed that the guidelines used also have some disadvantages. The majority (20) indicated that the design guidelines are only partly suitable for a specific application case. About half of the participants (16) noted that design guidelines are not detailed enough. Thirteen participants indicated that design guidelines are confusing and do not correspond to the current state of the art. Approximately one-third of the participants (9) stated that searching for appropriate design guidelines is too time consuming. (Butenko, Wilwer, et al., 2018)

Table 7 lists the number of entries and their percentage distribution regarding different disadvantages. A multiple selection of the listed causes was also possible when answering this question.

Table 7: Disadvantages of design guidelines for FRPs – based on (Butenko, Wilwer, et al., 2018)

The design guidelines I use have the following disadvantages:	Number of entries	in %
… design guidelines are usually only partly suitable for the application case	20	27%
… design guidelines are not detailed enough	16	22%
… design guidelines are confusing	13	18%
… design guidelines are not state of the art	13	18%
… searching for appropriate design guidelines is time consuming	9	12%
… I am satisfied with design guidelines I use	2	3%
Total	73	100%

4.3.3 Main results – Confirmation of the challenges from the interview study

The results of the survey indicate that the challenging topics mentioned in the interviews were confirmed and supplemented by the study participants, as presented in Figure 61 with percentage distribution in relation to the challenges assessed by the study participants.

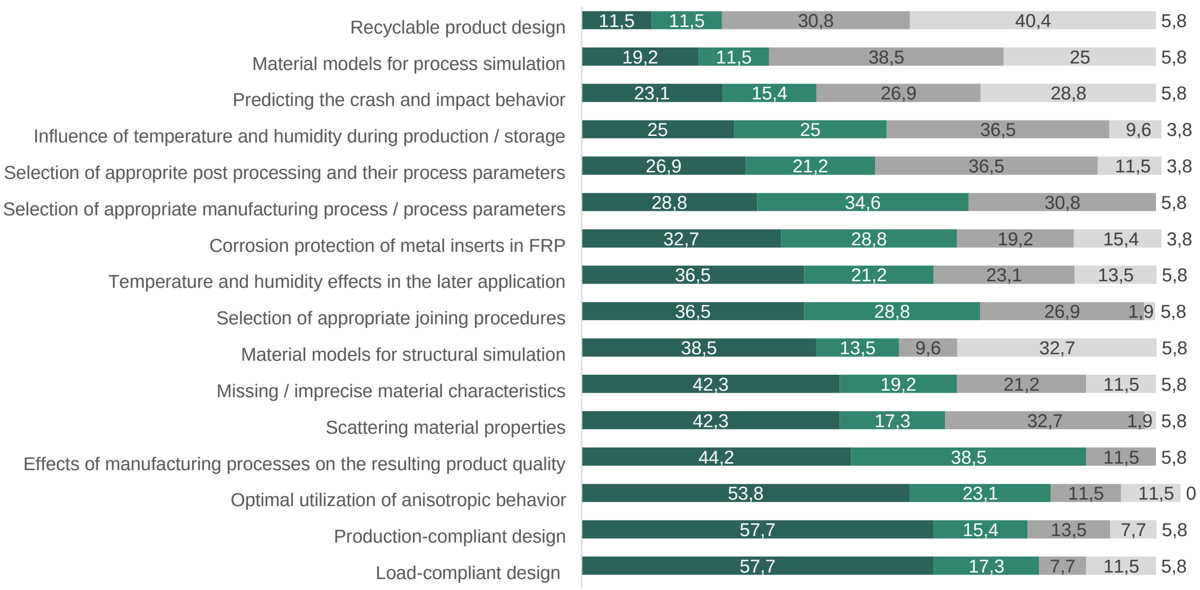


Figure 61: Assessing the relevance of different challenges from the participant side

The following were selected as the most important challenges: a load-compliant design, a production-compliant design and the optimal utilization of anisotropic behavior. Slightly fewer participants selected challenges such as recyclable product design and material models for process simulation. This may be due to the fact that these topics are relevant to fewer of the participants involved in the study. The dark green color represents the proportion with the highest relevance, while light green indicates moderate relevance, dark grey points to little relevance and light grey signals no relevance. White represents the proportion of missing answers, which is quite small.

In the following, the detailed assessments for each challenge and necessary support or content in design guidelines are presented in detail, and the results are visualized in tabular form. The evaluation is structured as follows: The column "number of entries" lists the number of times that participants indicated the characteristic of a challenge to be "strongly relevant.” The column "importance in %" represents the percentage share of each challenge characteristic with regard to the total number of entries per challenge.

The evaluation result of the challenge “scattering material properties” is presented in Table 8. This challenge was assessed by 22 participants as at least strongly relevant. On the left side are three descriptive characteristics for this challenge:

- Missing approaches for predicting the scattering of material properties
- Missing approaches for the prediction/consideration of the scattering in the behavior of components

- Incomplete exploitation of lightweight construction potential.

Grey indicates an additional characteristic of the challenge that a participant mentioned in the survey.

Table 8: Assessment of the challenge “scattering material properties”

Scattering material properties **22** valuations with assessments "strongly relevant" **Challenges**	Number of entries	Importance in %	**Desired contents / support**	Number of entries	Importance in %
Missing approaches for predicting the scattering of material properties	17	77%	Information about methods for the component behavior on the basis of the scatter in the material behavior	17	77%
Missing approaches for prediction / consideration of the scattering in the behavior of components	15	68%	Information about methods for determining the scatter in the materials properties	16	73%
Incomplete exploitation of lightweight construction potential	15	68%	Effects on production	1	
Scattering properties also relevant in production ("robust processes" necessary)	1				

Of the 22 participants, 17 specified the first characteristic as relevant, 15 the second one and 15 the third one. Therefore, 77%, 68% and 68% are the respective values that represent the importance in relation to the total nominal value for this overall challenge (22 valuations). Some participants selected all three characteristics of the challenge, some only one or two of them. Two participants out of 22 did not select any characteristic at all and did not add any further topics. One participant indicated a further descriptive characteristic of the challenge, such as “robust manufacturing processes” on the grounds that scattering material properties also are relevant in production. The column on the right lists the required contents or support. Either both options or only one was selected. Only one participant of the 22 made no selection. The additional topic "effects on production" was suggested by one participant.

The same number of participants (22) also rated the challenge of “missing/imprecise material characteristics” as strongly relevant. One out of 22 participants did not select any of the provided characteristics, but instead added another topic that was potentially important for his or her particular area of work. The remaining 21 participants selected at least one or both provided characteristics of the challenge. Several additional suggestions arose from the study participants, as presented in Table 9.

Table 9: Assessment of the challenge “missing/imprecise material characteristics”

Missing / imprecise material characteristics **22** valuations with assessments "strongly relevant" **Challenges**	Number of entries	Importance in %	**Desired contents / support**	Number of entries	Importance in %
Lack of knowledge about suitable innovative test methods for material characterization	18	82%	Recommendation of suitable test methods for material characterization	20	91%
Choice of safety factors not clear	17	77%	Recommendations for selection of suffient safety factor	14	47%
Data not known	1		Recommendation for dimensioning	1	
Failure mechanisms may not be assessable	1				
Direction of influence unknown (multiparameter study)	1				
Expenditure for characterization	1				
Estimation of missing material characteristics	1				

Although the challenge relating to “anisotropic behavior” was rated as highly relevant by 29 participants, a relatively low number of challenging characteristics and required content was selected. In comparison with all other assessed topics, this valuation appeared questionable, and possible reasons were therefore analyzed in more detail, resulting in the identification of two influencing factors. First, compared to the structure of the other questions on challenges, additional "if-then" operations were used. This decision was made based on the fact that in the interview study, the descriptive characteristics of the challenge associated with the topic of anisotropic behavior were different and strongly influenced by the respective activity of the participants. In addition, the IRTG project, there were different assessments from the perspective of specialists in the field of material characterization, manufacturing, simulation or design. Therefore, the decision was made to provide distinctive questions relating to this challenge for participants involved in manufacturing, design, simulation or research and development using the if-then operation. This means that the participant working in the manufacturing area had received different sub-items on the challenge of anisotropic behavior compared to the participant who was working for example in the verification/validation area. However, 68% of the participants in the study were active in research and development relatively broadly defined area, which may have resulted in the fact that the participants did not always indicate the content relevant to them. This assumption is also supported by the additional information about certain engineering activities of the participants which were raised at the end of the questionnaire. Out of 39 participants active in research and development, 22 rated the challenge "anisotropic behavior" as strongly relevant. Of these 22 persons, 15 indicated that they are active in the engineering activity of "model principle solution and embodiment" and 14 in the engineering activity of “detect ideas.”[121] For these participants, questions related to the associated challenges with anisotropic behavior in design activities might have been more relevant than questions provided relating to research challenges. This could explain why 13 of 15 participants involved in the activity “model principle solution and embodiment” did not select any of the options provided. Table 10 summarizes results of the assessing the challenge “anisotropic behavior of material” over all provided questions. The distinction in questions depending on field of activities can be found in Annex B. Figure 62 summarizes the background of participants, who selected the anisotropic behavior as a strongly relevant challenging topic.

Table 10: Assessment of the challenge “anisotropic behavior of material”

Anisotropic behavior of material (29) **29** valuations with assessments "strongly relevant" **Challenges**	Number of entries	Importance in %	**Desired contents / support**	Number of entries	Importance in %
Missing or inadequate material models	6	20%	Information about the influence of production parameters on the component properties	5%	17
Insufficient knowledge about the production-induced fiber orientations and their influence on the component	4	14%	Provision of material models	5%	17
Powerful computer-assisted methods for structural optimization with consideration of manufacturing-relevant restrictions	4	14%	Methods for prediction of component behavior based on scatterings in material behavior	3%	10
Missing / inaccurate material characteristics	3	10%	Provision of material characteristics	3%	10
Scattering material properties	2	7%	Approaches to the consideration of process-dependent fiber orientations directly in the simulation	3%	10
Uneven shrinkage / warping of the component	2	7%	Information on degradation of mechanical properties over time under external influences	1	
Uncertainties about process parameters for optimum component properties	2	7%			
Uncertainties about process parameters by the post-processing	2	7%			
Influence of environmental on material properties	1				

[121] According to iPeM engineering activities

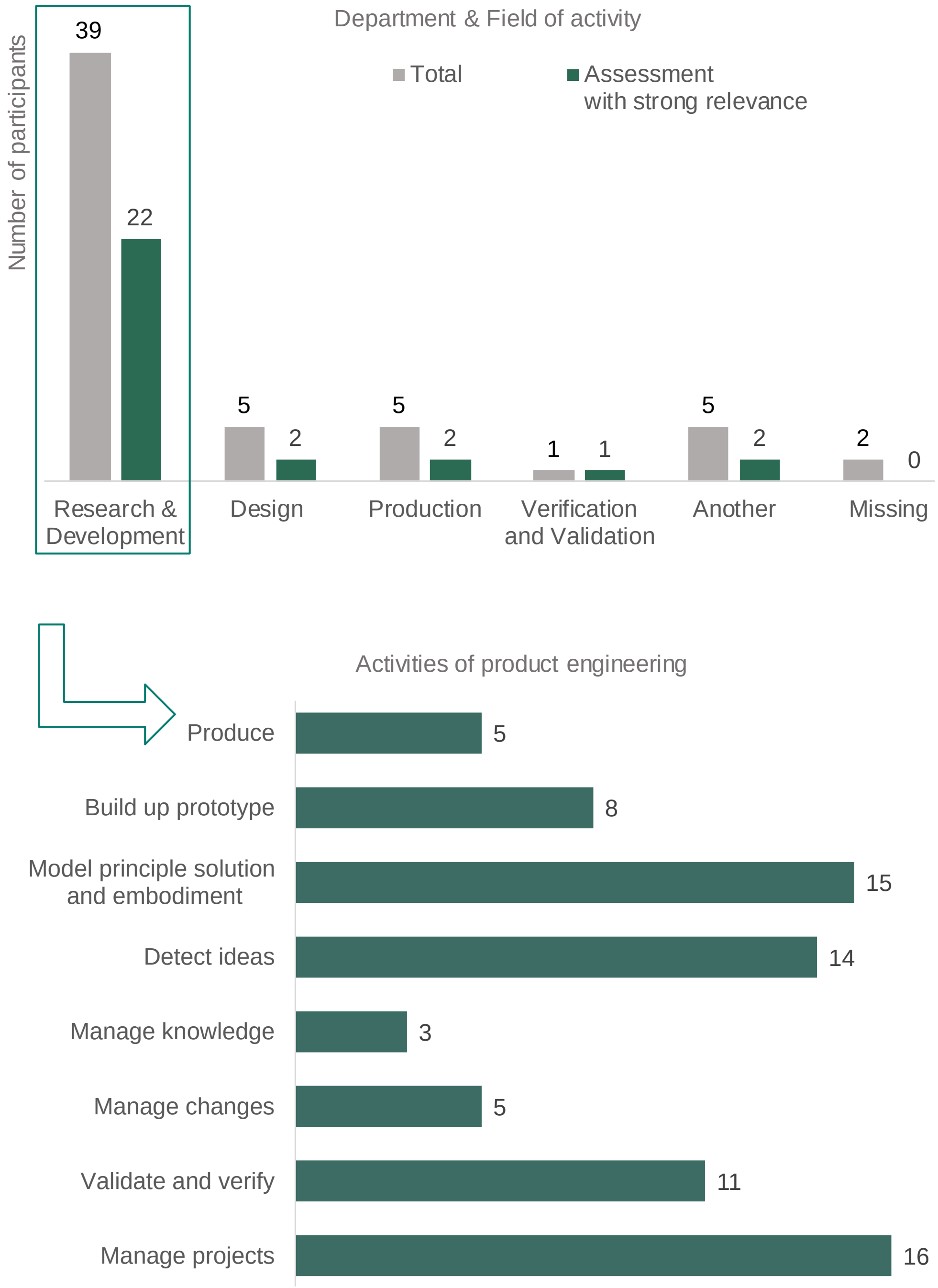


Figure 62: Background of participants from research and development who assessed "anisotropic behavior" as a strongly relevant challenge

Altogether, 10 of 57 of the study participants chose the challenge "material models for process simulation" as one with strong relevance. This comparable lower number can be explained by the fact that fewer participants from the field of process simulation were represented in the study. Furthermore, the topic of design guidelines and process simulation does not fit together directly. Support in the form of guidance, best practices and material database rather than design guidelines would be more conceivable here. Nevertheless, all four characteristics of this challenge were confirmed. Support in the form of the provision of necessary material parameters was approved by all 10 participants, as presented in Table 11. All 10 persons selected at least one of the provided challenging characteristics; in most cases between three and four options were selected.

Table 11: Assessment of the challenge “material models for process simulation”

Material models for process simulation **10** valuations with assessments "strongly relevant" **Challenges**	Number of entries	Importance in %	**Desired contents / support**	Number of entries	Importance in %
Missing / inaccurate material properties (matrix, fiber)	9	90%	Provision of necessary material characteristics	10	100%
Missing / inaccurate models for the simulation of curing and warpage	7	70%	Approaches for determining the drape strategy	8	80%
Missing / inaccurate models for the simulation of the extrusion process	6	60%	Approaches for determining the demoulding strategy after production	8	80%
Missing / inaccurate models for the simulation of the drape process	6	60%	Approaches for determining the insertion position under consideration of process boundary conditions	7	70%
Combination of different simulations + transfer to structural simulation / interface between simulation and production	1		Approaches for determining the process boundary conditions in mold filling process	6	60%

Twice as many of the study participants assigned the priority to the challenge “material models for structure simulation.” It is remarkable that four additional characteristics of this challenge were specified, as can be recognized in Table 12.

Table 12: Assessment of the challenge “material models for structure simulation”

Material models for structure simulation **20** valuations with assessments "strongly relevant" **Challenges**	Number of entries	Importance in %	**Desired contents / support**	Number of entries	Importance in %
Missing / inaccurate material characteristics	18	90%	Provision of material properties for fiber materials, matrix materials and typical composite materials	18	90%
Results of the process simulation do not correspond to reality	12	60%	Information about methods to consider process-dependent fiber orientation directly during the simulation	16	80%
Missing of material models	10	50%	Listing of material models that describe deformation and failure behavior	13	65%
Choosing the right material model is difficult	9	45%	Recommendations for selecting the appropriate material model	13	65%
Missing approaches in modeling and postprocessing	1				
Long-term influences: relaxation, prestressing losses, aging (especially of the matrix material), interactions with other materials (hybrid construction, corrosion).	1				
Structural response of the surrounding assemblies unknown, missing material models for hydroacoustic loads	1				
Often missing validation of the calculation by suitable structural tests	1				

The characteristic "missing/inaccurate material characteristics" was highlighted by most of participants, as well as the topic for desired support: “providing of material properties for fiber materials, matrix material and typical composite materials.” As with the previous topic, support in the form of guidance, best practices and material database rather than design guidelines would be more conceivable for the listed characteristics of this challenge. Out of all participants, only one selected none of the provided options, instead referring to an additional topic.

Twelve participants assessed the challenge “predicting crash and impact behavior” as strongly relevant, as seen in Table 13. Because this subject is relatively similar to the previous one, only questions on challenging characteristics were provided.

Table 13: Assessment of the challenge “predicting crash and impact behavior”

Predicting crash and impact behavior **12** valuations with assessments "strongly relevant"	Number of entries	Importance in %	**Addional characteristics**		
Challenges			**Challenges**		
Lack of damage model	83%		Simulation models are often very complex and to this day academic	1	
Lack of material models	67%		Material and damage models already exist, but they need to be extended	1	
Prediction of the deformation behavior is difficult	42%				

The challenge “load compliant design” is one of the two challenges most frequently chosen by the study participants and, with a total of 30 assessments, is well ahead in terms of relevance. All six of the characteristics provided with this challenge were confirmed with a rate between 33% and 60% with regard to the total number of entries per challenge, as can be obtained from Table 14. Out of 30 participants, four did not select any of the provided options for challenging characteristics, but instead indicating required content/support. In addition, 26 participants assessed between one and all six provided options for challenging characteristics with the range between 33% and 60% of relevance. All 30 participants selected between at least three and seven needed informative topics for design guidelines.

Table 14: Assessment of the challenge “load-compliant design”

Load-compliant design **30** valuations with assessments "strongly relevant" **Challenges**	Number of entries	Importance in %	**Desired contents / support**	Number of entries	Importance in %
Uncertainties in the design of force transmission areas	18	60%	Covering many load cases and the possibility of defining load cases in order to obtain a solution	22	73%
Unclear procedure for structural stiffening, such as position, geometry, number of ribs / beads depending on different load cases	17	57%	Recommendation for the detection of potential sources of damage	21	70%
Absence of efficient and reliable failure criteria	15	50%	Information about failure models with application recommendations and their advantages and disadvantages	20	67%
Local material properties are not known	14	47%	Proposed design solution for rib or bead (depending on loads and boundary conditions)	20	67%
Influence of the visible areas on the possible stiffening measures	10	33%	Approaches to reinforcements of parts in visible areas	19	63%
Lack of overview of advantages and disadvantages of different constructive reinforcements	10	33%	Information about advantages and disadvantages of different constructive reinforcements	18	60%
			Recommendations for damage progression calculation	13	43%

Table 15 visualizes the evaluation for the challenge "selection of appropriate joining procedures." Nineteen participants considered this challenge as highly relevant and confirmed all five characteristics with the range between 58% and 84%. The contents listed for design recommendations were also rated comparatively high, at over 84%. All 19 participants selected at least two of the provided characteristics of the challenge.

Table 15: Assessment of the challenge “selection of appropriate joining procedures”

Selection of appropriate joining procedures **19** valuations with assessments "strongly relevant" **Challenges**	Number of entries	Importance in %	**Desired contents / support**	Number of entries	Importance in %
Pretreatments (e.g. for gluing) must be considered	16	84%	Support in the selection of suitable join partners / fasteners	18	95%
Difficult dimensioning of the joining zones	15	79%	Advantages and disadvantages of different joining technologies	17	89%
Selection of the most suitable joining process not always clear	14	74%	Design instructions for joining zones	17	89%
Selection of suitable joining partners / connecting elements (galvanic corrosion, various thermal expansions) not always clear	13	68%	Description of any necessary pretreatments	16	84%
Preload losses due to different coefficients of thermal expansion cause problems	11	58%			
Environmental influences and durability, repair possibilities	1				
Creep behavior under preload	1				

The challenge related to the subject of "corrosion protection of metal inserts in FRP" was assessed as strongly relevant by 17 participants. All three specified characteristics of this challenge were evaluated with different significance between 65% and 82%. Assistance in the selection a suitable material combination to prevent corrosion, achieved the highest rating in terms of importance as desired information in design recommendations. Two further informative topics were suggested by study participants, as seen in Table 16.

Table 16: Assessment of the challenge "corrosion-resistant design"

Corrosion protection of metal inserts in FRP **17** valuations with assessments "strongly relevant" **Challenges**	Number of entries	Importance in %	**Desired contents / support**	Number of entries	Importance in %
Uncertainties in the selection of suitable material combinations	14	82%	Support in the selection of suitable material combinations	15	88%
Measures for corrosion protection of FRP components in joining zones are not always known	14	82%	Approaches for corrosion protection	14	82%
Consequences of possible corrosion are difficult to estimate	11	65%	Treatment of corrosion-inhibiting / corrosion-promoting factors	13	76%
			Information on the effects of corrosion	8	47%
			Information on long-term protection against unfavorable material pairing	1	
			Information on the effects of temperature and humidity on corrosion	1	

The challenge of "recyclable product design" was listed relatively briefly in the survey, as this topic was only mentioned in one interview. Nevertheless, this subject was considered as strongly relevant by seven participants, as seen in Table 17.

Table 17: Assessment of the challenge "recyclable product design"

Recyclable product design **7** valuations with assessments "strongly relevant" **Challenges**	Number of entries	Importance in %	**Challenges**	Number of entries	Importance in %
Procedure for recycling-compatible design unknown	5	71%	Deterioration of properties due to recycling	5	71%
Recycling is only possible to a limited extent when combining different materials	4	57%	Pure separation of the matrix material is complex	4	57%
Recovery and reuse of the fibers	3	43%			

"Production-compliant design" is the challenge second most frequently rated as strongly relevant, a designation made by 30 study participants. All three characteristics of this challenge and two topics as desired content in design guidelines were confirmed. As desired support, topics such as "recommendations for a suitable design type taking into account manufacturing requirements” scored most frequently, as seen in Table 18.

Table 18: Assessment of the challenge “production-compliant design”

Production-compliant design **30** valuations with assessments "strongly relevant" **Challenges**	Number of entries	Importance in %	**Desired contents / support**	Number of entries	Importance in %
Feasibility of certain construction types is not clear	20	66%	Recommendations for a suitable design type taking into account manufacturing requierements	25	83%
Manufacturing restrictions for geometric constrains not always known	20	66%	Proposed design for rib or bead depending on production restrictions	20	66%
Results of the process simulation do not correspond with reality	6	20%			
Strong restictions in automatic laying processes and forming behaviour of organic sheets	1				

The next challenge, designated as “effects of manufacturing processes on the resulting product quality,” also had a high relevance rating. Of 24 study participants, at least 14 confirmed all six aspects of the challenge. Most participants chose the subject “occurrence of defects in the component” as the most challenging aspect and “information on the influences of manufacturing effects on the component properties,” as desired content, as seen in Table 19. Of 24 participants, two did not select any of the provided challenging characteristics or desired content.

Table 19: Assessment of the challenge “effects of manufacturing processes on the resulting product quality”

Effects of manufacturing processes on the resulting product quality **24** valuations with assessments "strongly relevant" **Challenges**	Number of entries	Importance in %	**Desired contents / support**	Number of entries	Importance in %
Occurrence of defects in the component (e.g. pores, voides)	21	88%	Information on the influences of manufacturing effects on the component properties	18	75%
Reproducibility of component quality not always guaranteed	16	67%	Information about typical manufacturing effects and their causes	17	71%
Uneven fiber volume distribution	15	63%	Recommendations on suitable process boundary conditions for a given material system to avoid production effects	16	67%
Uneven fiber orientation distribution	14	58%	Information about suitable test methods for quality assurance	16	67%
High costs for quality assurance, many tests are necessary	14	58%	Information on the influence of process boundary conditions on the occurrence of manufacturing effects	15	63%
Insufficient form filling	9	38%	Information for manufacturing process control	1	
Chemical-thermal warpage	1				

Twenty study participants assessed the challenge “temperature and humidity effects in later applications” as important with high relevance. All six characteristics of this challenge and six topics of desired content were confirmed with varying degrees of importance, as seen in Table 20. Of 20 participants, one selected none of the provided challenging characteristics or desired content.

Table 20: Assessment of the challenge “temperature and humidity effects in later applications”

Temperature and humidity effects in the later applications **20** valuations with assessments "strongly relevant**"** **Challenges**	Number of entries	Importance in %	**Desired contents / support**	Number of entries	Importance in %
Influence on mechanical properties and strength values	16	80%	Information about creep and relaxation processes, maximum operating temperatures and maximum loads	18	90%
Creep and relaxation processes	15	75%	Calculation of thermal distortion / thermal residual stress	14	70%
Thermal distortion and residual thermal stresses	14	70%	Information on the influence of temperature on corrosion	11	55%
Influences on the corrosive behavior	11	55%	Approaches for a desired heat conduction	8	40%
Frost cracs caused by water deposits in pores/voids	9	45%	Calculation of mass increase by moisture absorption	7	35%
Increase in mass due to moisture absorption	9	45%	Information about influences of temperature on electrical conductivity	4	20%
Residual thermal stresses, especially in hybrid structures	1		Recommendation for fiber orientation of layers in multilayered unit for dimensional stability	1	
			Information on the degradation of mechanical properties over time	1	

The last challenge “selection of appropriate post-processing and their process parameters” was selected by 14 participants as strongly relevant. All listed challenges and necessary content for design recommendations were confirmed. The majority of the participants (86%) rated the subject “possible delamination.” Table 21 demonstrates all assessments.

Table 21: Assessment of the challenge “selection of appropriate post-processing and their process parameters”

Selection of appropriate post-processing and their process parameters **14** valuations with assessments "strongly relevant" **Challenges**	Number of entries	Importance in %	**Desired contents / support**	Number of entries	Importance in %
Possible delamination	12	86%	Approaches against delamination for different post-processing	11	79%
Uncertainties in the choice of suitable processes	9	64%	Information on advantages and disadvantages of different post-processing	11	79%
Uncertainties in the selection of suitable process variables (e.g. cutting speeds, drilling speeds)	9	64%	Recommendation for design of process zones	11	79%
Uncertainties regarding the coating (e.g. pretreatment, required surface quality)	8	57%	Recommendation for suitable post-processing strategies including process parameters	10	71%
Thermal influence on the component leads to local quality losses	8	57%	Information on surface pretreatment for coating	8	57%
Possible preparations for the suitability of cathodic dip painting coatings	1		Information on heat dissipation during machining	6	43%

As a result of the qualitative study, a total of 20 additional characteristics of the challenges and eight further topics for design guidelines were named for all challenges analyzed.

In addition to the 16 subjects defined for challenges, the study participants mentioned further topics, as listed in Table 22.

Table 22: Other challenges relating to product development with FRPs

	Others challenges
1	As a manufacturer of testing machines, we only deal with the destruction of the material to measure the material properties. Methods for predicting the expected scatter in the material properties are relevant for us.
2	Cost-effective design of components and manufacturing processes. Process reliability of manufacturing processes
3	Manufacturing process: The longevity of glass-fibre reinforced products depends to a large extent on the enclosed air volume. (Reference values for a "good" Lamimat for system pressure for VARI parts before the start of infusion would then be interesting)
4	Long-term influences on the technical properties
5	Vibration, Acoustics, Damping
6	Influence of the production process on the material parameters
7	Material combination - permanent protection in case of unfavourable material combination.
8	Connection technique
9	Possibilities of reworking in case of construction deviation, and repairs in case of damage.
10	Evaluation of defects (with high component value) such as: Porosity, delamination in the layer package, disbonding of core and layer package, deviation in fiber volume content, effect of leakage (workpiece vacuumed - overpressure in autoclave), differentiation (because process is so complex)
11	Process instability

These topics are not further examined in this work; however, they must be explored in more depth in future surveys to understand exactly what lies behind them.

Need to provide interactive design guidelines: When asked whether there is a need for the interactive provision of the situation-related design guidelines, the majority of the participants clearly answered "yes." Only 4% answered "no" to this question, and the remaining 23% did not provide any answer, as seen in Figure 63.

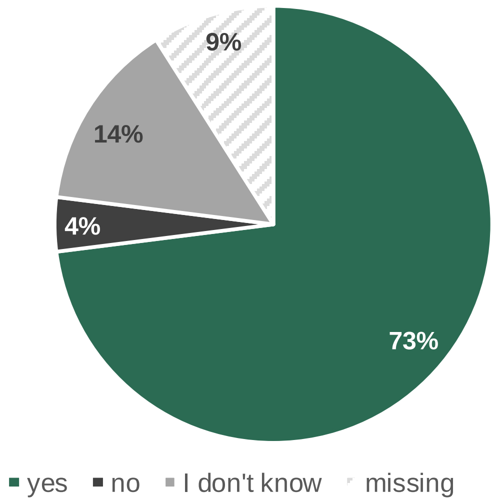


Figure 63: Need to provide interactive design guidelines

4.3.4 Main results – Pearson correlations between challenges

The Pearson correlation coefficient was calculated to investigate whether there are challenges with a positive or negative linear relationship and whether they have significant values. Values between -1 and +1 are possible, with a value of +1 indicating a completely positive linear relationship between the challenges under consideration and a value of -1 indicating a negative linear relationship. A positive correlation means that one variable rises if the other rises. (Boslaugh, 2014, pp. 173–191) This means that if one challenge is relevant, then the likelihood of the other challenge also being relevant increases. This information can be important both for the development of design guidelines and for the conception of their provision within the framework of a decision-support tool. The calculations were made with the help of the IBM SPSS tool; the main results are presented in Figure 64.

According to Cohen (1988), the average correlation exists from the value $r = 0.30$, and there is high correlation at the value $r => 0.50$. All correlation coefficients highlighted in dark green color have a high significant value between the challenges in the same row and column. Both light green colors indicate the average significant value. There is a high significance (0.668) between “load-compliant design” and “production-compliant design,” as well as between “load-compliant design” and “anisotropic behavior of material” (0.604). This means that if the study participants selected one of the challenges as relevant, then in most cases, the second challenge was also considered relevant. The statistic represents logical connections: If a product developer deals with the design of a component, then his or her responsibility is also to ensure the manufacturability of that product.

Another point of awareness is that some challenges have more significant correlations and others rather few. There are three challenges that have the maximum number (nine) of significant correlations with other topics, while many challenges have between five and seven significant relationships. However, there are also cases in which only one or no connection was recognized. It is interesting to note that “scattering material properties” has no discernible significant correlation with other challenges. A possible reason for this could be that study participants evaluated this topic differently in connection with other topics.

Pearson Correlation

Challenges	Scattering material properties	Missing / imprecise material characteristics	Selection of appropriate manufacturing process	Effects of manufacturing processes on the resulting product quality	Selection of appropriate post processing and their process parameters	Selection of appropriate joining procedures	Material models for structural simulations	Material models for process sim	Predicting crash and impact behavior	Anisotropic behavior of material	Temperature and humidity effects in the later application	Corrosion protection of metal inserts in FRP	Production-compliant design	Load-compliant design	Recyclable product design
Scattering material properties	1	0.191	0.053	0.25	-0.151	-0.18	0.111	0.015	0.214	0.281	0.07	-0.02	0.15	0.199	0.114
Missing / imprecise material characteristics	0.191	1	0.094	0.167	0.107	-0.029	0.288	0.31	0.233	0.364	0.227	0.386	0.106	0.136	0.337
Selection of appropriate manufacturing process	0.053	0.094	1	0.349	0.282	0.195	0.077	0.272	0.268	0.273	0.298	0.143	0.486	0.283	0.276
Effects of manufacturing processes on the resulting product quality	0.25	0.167	0.349	1	0.177	-0.054	0.093	0.315	0.161	0.308	0.041	0.192	0.407	0.426	-0.034
Selection of appropriate post processing and their process parameters	-0.151	0.107	0.282	0.177	1	0.466	0.23	0.211	0.108	-0.063	0.234	0.237	0.149	0.213	-0.135
Selection of appropriate joining procedures	-0.18	-0.029	0.195	-0.054	0.466	1	0.207	0.218	0.214	-0.084	0.27	0.075	-0.055	0.157	0.107
Material models for structural simulations	0.111	0.288	0.077	0.093	0.23	0.207	1	0.287	0.426	0.377	0.229	0.375	0.156	0.426	0.164
Material models for process simulation	0.015	0.316	0.272	0.315	0.211	0.218	0.287	1	0.488	0.493	0.415	0.314	0.141	0.289	0.549
Predicting crash and impact behavior	0.214	0.233	0.268	0.161	0.108	0.214	0.426	0.488	1	0.493	0.231	0.199	0.246	0.415	0.285
Anisotropic behavior of material	0.281	0.364	0.273	0.308	-0.063	-0.084	0.377	0.493	0.493	1	0.381	0.487	0.452	0.604	0.252
Temperature and humidity effects in the later application	0.07	0.227	0.298	0.041	0.234	0.27	0.229	0.415	0.231	0.381	1	0.373	0.286	0.353	0.283
Corrosion protection of metal inserts in FRP	-0.02	0.386	0.143	0.192	0.237	0.075	0.375	0.314	0.199	0.487	0.373	1	0.554	0.479	0.15
Production-compliant design	0.15	0.106	0.486	0.407	0.149	-0.055	0.156	0.141	0.246	0.452	0.286	0.554	1	0.668	-0.033
Load-compliant design	0.199	0.136	0.283	0.426	0.213	0.157	0.426	0.289	0.415	0.604	0.353	0.479	0.668	1	0.005
Recyclable product design	0.114	0.337	0.276	-0.034	-0.135	0.107	0.164	0.549	0.285	0.252	0.283	0.15	-0.033	0.005	1

Figure 64: Pearson correlation between challenges

4.3.5 Summary

The main aims of the qualitative and quantitative studies were to find out how the industry representatives assess the practicability of the available design guidelines for FRPs and what information should be included in the design guidelines in order to optimally support the design process.

The participants in the study considered the practicability of the published design guidelines for FRPs to be rather insufficient. This conclusion is based on participants' statements regarding the reasons for not using design guidelines and their current disadvantages, as presented in Table 23. The statements highlighted in grey relate directly to the disadvantages of the guidelines.

Table 23: Summary of statements regarding lack of use and disadvantages of design guidelines for FRPs

Summary of all statements	Number of entries	in %	Potential for improvement
… I am above the state of the art	13	11%	
… there are no design guidelines for my area of specialization	13	11%	
… searching for appropriate design guidelines is time consuming	12	10%	
… design guidelines are usually not suitable for the application	9	8%	67%
… design guidelines are usually only partly suitable for the application case	20	17%	
… design guidelines are not detailed enough	20	17%	
… design guidelines are confusing	17	14%	
… design guidelines are not state of the art	13	11%	
… I am satisfied with design guidelines I use	2	1%	
Total	119	100%	67%

It is important that the contents and topics of the design guidelines correspond to the needs of the industry representatives. The generalized and abstract information in the design guidelines is limited with respect to its transferability to real application cases. The generalized information has less added value, as what works with one material system or manufacturing process is not necessarily transferable to design with another material system.

"The properties change depending on the mix and on the manufacturing process, and people don't realize it. If you give the material to the supplier and say you want the same component with this layout, you will receive back two components, that look the same but have totally different properties."[122]

[122] Statement of one participant in the interview study

The results of the survey demonstrate that in addition to design recommendations on embodiment design, other general information is also required, referring to technical details with descriptions of the advantages and disadvantages of different technologies, methods or production processes. (Butenko, Wilwer, et al., 2018, p. 76) In early phases of product development, design engineers are concerned with various questions that involve a high level of effort in searching for relevant and approved information. For this reason, it is necessary and preferred to not only focus on design guidelines, but also to be able to provide them in a meaningful context with additional technical information. The Pearson correlation has underlined the great correlation between material, manufacturing and design issues. Their dependencies should be considered more closely in design guidelines and not separately from each other.

The results of the conducted studies revealed a need for 22 subject areas for design guidelines and 29 subject areas for technical information. The summary is set out in the Annex C in two tables. This is certainly not a complete overview of all the needs of the industry, and there are certainly more topics for design guidelines that were not mentioned in the interviews and questionnaire. These results nevertheless provide a solid basis from which to begin developing the decision support system and to meet a certain basic support need.

5 Further investigation and evaluation studies

Within the findings gained during the industry surveys, three further studies are concepted. The aim of the first study is to examine the different forms of information representation regarding their suitability for knowledge transfer. The second study deals with examining of design guidelines available in literature with regard to their applicability to the concrete design tasks. The aim of the third study is to investigate which methodological aids can support creating of design guidelines for FRPs. A distinction is made between aids needed to support data generation when creating design guidelines, and aids to support the formulation of essential information in design guidelines.

5.1 Investigation of different forms of information representation

The aim of the first study is to investigate different forms of information representation regarding their suitability for knowledge transfer within two case studies. This study was conducted in the framework of a co-supervised bachelor thesis[123] and published at the NordDesign Conference (Butenko, Gladysz, et al., 2018). Two research questions are in focus of the study.

> 1) Which form of information representation in design guidelines (text-based, text with a represention of ideal and poor solutions or text with C&C²-based representation of ideal and poor solutions) is best suited for knowledge transfer?

These three forms of visualization are analyzed with regard to the three criteria: efficiency of knowledge transfer, transfer of functional information and information density, as exemplified in Figure 65. The efficiency criterion stands for the quick understanding of the information in the provided documents. The “transfer of functional information” concerns clear presentation and transmission the interdependencies for the fulfillment of the function. The third criterion “information density” means the suitability assessment of information’s wealth for the solution of the underlying tasks in the created cases. (Butenko, Gladysz, et al., 2018)

The second research question is:

> 2) What are the differences between experienced and less experienced product developers in assessing the suitability of information for knowledge transfer?

[123] Maurath, 2018 (co-supervised bachelor thesis)

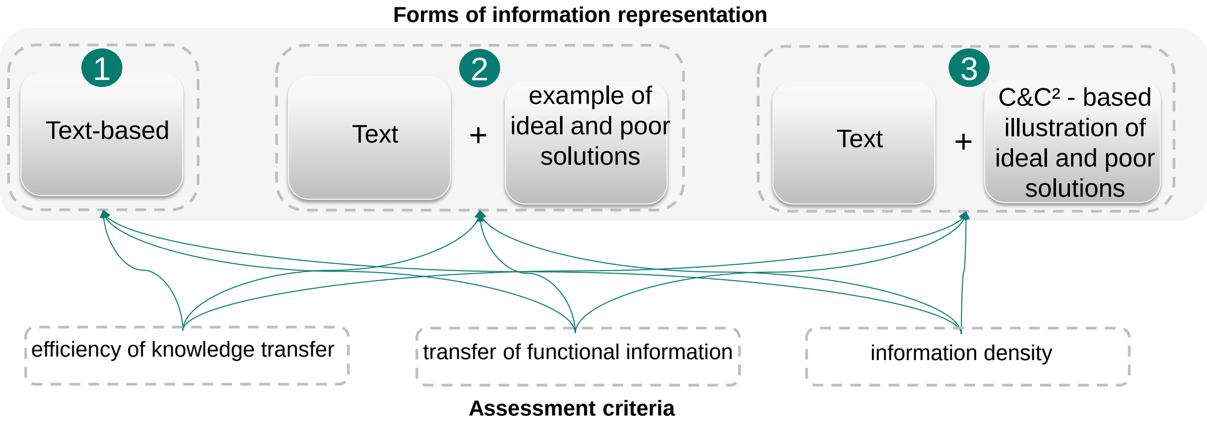


Figure 65: Investigated forms of information representation

Tasks consisting of a description of the initial situation and concrete questions were prepared. Regarding each task, corresponding recommendations in three different forms: text, text with a representation of an ideal and a poor embodiment design solution and C&C²-based representation of an ideal and a poor embodiment design solution were provided. Furthermore, a fully structured questionnaire was created to assess the suitability of the created recommendations with the focus on three ctiteria described above. The study participants had to compare and evaluate which of the three provided recommendations best met these three criteria. The study was conducted with 14 industry representatives, including both experienced and less experienced design engineers. First, the aim of the study, the procedure and the C&C²-Approach were briefly introduced to the study participants. After the briefing, the tasks were distributed to the participants together with the prepared recommendations. (Butenko, Gladysz, et al., 2018)

5.1.1 Task definition

In general, various case situations were created with tasks on different topics. In this thesis two examples of case situations are introduced hereafter. The first case is slightly more challenging compared to the second and deals with assembly of a pressure compensation element. The second case demonstrates an easy task where a suitable design for the casting tool should be selected. The tasks of varying complexity were purposely selected to examine differences in the assessment of introduced forms of information representation. The first task is exemplified in Figure 66.

Situation:
You work as a development engineer for a company that develops cooling blower motors for various OEMs. In the new product generation, a higher flow rate should be made possible due to the changed requirements. To meet the requirements, the decision was made to use a clip pressure compensation element.

Problem:
During installation, various types of faults occurred in the shorter time. You were commissioned to find possible causes and to gather clear instructions on how to avoid them.

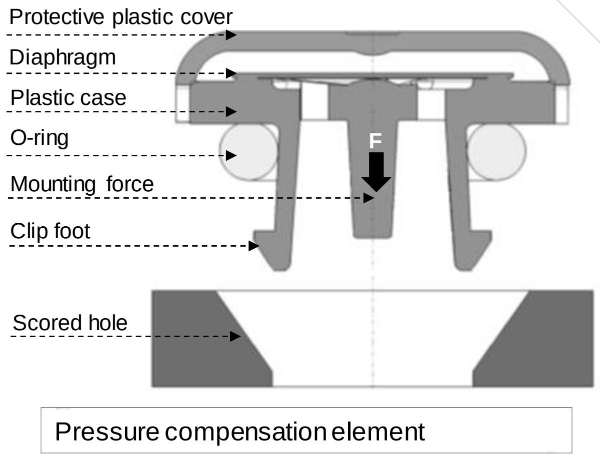


Figure 66: Example of the case study “assembly of a pressure compensation element”[124]

The example of the provided text−based recommendation is illustrated in Figure 67.

When mounting the pressure compensation element, a force is applied to the housing, which presses this element into a scored hole. The clip feet are elastically compressed by the wedge-shaped snap connections and the bevel of the bore. By pressing in, the O-ring is squeezed, and the feet are brought together until the snap connection can pass through the hole. Thereafter, the feet spring back to the original position, forming a positive connection with the edge of the housing bore. After mounting, the press-in force is removed. The crimped O-ring provides a permanent force opposite to the mounting direction. With this force and the positive snap connection, the pressure compensation element is held in position. When mounting, make sure that the press-in force acts vertically and evenly on the housing. Non-centric pressing should be avoided. Here, it can happen that snap-in feet can not hook in correctly, or they can even break off due to excessive load. This can also occur with minor damage to the feet. A secure seal of the housing is therefore no longer guaranteed.

Figure 67: Text−based recommendation adapted from Butenko et al. (Butenko, Gladysz, et al., 2018)

Figure 68 illustrates the second provided recommendation in from of images representing ideal and poor assembly results with the brief explanatory text.

[124] Image of the pressure compensation element is adapted from Maurath (2018, p. 56), co-supervised bachelor thesis.

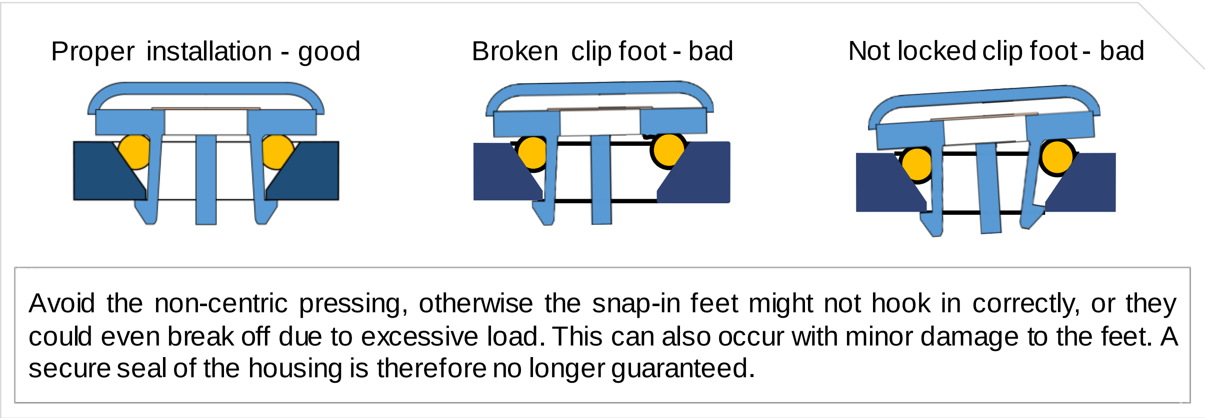


Figure 68: Recommendation in form of ideal and poor assembly results with the brief explanatory text adapted from Butenko et al. (Butenko, Gladysz, et al., 2018)[125]

Figure 69 illustrates the second provided recommendation in from of images representing ideal and poor assembly results with the brief explanatory text.

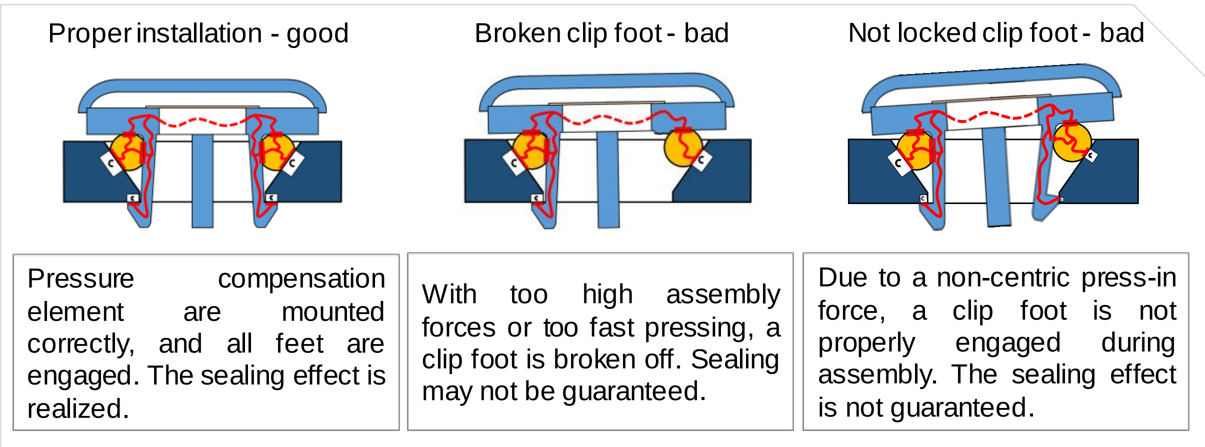


Figure 69: C&C²−based representation of ideal and poor assembly results with brief text adapted from Butenko et al. (Butenko, Gladysz, et al., 2018)[126]

The task for the second case study is illustrated in Figure 70.

[125] Images of the pressure compensation element were created by Maurath 2018, co-supervised bachelor thesis.

[126] Images of the pressure compensation element were created by Maurath 2018, co-supervised bachelor thesis

Situation:
You are hired for with the development of a casting tool. What should you consider in the construction? Name the relevant characteristics that should be considered.

Problem:
In the past, there were already situations in which problems occurred in the production due to the unsuitable tool design.

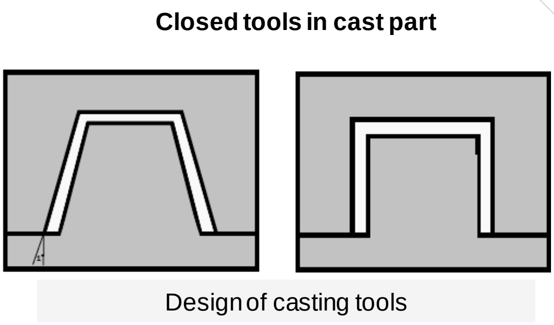


Figure 70: Second case study “casting design”[127]

The example of the text−based recommendation to solve the introduced task above is illustrated in Figure 71.

In the case of a casting design, draft angles in the lifting surface must be provided in the component surface. Here, the product can be removed from the mold quickly and without damage. The larger the angle, the better the removal from the tool. If the workpiece is designed without draft angles, it is possible that it will either be damaged during removal or not be released from the mold at all. Undercuts and cavities should be avoided, as cores are expensive because they provide extra work. They must be set correctly with a longer process time and removed or destroyed again after casting. Therefore, open cross sections with sufficiently large draft angles are preferred

Figure 71: Text−based recommendation adapted from Butenko et al. (Butenko, Gladysz, et al., 2018)

Figure 72 illustrates the second recommendation in form of images representing ideal and poor design solutions of the casting tool with the brief explanatory text.

[127] Images of the casting tools adapted from (Sauer, 2011, p. 60)

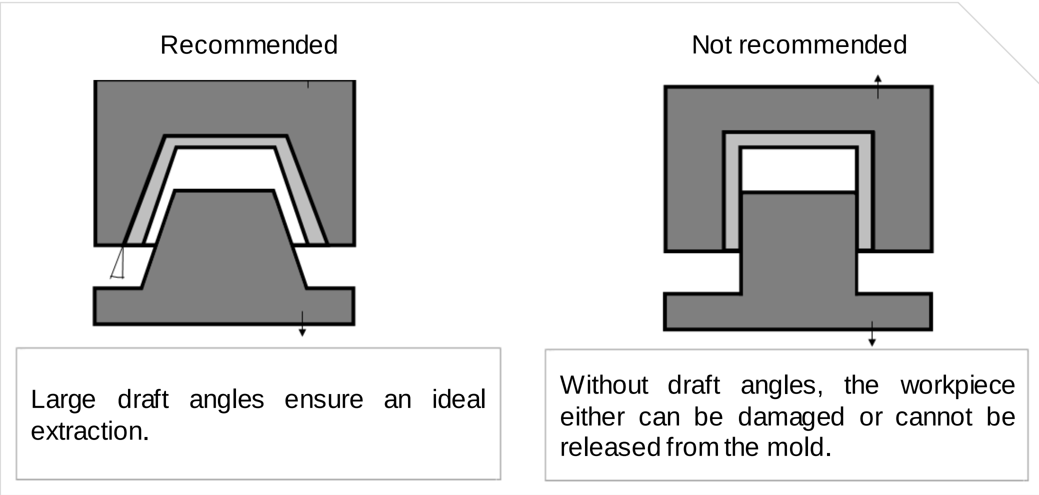


Figure 72: Recommendation in form of ideal and poor design solutions of the casting tool with brief text adapted from Butenko et al. (Butenko, Gladysz, et al., 2018)[128]

Figure 73 illustrates the C&C²−based representation of ideal and poor design solutions of the casting tool with the short explanatory text.

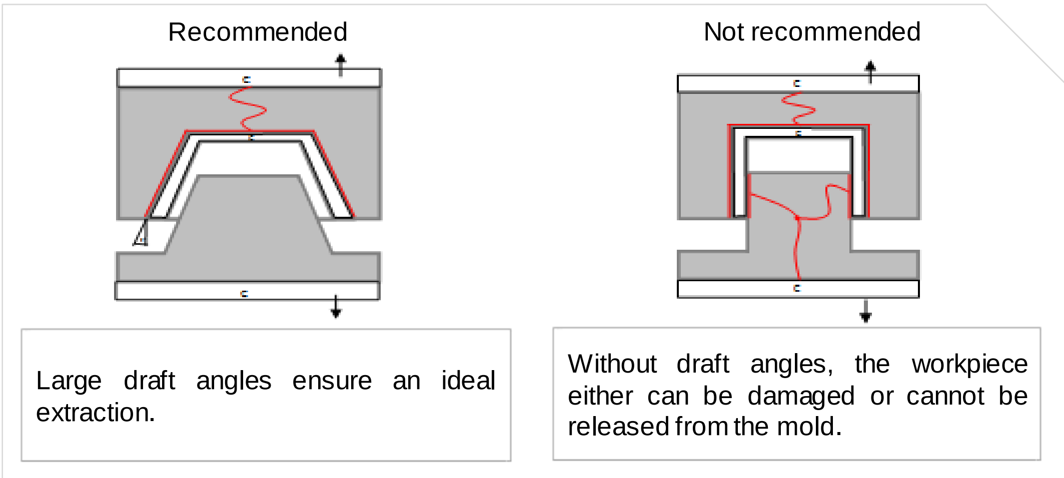


Figure 73: C&C²−based representation of ideal and poor design solutions with brief text adapted from Butenko et al. (Butenko, Gladysz, et al., 2018)[129]

In the evaluation questionnaire, the following scale of assessments regarding the provided information were possible:

- Information is highly inappropriate
- Information is somewhat inappropriate
- Information is somewhat appropriate
- Information is highly appropriate.

[128] Images of the casting tools adapted from (Sauer, 2011)

[129] Images of the casting tools adapted from (Sauer, 2011) and modified for the case study in Maurath 2018, co-supervised bachelor thesis

5.1.2 Main results

Each study participant processed all created case situations. Of the eight experienced participants, three had between two and three-and-a-half years, one had eight years and four had between eighteen and thirty years of experience in the field of mechanical engineering.[130]

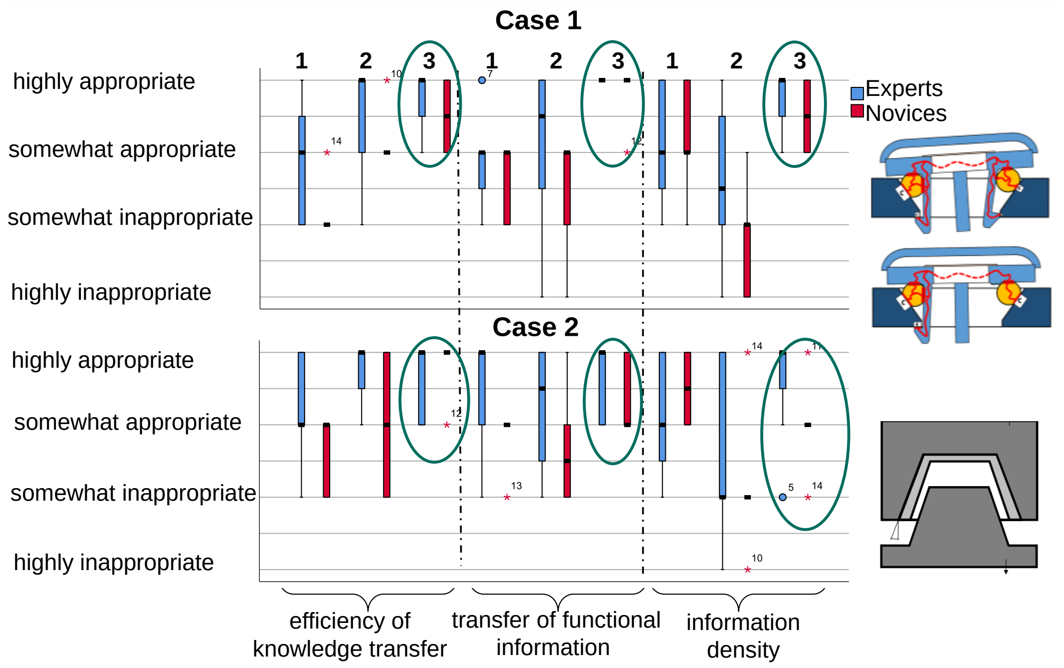
A box-plot diagram was used to depict the evaluations of the study participants in a condensed form, as illustrated in Figure 74. The upper part shows the ratings for the first case, and the lower part for the second case. The three forms for representing information are marked as 1, 2 and 3, where 1 represents the text-based representation, 2 is the ideal and poor assembly results with brief text and 3 indicates C&C²-based representation of ideal and poor design solutions. The evaluations of experienced participants are illustrated in a blue color, and the red color depicts those of inexperienced participants. The size of a box corresponds to the range in which the average 50% of the data are located. The values outside the box are indicated by antennas (whiskers) – they represent the ranges for the lower 25% and the upper 25% of the data values, excluding the outliers. The outliers are marked with stars, which represent the values that are far away from the other data values.

When assessing knowledge transfer according to all three criteria, there are fewer differences between experienced and less experienced study participants with regard to the evaluation of C&C²-based recommendations in the first case study. The suitability is evaluated between highly appropriate and somewhat appropriate. The C&C²-based recommendation is rated as highly appropriate by both groups, especially with regard to the criterion “functional information transfer”. The evaluation of the C&C²-based recommendations by experienced and less experienced study participants has slight differences in the second case study. The experienced participants rated the suitability of knowledge transfer with C&C²-based recommendations for all three criteria slightly higher than the less experienced participants. The suitability of text-based recommendations for knowledge transfer is equally evaluated by the experienced participants in case of the first and second case studies and reveals a dispersion in the evaluation between high appropriate to somewhat inappropriate. The less experienced participants assess the suitability of the text-based explanations in terms of knowledge transfer for the second case study as slightly better than for the first case study. There are the biggest differences between experienced and less experienced participants in terms of all three criteria by the second representation form. The experienced participants rated this form as well suited in the case of the

[130] According to Maurath 2018, co-supervised bachelor thesis

second case study with regard to the criterion “efficiency of knowledge transfer”. The valuations of the less experienced, however, reveal a wide-spread between high appropriate and somewhat inappropriate.

It is recognizable that the C&C²-based illustrations have been evaluated significantly better or equally well, whereby in the first case, the benefits are evident in all three categories. The median value indicates the improvement of ratings in both groups (experts and beginners) from text-based to C&C²-based recommendations in both cases. The criterion "transfer of functional information" indicates a greater deviation in the assessments of the second case. In the first case, the evaluation is better assessed in terms of the C&C²-based recommendations. Regarding the third criterion "information density", the text-based recommendation is better rated as recommendation in form of ideal and poor solutions with brief text. The C&C²-based recommendation is rated slightly better by experts than by novices. (Butenko, Gladysz, et al., 2018)



1. Text-based
2. Ideal and poor solutions with brief text
3. C&C²-based representation of ideal and poor solutions with brief text

Figure 74: Box-plot diagram for evaluation of study results adapted from Butenko et al. (Butenko, Gladysz, et al., 2018)

5.1.3 Conclusion

The results of the conducted study indicate that the differences in the evaluation of provided recommendations are not large between experts and novices (Butenko, Gladysz, et al., 2018). However, based on observations made during the study, it is recommended to avoid only text-based explanations in design guidelines. The combination of text and images in form of ideal and poor design solutions is recommended. It was obvious that the study participants first analyzed the images and after that read the text. The time needed to understand facts was much shorter for the provided documents with text and images than for the documents with textual descriptions. The C&C²-based representation of ideal and poor design solutions brings added value to design guidelines, but not in every situation the added value is greater than simplified representations. When it comes to simple issues, C&C²-based representation is not necessarily recommended, as the effort required for preparations is much greater than for simplified representations.

5.2 Development of the demonstrator within the IRTG project

The aim of the second study is to examine the design guidelines for SMC prepregs available in literature with regard to their applicability to the concrete design tasks. The investigation was carried out within the framework of a demonstrator,[131] which was developed as part of the IRTG project. Design guidelines, which include recommendations for the rib design for SMC material, are selected for this purpose, since on the one hand, sufficient information is available on this topic in the literature, and on the other hand, the SMC material is used within the IRTG project.

5.2.1 Demonstrator

All IRTG subprojects were involved in the development of the demonstrator. As the material, a long 1-inch (25-mm) glass fiber, based on a vinyl ester resin type Atlac XP810X by Aliancys, is applied for the manufacturing of the demonstrator. The weight content of the reinforcing glass fiber (type Multistar 272 by Johns Manville) is set to 41 wt.-%, which equals 23 vol % content. (Trauth & Weidenmann, 2016) The demonstrator in the IRTG project has a simple shell geometry, with a length of 230 mm, a width of 180 mm, a height of 20 mm, and a wall thickness of 2 mm. The demonstrator should be stiffened with ribs and loaded by a four-point bending test. The CAD model of the shell geometry for the demonstrator is illustrated in Figure 75.

[131] Demonstrator represents a model that demonstrates the feasibility of the solution. This is a prototypical, mostly simplified implementation to visualize the research results.

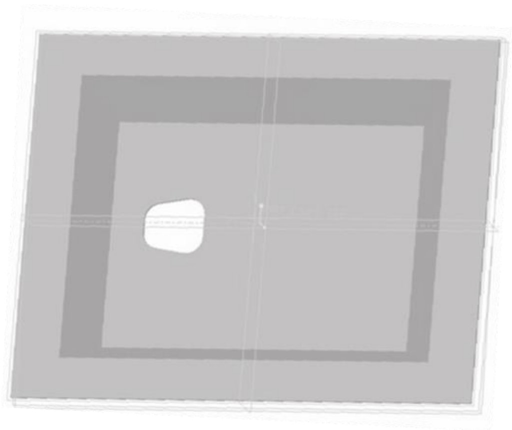


Figure 75: CAD model of the shell geometry based on Böhlke et al. (2019, p. 8)[132]

After the CAD model was created, a favorable basic shape (topology), under defined mechanical loads, was determined within the FEM simulation. Topology optimization was used to support the design of the rib arrangement by generating design proposals, as illustrated in Figure 76. The single challenge was to interpret the results of topology optimization and its implementation in a feasible CAD construction.

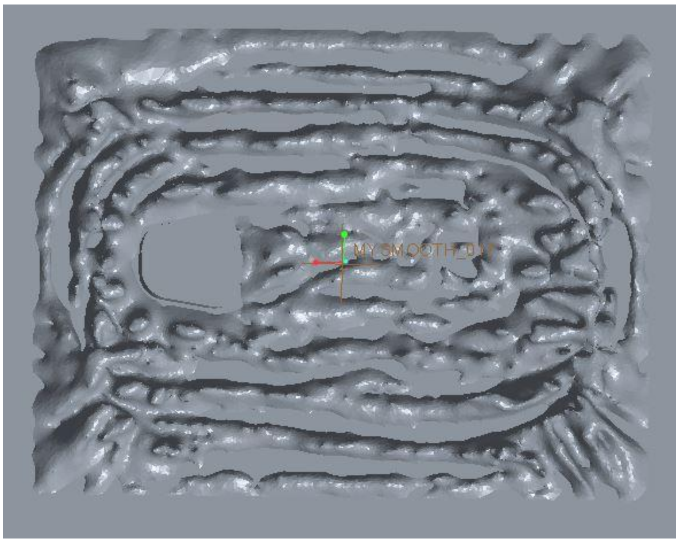


Figure 76: Results of the topology optimization based on Spadinger and Albers (2019, p. 275)[133]

It appears that some areas visualize a clear course of the ribs, whereas others are rather confusing and can be interpreted differently. The rib arrangement should be modeled close to the results of the topology optimization in order to validate the research results of the other IRTG sub-projects involved in the development of the

[132] Author's own representation

[133] Author's own representation based on the topology optimization results created within the framework of the IRTG Project

demonstrator. From a large number of design proposals, two were selected and loaded onto four-point bending in the FEM simulation in order to select the best solution. Figure 77 visualizes these two design solutions – the difference between them lies in the arrangement of the ribs in those areas that could be interpreted ambiguously in the image with topology optimization results. Red circles mark these areas in Figure 77.

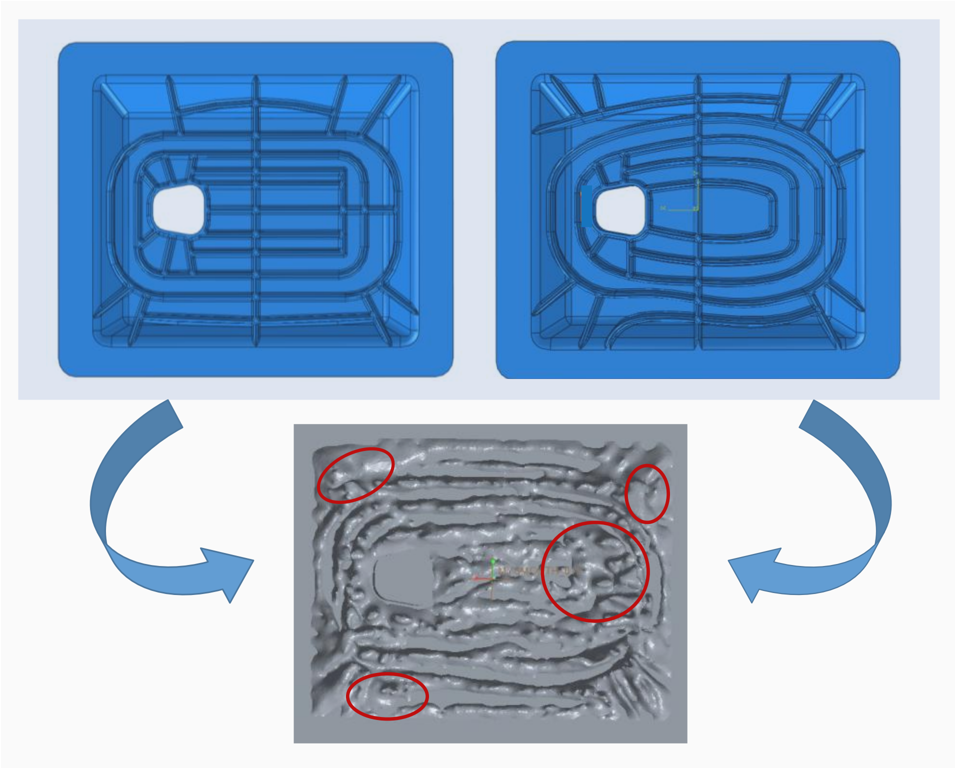


Figure 77: Design solutions for rib based on topology optimization (left – the first solution and right – the second solution)[134]

When designing the ribs, the aim was to avoid sink marks and ensure that the ribs are completely filled with fibers and resin. With regard to the avoidance of sink marks, some recommendations are found in literature on the influence of the ratio of the rib wall thickness to the wall thickness of the component, the radii at the rib base and the draft angle, as exemplified in Figure 78. According to these literature sources (AVK – Industrievereinigung Verstärkte Kunststoffe e. V., 2013; European Alliance for SMC/BMC, 2007), the wall thickness of the rib should be 0.75% component's wall thickness to avoid sink marks, which would be 1.5 mm in the case of the demonstrator. The experts from the production and molding process simulation stated that the rib's wall thickness of 1.5 mm is inappropriate and should be at least 2 mm to ensure proper filling of the rib. The other recommendations from the literature with regard to the radii – 0.5 mm – and the demolding angle – 0.5° – were accepted and applied directly. None

[134] The CAD-models were created within the framework of the IRTG project

of the recommendations illustrated in Figure 78 deals with the proper filling of ribs with fibers and resin.

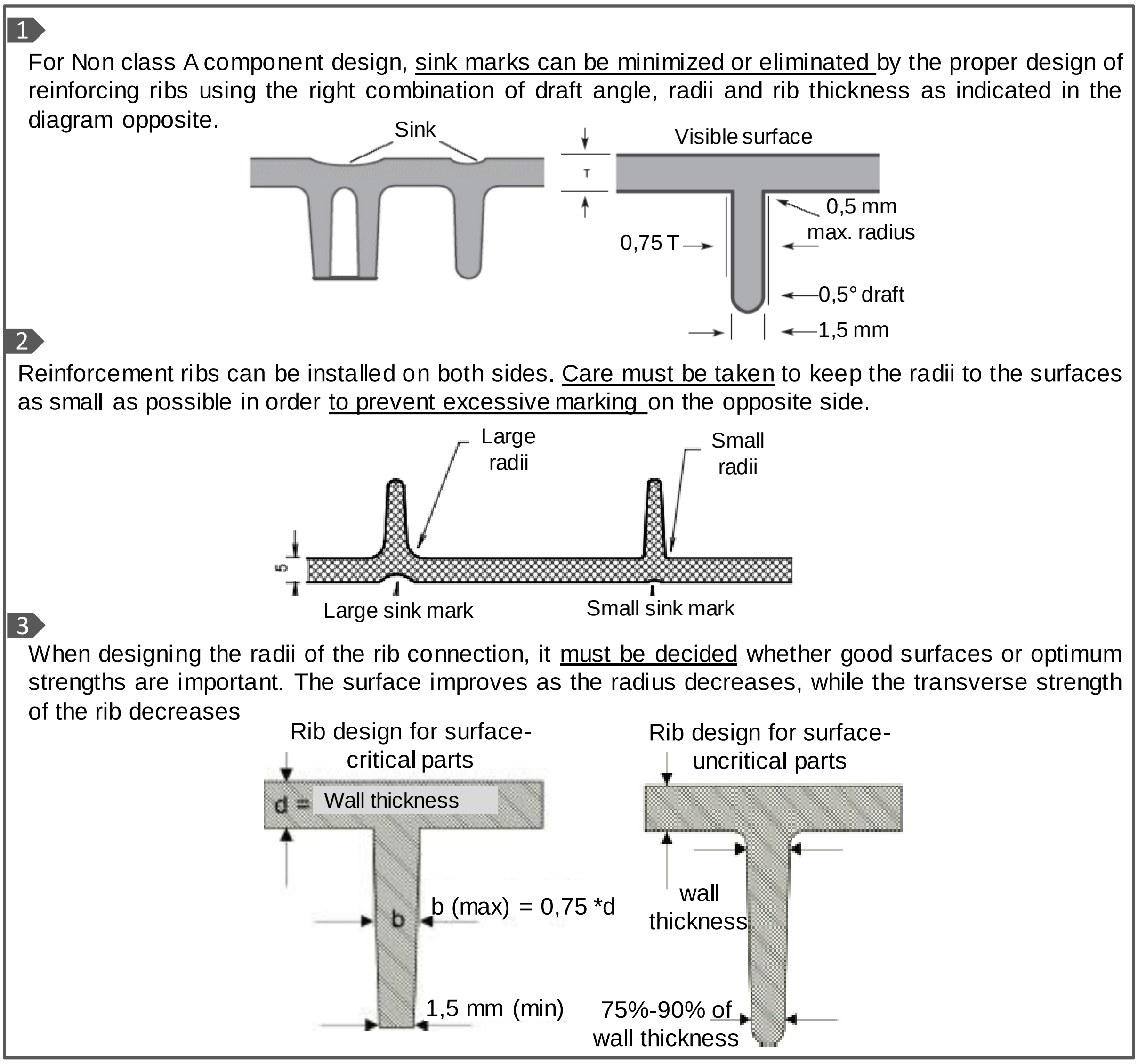


Figure 78: Design recommendations for rib design for SMC material (1) (European Alliance for SMC/BMC, 2007), (2) (Wernli, 1998)[135], (3) (AVK – Industrievereinigung Verstärkte Kunststoffe e. V., 2013, p. 420)[136]

5.2.2 Results

The experiments were carried out at the Fraunhofer Institute for Chemical Technology (ICT) in Pfinztal on a Dieffenbacher COMPRESS PLUS DCP-G 3600/3200 AS. The institute determined the manufacturing parameters based on its experience with this material. The temperatures for the upper tool and the lower tool were set to 140 °C and 145 °C respectively. The pressure time was set to 112 seconds and a constant

[135] The text is translated from German to English
[136] The text is translated from German to English

closing speed of 1 mm per second, and the pressing force was set to 2500 kN. (Bücheler & Henning, 2016)

The results of the manufacturing are illustrated in Figure 79. It can be seen that the rib filling with fibers is poor. The ribs are almost fibreless, and in some places, the resin is also missing. The dark areas indicate fiber accumulation, and the light-yellow areas represent the resin without fibers. In addition, in production, there were difficulties with the removal of the demonstrator from the mold.

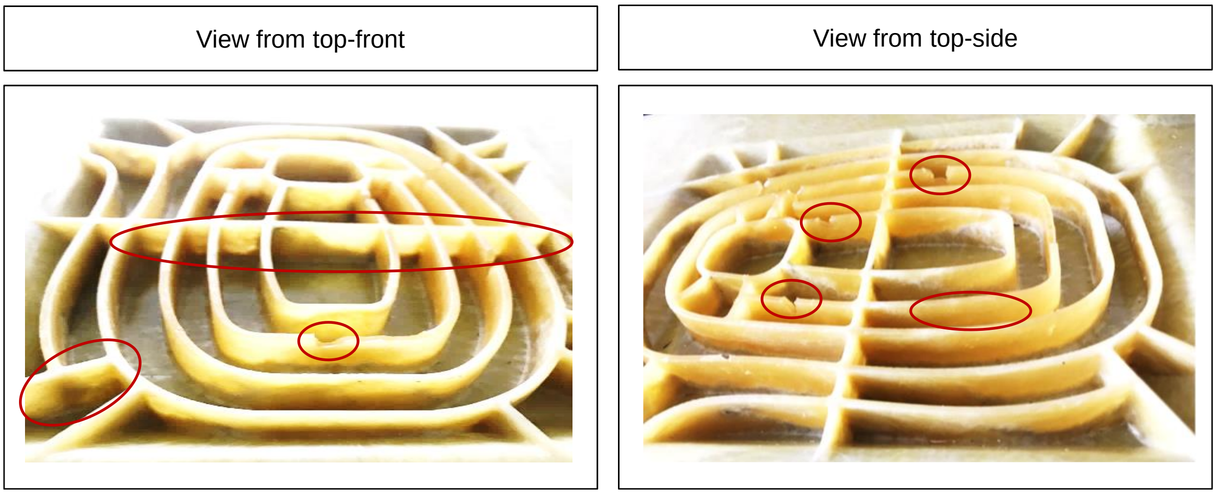


Figure 79: Demonstrator with views from top-front and top-side adapted from Butenko and Albers (2018)[137]

To understand the filling process of the rib, the mold filling process was stopped after a certain time to determine which areas are shaped first. Figure 80 presents the results with 3.3-second and 3.7-second filling times of demonstrator. It can be seen that the rib oriented in the direction of flow is the first to be filled. The inner ribs are only partially and decreasingly shaped towards the middle. They are first formed later due to the increased pressing force, which is needed to push the fiber into the ribs.

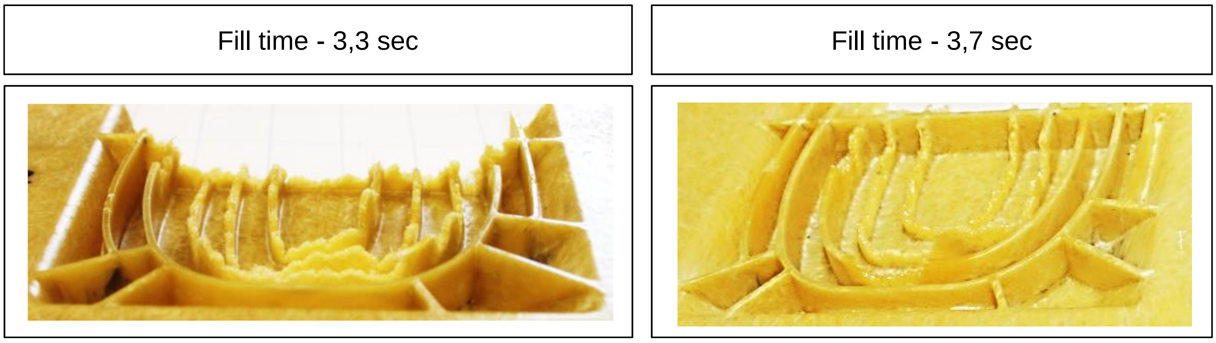


Figure 80: Fill time of 3.3 and 3.7 seconds – shaping of the rib[138]

[137] Experiments within the IRTG project
[138] Experiments within the IRTG project

In addition, the influence of the material's position on the rib filling with fibers was investigated. For this purpose, the material was positioned once at the beginning and once in the middle of the tool. The results reveal significantly more fiberless areas at the position of the material in the middle, compared to the position of the material at the beginning of the mold as illustrated in Figure 81. The fiber-free areas are easily recognizable by their color, and they are marked on the image by red circles.

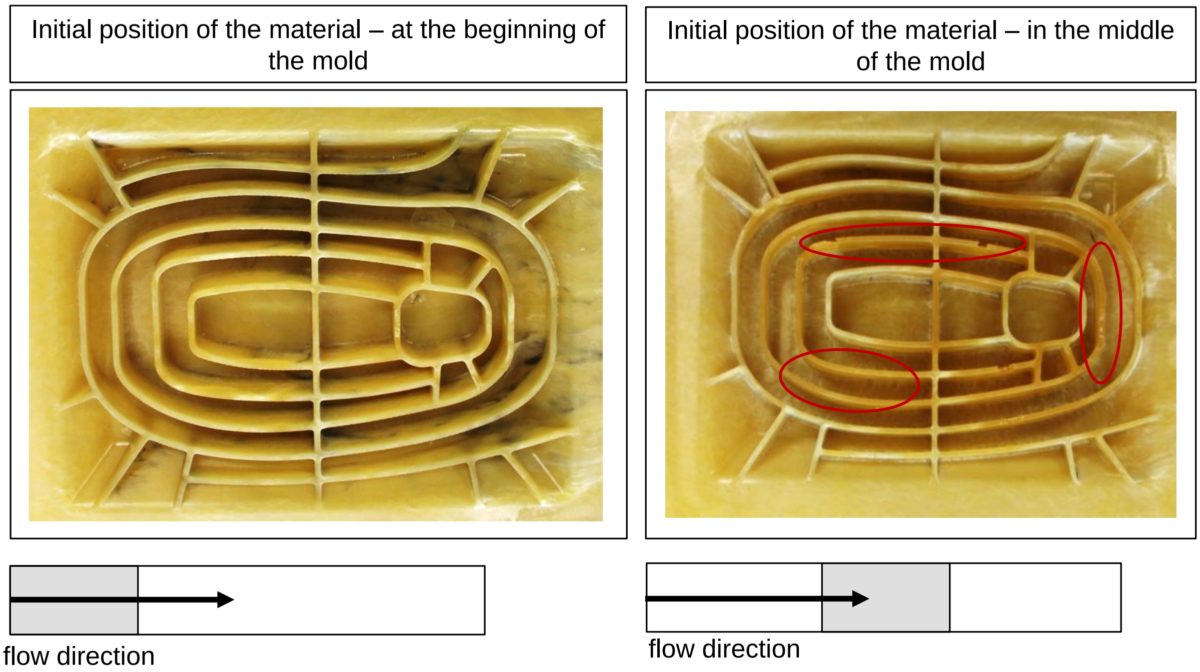


Figure 81: Influence of the initial position of the material on the rib filling[139]

The following four assumptions were made in a regular IRTG meeting based on the results and observations during the manufacturing process: 1) the ribs' wall thickness of 2 mm is not sufficient for the homogeneous filling of the rib with fibers, 2) a greater draft angle would be better to easily remove the part from the tool, 3) a large radii at the rib would be better to promote better filling of the rib with fibers and 4) the position of the material at the beginning of the mold results in better rib filling.

To prove the assumptions, a second demonstrator, with a modified shape of the ribs, was designed. The rib wall thickness was increased from 2 mm to 2.5 mm, the radii from 0.5 to 1 mm and the draft angle from 0.5 to 1 mm. The position of the ribs and the process parameters were not changed in order to investigate the influence of geometry in a targeted manner. Figure 82 depicts the difference between the first and second demonstrators. The rib filling was significantly improved by changing the geometry parameters. There are no areas observed with missing resin. By increasing the

[139] Experiments within the IRTG project

demolding angle, removal from the mold was much easier than with the first demonstrator.

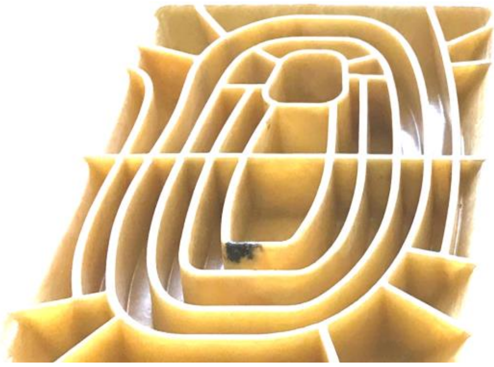
First demonstrator part with the rib thickness: 2 mm	Second demonstrator part with the rib thickness: 2.5 mm
	

Figure 82: Comparison of first and second demonstrators – improved rib filling adapted from Butenko and Albers (2019, p. 280)[140]

Following production, technical discussions were held with experts from Fraunhofer ICT to understand the achieved results. The main questions concerned why the recommendations in design guidelines were not suitable for the demonstrator and whether Fraunhofer ICT has already manufactured the ribs for customers according to these guidelines. The results of the discussion have provided the following findings:

- The rib geometry with a 1.5 mm wall thickness was already produced with other SMC material, and the filling of the ribs with fibers was good and homogenous.
- The major difference lies in the material composition used in the IRTG project and the commercial SMC material used in other projects. The formulation of the resin is different, which influences the rheological properties and thus the flow behavior of the material.

Various commercial SMC materials are available on the market. The question is whether the design guidelines are suitable for other SMC materials or whether the same effects will result as those in the demonstrator in the IRTG project. The text in the design guidelines does not indicate the specific SMC materials for which the recommendations apply. None of the concrete specifications regarding wall thickness size, draft angle or radii in the recommendations were exactly suitable for the demonstrator. However, the information about the geometric characteristics that had to be taken into account in the design was helpful. This information provides added value, especially for less experienced designers.

[140] Experiments within the IRTG Project

5.3 Creation of design guidelines

The aim of the third study is to investigate which methodological aids can support the creation of design guidelines for FRPs.

The following research question is the focus of this study:

> How can the target-oriented documentation of information in design guidelines be methodically supported?

As part of the study, a guide was developed to support the drafting process of design guidelines. This guide was provided to a student who could test it in his master thesis by creating recommendations for edge processing when milling CoDico-FRP plates. Through observations and feedback on the given guideline, continuous improvements were incorporated.

5.3.1 Background information

In research projects, simulations and experiments are often the most valuable sources for data generation needed to create design recommendations. The aim of the experimental testing is to establish a reliable and trustworthy database. Boundary conditions under which the generated data are determined represent important information that can restrict or generalize the scope of design guidelines accordingly. Therefore, the quality of the planning and execution of experiments has an influence on the significance of the design guidelines. Observations in various study projects, as well as active exchange with industry representatives, have demonstrated that uncertainties often arise in the creation process of design guidelines. These uncertainties already begin with the question of how the generated data can be transferred into design guidelines and what is proper way for their formulation and structuring. Figure 83 visualizes the described uncertainties exemplarily.

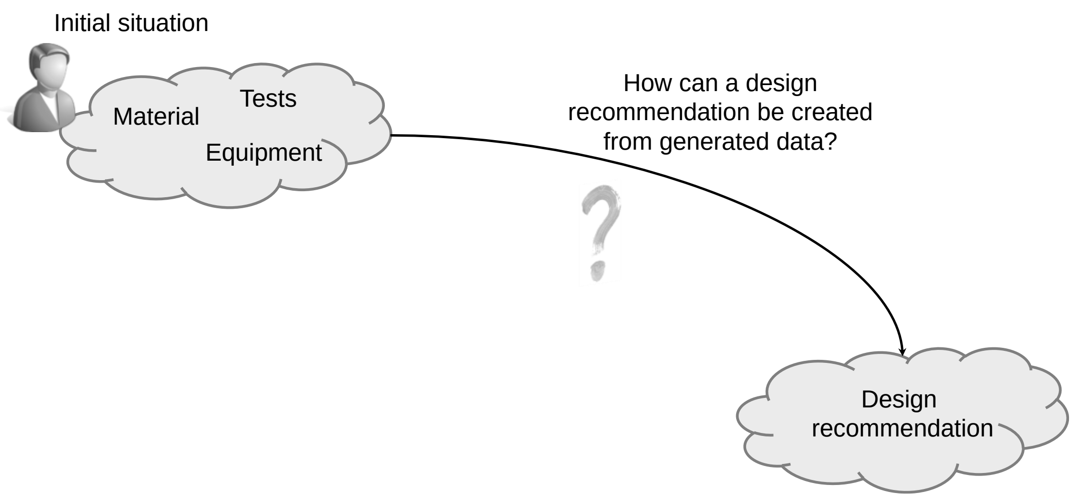


Figure 83: Uncertainties in the creation of design guidelines

5.3.2 Experiment

The student had to familiarize himself with the milling process of SMC material. The familiarization process included the understanding of the milling process as well as the correlation between milling process parameters and the occurrence of possible material failures during the processing. Six different types of composite laminates[141] should be investigated within the experiments, and as result design guidelines should be created.

- 1) GF-SMC/UD/GF-SMC → the upper- and lower-layer SMC reinforced with glass fibers and the middle layer with carbon UD
- 2) UD/GF-SMC/UD → the upper- and lower-layer carbon UD and the middle layer SMC reinforced with glass fibers
- 3) CF-SMC → SMC reinforced with carbon fibers
- 4) UD/CF-SMC → the upper layer is carbon UD and the lower layer is SMC reinforced with carbon fibers
- 5) GF-SMC → SMC reinforced with glass fibers
- 6) UD/GF-SMC → the upper layer is carbon UD and the lower layer is SMC reinforced with glass fibers.

Figure 84 illustrates the six types of composite laminates described above.

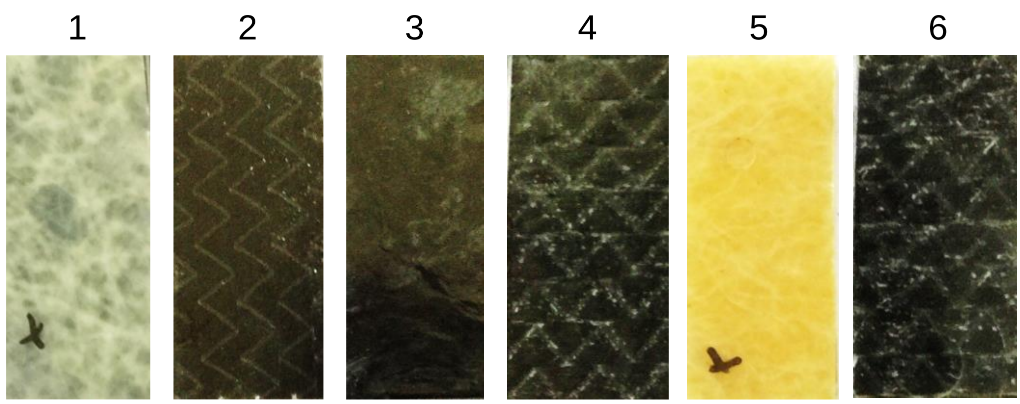


Figure 84: Composite laminates investigated in the study adapted from Li 2018, p.75[142]

Four different milling tools were investigated in combination with six SMC materials. The difference was in helix angle, number of cutting edges and surface coating of the milling tools, as visualized in Figure 85.

The first milling tool, designated as (a) in figure below, had a conventional end mill with a helix angle of 0°, and 6 mm diameter. The second milling tool, designated as (b), had

[141] All these composite laminates were produced within the IRTG project

[142] Co-supervised master thesis

a hexacut end mill with a helix angle of -8°, and 8 mm diameter. The third milling tool, designated as (c), had a polycrystalline diamond end mill with a helix angle of 0°, and 8 mm diameter. The last milling tool, designated as (d), had a carb star twister end mill with a helix angle of -2°, and 6 mm diameter. (Helfrich et al., 2019, p. 71)

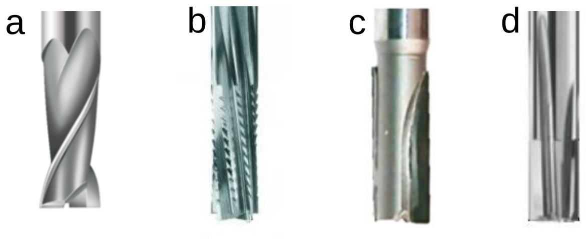


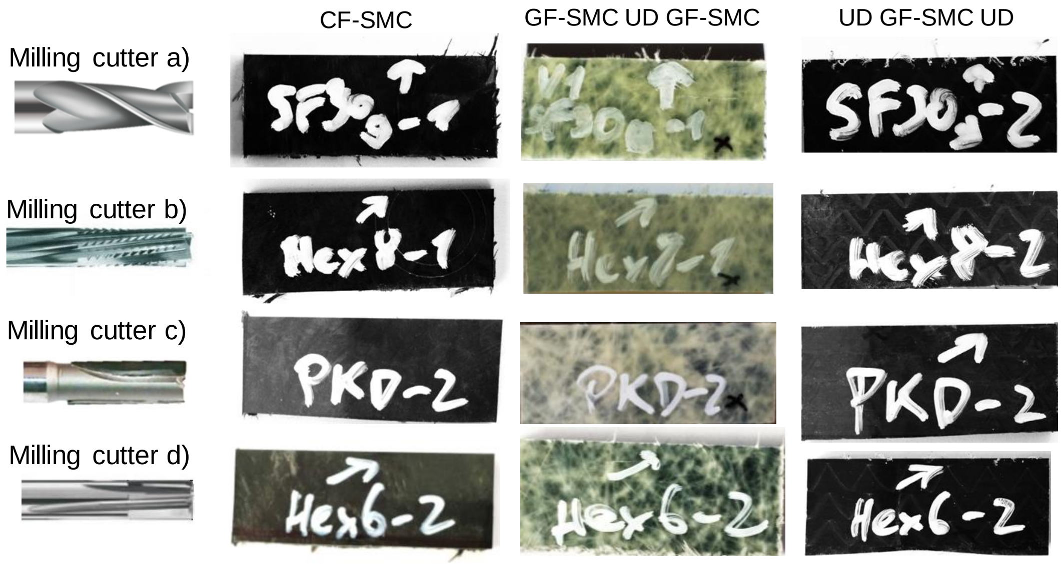
Figure 85: Investigated tools adapted from Helfrich et al. (2019, p. 71)

The Institute of Production Engineering (WBK) conducted all milling tests and supported in the selection of parameters and milling tools. All tests were performed in the framework of the IRTG project. Since a limited number of plates were available, a restricted number of tests could be performed.

5.3.3 Results

One of the student's task was to create recommendations for edge processing in order to achieve the smoothest possible cutting edge and to avoid the formation of delamination. The recommendations should be created for the materials presented in Figure 84. After completion of the milling trials, the final step was to document the recommendations based on the data and observations obtained. The student should initially document the collected information as recommendations without using a methodological guide. The aim was to observe differences in the results through application and non-application of the developed guide. Figure 86 presents an example of a recommendation prepared by the student without the use of any guide. It is obvious that the provided documentation was too brief and is not formulated as a recommendation. The exchange with the student has proven that it was difficult for him to decide how to condense all the information collected in experiments and derive a recommendation from it.

Diamond-coated cutters produce higher surface quality and less damage as cutters without coating



Milling cutter c) – is diamond coated; Cutting velocity – 200 m/m; Feed per tooth – 0.05 mm

Figure 86: An example of the recommendation created without a methodological guide[143]

In the next step, a preparation check list, formulation rules and a template for the documentation of recommendations were provided to the student.

The preparation check list consists of several questions to support creating of the recommendations, as illustrated in Figure 87.

- **Who** is the target group for the recommendation?
- **What kind** of information should be documented in the recommendation?
- **What** is the scope of the recommendation (for which e.g. material, production process does the recommendation apply)?
- **What** is the target of the recommendation?
- **When** is this information relevant? (e.g. certain activities of product engineering, product development phase)
- **Why** is the recommendation important to consider?
- **What** will happen if the recommendation will not be considered? **Why** it will happen?
- **What** is a positive result when applying the recommendation, negative result when not applying it?

Figure 87: Preparation check list

[143] First draft of a design recommendation prepared by the co-supervised master student without using the methodological guide. The images are result of the milling tests performed at the WBK Institute. The images of the milling tools are adapted from Helfrich et al. (2019, p. 71)

Formulation rules should set out general instructions for the documentation of information and serve as an orientation by the creation of recommendations as illustrated in Figure 88.

- An easily understandable vocabulary should be used in the documentation of the recommendation.
- Long and complicated sentences should be avoided.
- Content of the recommendation should be clearly linked to the target of the recommendation.
- Explanation in one sentence the main statement of the recommendation.
- Explanation in one-two sentences the reasons why the stated recommendation should be taken into account.
- Explanation in one sentence the negative consequence which could occur in case of non-compliance with the recommendation.

Figure 88: Formulation rules for the documentation of information

A template represents a generic framework that specifies where certain information is to be documented, as presented in Figure 89.

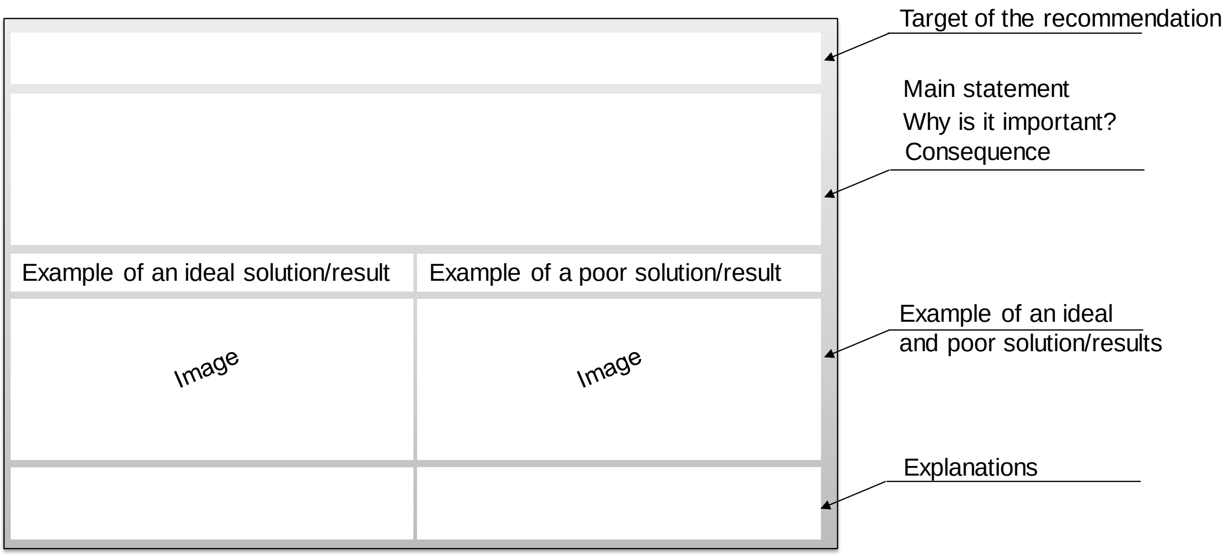
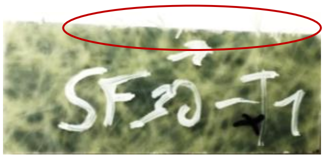


Figure 89: Template for the documentation of design recommendations

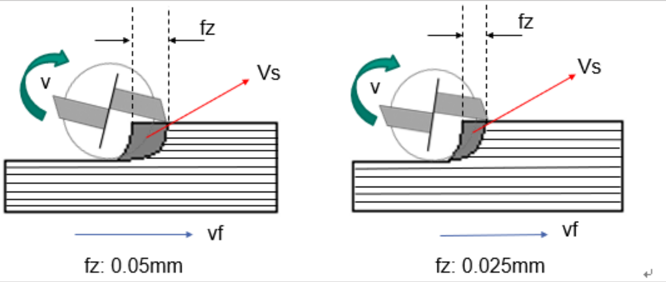
The provided check list, formulation rules and the generic framework resulted in a much more informative and structured documentation of recommendations, as demonstrated in Figure 90.

Increase of surface quality and reduction of damage during post-processing of FRP

When milling FRPs, the feed per tooth and feed speed should be reduced to improve surface quality and reduce damage. The larger the feed per tooth, the larger the cutting volume and the greater the material resistance. An unstable milling process results in poorer surface quality.

Example of a milling result using 0.025 mm feed per tooth and 200 m/min feed speed	Example of a milling result using 0.05 mm feed per tooth and 200 m/min feed speed
 UD CF-SMC	 UD CF-SMC
 GF-SMC UD GF-SMC	 GF-SMC UD GF-SMC

The test results demonstrate that with the same milling cutter and the same cutting speed, smaller feed rates per tooth significantly increase the machining quality. The explanation for the improved quality is that a larger cutting volume is formed at the higher feed per tooth, as illustrated in Figure below in dark colored segments. This large cutting volume increases the resistance, which leads to an unstable milling process and finally to a poor surface quality.



f_z – feed per tooth
V_s – cutting volume
v – cutting speed
V_f – feed speed

Figure 90: Created recommendation using provided guide adapted from Li 2018, p. 88[144]

5.3.4 Conclusion

Even though only a limited number of milling tests could be carried out, it was quickly apparent how much data was generated. The handling of the information obtained and its derivation in meaningful recommendations turned out to be difficult without methodological support. The results and observations during the study have revealed that methodological support leads to better and more consistent documentation. A template supports structured documentation of information in design guidelines. The provided questions help to concentrate on the essential and to reflect relevant information in a defined scope.

144 Co-supervised master thesis, the recommendation is translated from German to English

6 Development of the approach

As Section 2.5.3 described, different methods and tools in context of knowledge management are developed at the IPEK – Institute of Product Engineering. The "Inno-Fox" method[145] has a comparable objective to the method developed in this thesis, namely, providing support according to the situations and needs of users. The aim of Inno-Fox is to support product developers in their search for suitable methods, with all methods being described in the form of standardized profiles with a predefined structure. The provided information (certain methods) changes only its order in the ranking list, and the provided contents always remain the same. The method developed in this thesis involves providing situation-specific information in design guidelines, whereby the contents of design guidelines change and are always dynamically adapted according to the given situations of users. However, there are also great differences in the way in which the information is provided, the type of information itself and the decision support techniques that are used (Butenko & Albers, 2019, p. p.287).

Chapter 6 presents the methodological guide for developing a method to support product developers in the early phases of product engineering with FRPs in the activities "detect ideas" and "model principle solution and embodiment" through the provision of situation-related design guidelines specific to these activities. The development of the method consists of several steps, which are presented systematically with some examples in Section 6.1. The description of certain steps reflects to a large extent authors' experiences, which were gathered during the development of the method. At some points, the references to the other applicable methods are provided, accompanied by several recommendations. The main target is to provide a guide with the most important information to enable the efficient transfer of this method to other materials such as metals, plastics, ceramics or certain fiber-reinforced composites. Section 6.2 presents developed knowledge management–based decision support tool, CoDico-FiberFox.

6.1 Process model

According to Fischer et al. (1998), a process model is understood to be an expression of a development scheme, based on structured descriptions and instructions and visualized as a model, thus becoming transparent and plannable. The process model developed in this thesis serves to systematize the development processes of the

[145] Developed by Albers et al. (Albers, Reiß, et al., 2015)

method with the aim of more efficient implementation through the precise description of the necessary development steps and a reduction in the planning time of the development organization. The developed process model is visualized in Figure 91.

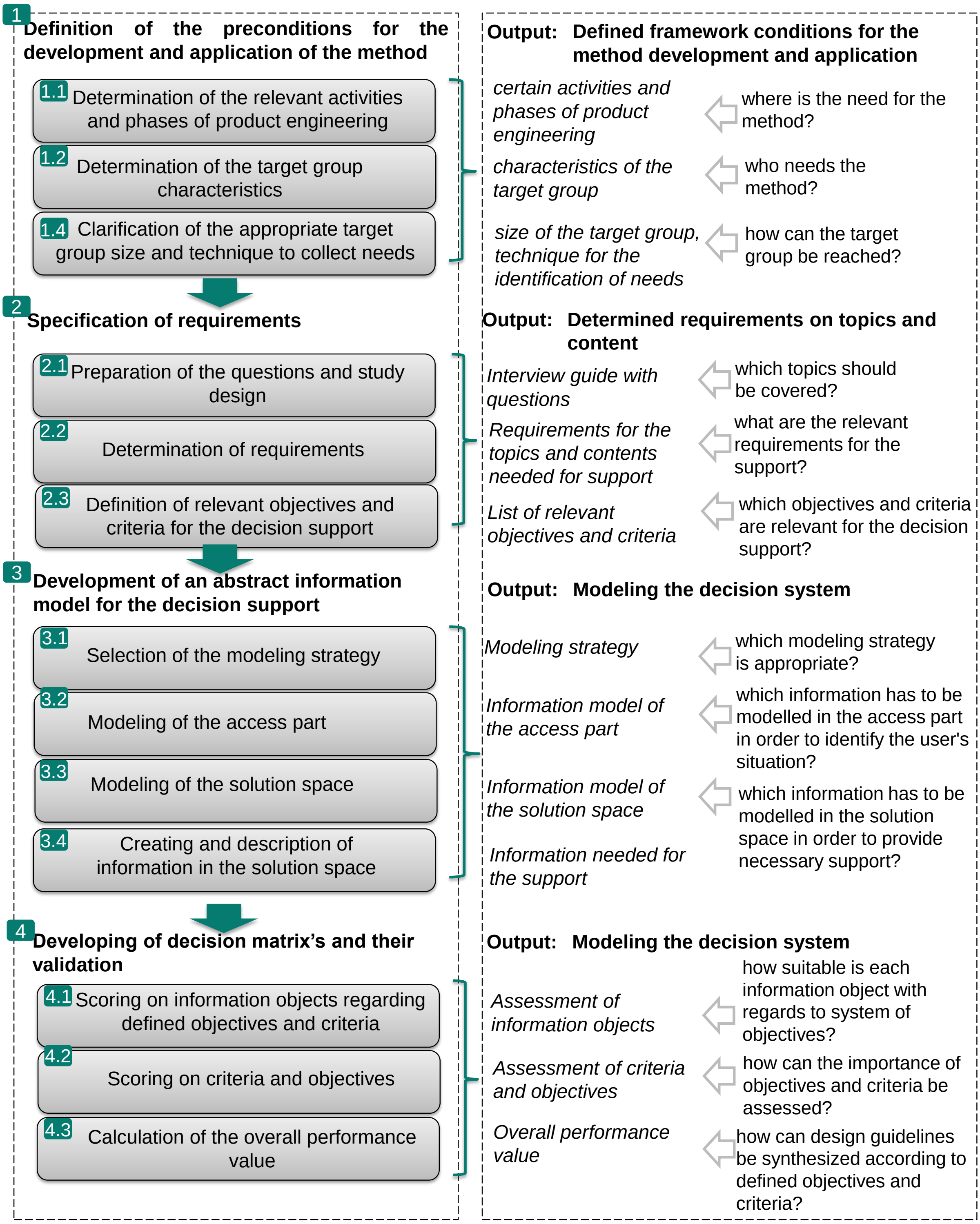


Figure 91: Process model for the development/transfer of the method

The structure is described generically and can therefore be transferred to other similar methods mentioned above. The process model consists of four essential steps:

- Definition of the preconditions for the development and application of the method
- Specification of target group requirements
- Development of an abstract information model for the representation of a decision support system
- Development of decision matrices and their validation.

6.1.1 Preconditions for the development and application of the method

In the first step, the focus is on determining the framework conditions necessary for successful method development. The fundamental situation analysis according to SPALTEN (Albers et al., 2005) can be carried out to give answers to the following questions:

1. In which phases and activities of product engineering is methodical support required in the provision of information?
2. Who is the target group and how should the target group benefit from the method to be developed?
3. How can the target group be reached and what is the appropriate size of the sample for a representative assessment of target group needs?

Determination of the relevant activities and phases of product engineering: It is important to clearly specify the scope of the method and identify the framework for its applicability in order to ensure the targeted development of the method. This means deciding at the start whether the method is necessary for support in the early or later phases of product engineering, or for the entire product life cycle. Focusing is helpful to reduce the number of iteration loops and to keep the effort required for the possible re-conceptualizing of the method to a minimum. Additionally, the activities of product engineering must be defined in terms of where the method should provide support. Even though the phases of product engineering reflect the time-related assignment of the activities and their dependencies, some of the activities are repeated time-delayed (Verein Deutscher Ingenieure 2221, 2019a). Some of the activities can extend through all phases of product engineering, and others can be rather limited to the certain phases.[146] Product developers need various types of information and support depending on the phase and activity of product engineering. For example, in the “detect idea” activity, other more general information than in the “model principle solution and embodiment” is necessary to provide support. Companies have their own designation and definition of phases and activities of product engineering, depending on the context and the process knowledge of the company (Verein Deutscher Ingenieure

[146] Based on various process descriptions in VDI 2221 (2019b)

2221, 2019a). However, the need for various types of information depending on the phase and activity of product engineering is always present, regardless of the designations used.

Determination of the target group characteristics: The target group consists of the individuals who benefit directly or indirectly from the developed method, who have the greatest influence on how the method should be designed and implemented. Therefore, it is important to describe the characteristics of the target group in order to systematically identify the relevant persons to determine the needs and requirements of the method to be developed. Examples of the characteristics of the target group are as follows:

- Individuals responsible for the development of certain technologies/products or processes
- Individuals with certain experience level in field of certain technologies/products
- Individuals who are active in certain product engineering activities
- Individuals who are active in specific product development phases.

Without the involvement of the target group in the development of such a method, important aspects may be overlooked, and the method may not be optimally tailored to the needs of the target group. The subsequent adjustment involves a high level of effort. An example describing the characteristics of the target group is illustrated in Figure 92.

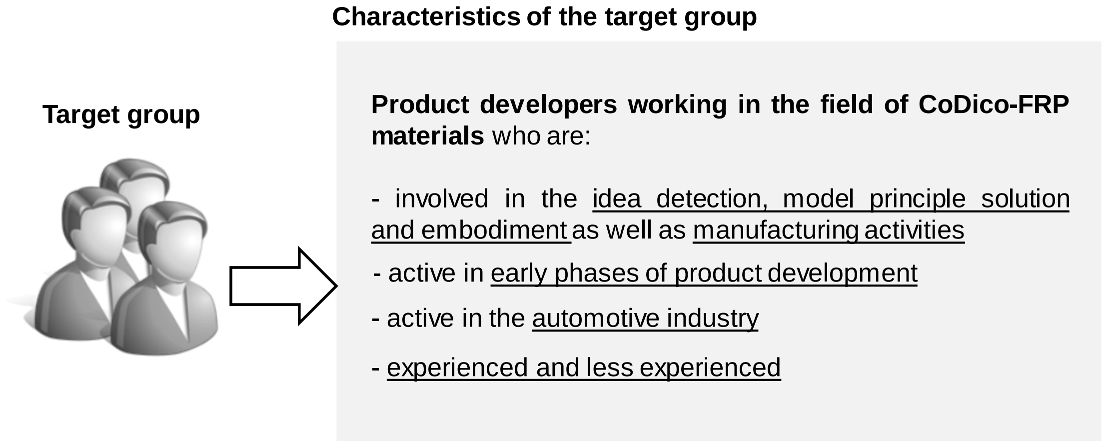


Figure 92: Example of the description of target group characteristics

Clarification of the appropriate target group size and technique to collect target group needs: The method to be developed can be relevant for a large or small number of individuals. The important question is how many person from the target group should be involved in the study in order to achieve representative results. One should be aware that with a quantitative research technique, the focus is on statistical representativeness, while in the case of qualitative research technique, the focus is on content representativeness (Queirós et al., 2017). However, independent of the selected survey technique, it is important that the sample composition be as similar as possible to the relevant characteristics of the target group. The rules for determining the target group size depending on the sampling method can be obtained in Akremi (2014, pp. 265–282), Merkens (1997) or Flick et al. (2005). The choice of the sample size and technique for gaining requirements depends on the specific situation, objectives and boundary conditions of the method developers. Authors' experience has revealed that semi-structured interviews are well suited not only to assess target group needs but also to better understand them. If a large target group is in focus and there is little or no knowledge of the area in which the method is to be developed, it is advisable to first conduct a qualitative study in order to gain understanding and then to evaluate the results in a quantitative questionnaire involving a larger number of participants. Figure 93 presents an example of the statements gained in a qualitative study and converted into a closed format to be verified by a larger number of participants in a quantitative study.

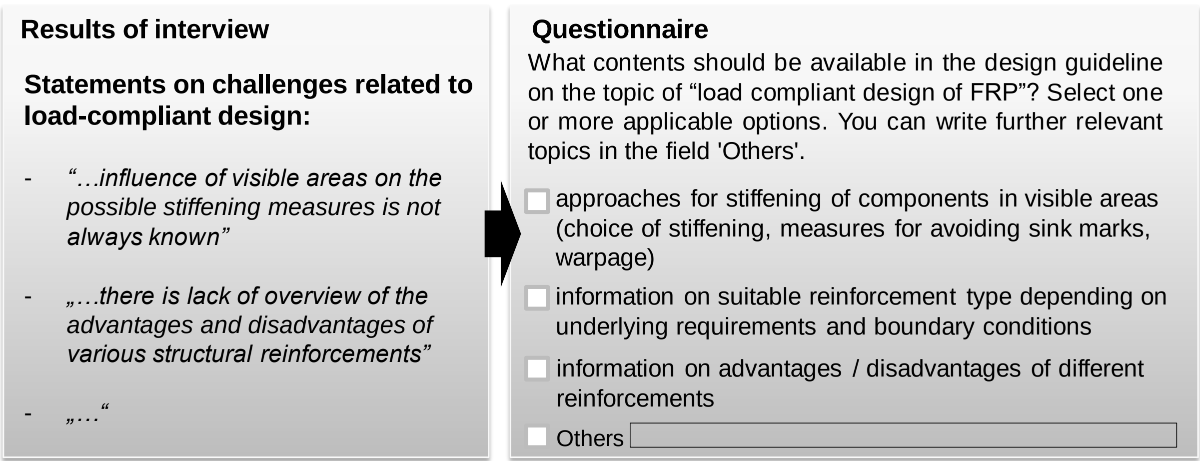


Figure 93: Transferring the interview results into a multiple-choice questionnaire

Further information on topic of qualitative and quantitative techniques, including the questioning technique, advantages and disadvantages of certain techniques and advice on what to look out for, can be obtained in Schnell et al. (2008), Häder (2019), Liebau et al. (2018).

The main results of the stage "Definition of the preconditions for the development and application of the method" are summarized in Figure 94.

- Certain activities and phases of product engineering are defined
- Target group characteristics are specified
- Technique for identification of target group needs is determined
- Target group size and technique for identifying of requirements are specified

Figure 94: Main results of the first stage

6.1.2 Specification of requirements on the method to be developed

In this step, the target group's needs and requirements regarding the method to be developed should be specified. The specification of requirements includes the following:

- Definition of topics for which support must be provided (an example can be obtained from Section 4.2.4)
- Definition of requirements for the documentation of information in design guidelines through which support should be ensured (an example can be obtained from Section 4.2.5)
- Definition of requirements for the search for and provision of information (an example can be obtained from Section 4.2.6)
- Definition of objectives for which decision making should be supported.

It is important that all mentioned aspects above are taken into account in the specification of requirements. If, for instance, the requirements for the information documentation are omitted and these later do not meet the needs of the target group, for example, because of a too brief description or missing content, then regardless of how well the future method works, the necessary support is not guaranteed. Therefore, a method should not be developed as an end in itself. The individuals in the target group must be actively involved in the development of the method, and their needs must set the goal for the method development.

Preparation of questions: A central component of qualitative and quantitative surveys is questions that are defined to collect information on the certain investigation subject. Author's experiences confirmed that validation of questions in advance helps to determine whether the necessary information can be fully collected by the answers given to the questions. The quality of the questions can be verified for interview studies, for example, by one or two exemplary interviews. The comparison of the results with the underlying targets quickly indicates whether further questions are necessary or whether the questions should be more specified. In the standardized survey, more attention must be paid to the review of the questions and the answer options than in the interviews, since there is no possibility of adjusting questions once the questionnaire is sent out to participants. Authors' experience proved that a pre-test contributes to optimization of the study questions and improves the quality of the survey. Further information can be obtained in Schnell et al. (2008) and Häder (2019).

Procedure for the determination of requirements in interview studies: Author's experience has demonstrated that identifying the requirements for design guidelines and the method to provide them works better indirectly, meaning that the determination takes place in context, for example, by outlining a certain case situation relevant to the interviewee. Therefore, a recommendation is to start with general questions regarding the person's experience in the area of interest, position in the company, typical tasks and related challenges in the context. Once the question relating to tasks and associated challenges is asked, the target person usually begins to explain in detail what the current state is, how tasks are currently handled and what would be useful to have as support to be able to complete them more efficiently. This is the starting point for going into detail and gathering specific information on the current needs and measures that are necessary to improve the current, sub-optimal condition. The following questions should be clarified and answered:

- What challenges/tasks are typical for the activity and the phase of product engineering in which the target person is actively involved?
- Why is the task challenging/arduous?
- What information, tools or other means currently support the person in these activities?
- Which support means are optimal/less optimal from the point of view of the target person?
- What is needed to improve support?
- Which requirements should be fulfilled in order to enable optimal support?

From the surveys, a number of subject areas for improvement appeared. As described in SPALTEN (Albers et al., 2005), information compression takes place after information generation. Therefore, all identified topics are to be sorted, evaluated and prioritized with regard to their relevance for the target group as well as the pre-defined phases and activities of product engineering for which the method is planned. The topics that can be assigned to several activities should be specified, enabling a clear assignment to a certain activity. Topics that cannot be assigned to any of the focused activities or phases should be excluded from further consideration, while topics with similar issues should be summarized.

Determination of objectives and criteria relevant for decision support: Identifying decision-relevant objectives and criteria plays an important and central role in the development of the method. Some of decision-relevant objectives can be identified in discussions with the target group. However, it is advisable to obtain them additionally through the examination of relevant information sources such as available design guidelines, recommendations, lessons learned or requirements specifications from previous product generations. If no such information is available, then decision-relevant objectives can be identified by analyzing the prototypes or final products with the aim of understanding why a certain design was chosen and what goals were pursued with a particular design solution. It is important to select products with relevant properties in order to gain relevant insight. Other methods can be obtained in Manheim and Hall (1967), MacCrimmon (1969), Kenee and Raiffa (1976, pp. 63–65), Buede (1986) and Keeney (2007, p. 13). The identification of the relevant objectives and criteria should always take place in the context of the identified topics for which decision support is required.

1) Examination of available information sources

Authors' investigations has shown that a lot of information is already available in the literature. The challenge often lies in finding relevant information, as information is distributed among various sources such as publications and books. There are two common ways to analyze relevant information sources: 1) manual analysis, reading and marking relevant text passages, and 2) tool-based support using queries for the automatic retrieval of relevant text passages. A selection depends on the number of topics for which decision-relevant objectives are to be identified. The procedure for using tool-based support, in this case, data mining, is described in detail below based on the investigations in the framework of a co-supervised bachelor thesis.

Data mining tools support the identification of documents containing the decision-relevant objectives by searching for signal words meaning that signal words must first be defined. The signal words differ depending on the investigated topic. However, the following examples have proven useful for identifying text passages in connection with objectives:[147]

- *aim/purpose/target/objective is to . . .
- *it is recommended to . . .
- *in order to / in order to avoid . . .
- *serve to . . .

In addition to such signal words, further descriptive signal words must be defined in order to focus search results on certain subject. It is not necessary to search for all possible objectives – but only for those related to the topic under consideration.

[147] According to Zhang (2018, p.35), co-supervised bachelor thesis

Defined signal words must then be formulated as search queries using the appropriate syntax rules. With the assistance of the data-mining tool, combined search expression queries can be efficiently designed and executed using, for example, Boolean operations, wildcards or a thesaurus.[148] Boolean operations can be used, for example, to include several search words in one query. To identify objectives in connection with a specific term, all descriptive words, such as {objective}, {target}, {aim}, {goal}, {purpose}, {in order to}, {serve to} and {recommend} can be connected by the <OR> Boolean operation. The command depicted as follows

```
(bead) AND (objective OR target OR aim OR goal OR purpose OR in_order_to OR serve_to OR recommend)
```

means a search for the "bead" and any search unit containing either of the words connected with OR. The <_> from the wildcard can be used to connect the words {in_order_to} in one phrase and search for them. Without this syntax, {in} and {order} and {to} are all searched for; however, this is not efficient and leads to a proliferation of results. Another important syntax is <*>, which can be used to replace contiguous characters.[149] The change of the above command to the following

```
(bead*) AND (objectiv* OR target* OR aim* OR goal* OR purpos* OR in_order_to OR serve_to OR recomm*)
```

means that not only both plural (goals) and singular (goal), but also the extensions "recommendation," "recommended" and "recommend" are searched. Table 24 presents the relevant syntax for the analyses and a short description of each.

Table 24: Some expression queries of QDA Miner (Provalis Research, 2014, pp. 144–150)

Boolean operations (AND, OR)	
AND {bead AND target}	will retrieve all those words in one sentence or paragraph
OR {aim OR purpose}	will retrieve any search unit containing either the word "aim" or the word "purpose"
Wildcard (?, *, _)	
? {wom?n}	will matche any single character (women, woman)
* {recomm*}	will match any number of contiguous characters (recommendation, recommended, …)
word_word_word	will retrieve text segments containing this phrase
Thesaurus-based searches (@)	
@GOOD	will retrieve several words or phrases associated with a single thesaurus entry previously defined ("good", "fine", "excellent", "all right", "topnotch")

[148] The description of syntax rules such as Boolean operations, wildcards and thesaurus is based on the QDA-Miner Tool. Other data-mining tools may use different designations.

[149] Ibid

The procedure for identifying objectives with the data-mining software is visualized in Figure 95 using the example of one topic gained in the interview study: "recommendation of suitable constructive reinforcements depending on targets and criteria." The term "constructive reinforcement" – also called "constructive stiffening" – refers to a particular design of a geometric element according to the acting load case and specific requirements with the aim of increasing stiffness. A stiffening effect can be achieved, for example, by applying appropriate design elements such as ribs, beads, profiles, sandwich structure and their combinations thereof (e.g., profile structure stiffened by ribs), selecting the appropriate fiber type/fiber orientation and so on.

In Figure 95, known structural elements such as beads, ribs and sandwich structures are assigned to the solution space and can be used as a first step in the search for objectives associated with these design structures. The defined search queries must be performed with each of the known solutions in the solution space. The search can also lead to the identification of further solutions for constructive stiffening, which can be iteratively included in the solution space to repeat the search for objectives with already defined queries. As soon as the syntax and important signal words are defined, the data-mining tool looks for relevant search hits in all uploaded documents. The search process for a request takes between 30 sec and 1.5 minute depending on the number of documents to be queried and the complexity of the searched query. The results should be briefly reviewed after each operation to verify the searching quality. Sometimes mistakes in defined queries can lead to irrelevant search results. Sometimes defined queries lead to a large number of search results, so further specification of the queries is useful to ensure manageability. If the search results are satisfactory, they can be saved accordingly and the search for the next topic can be started. As category A, B, C, D exemplary folders are visualized, which contain search results for a certain query. The results stored in each category need to be analyzed in the next step. This can be done directly in the tool by using for example frequency analysis or the results can be extracted in Excel tool.

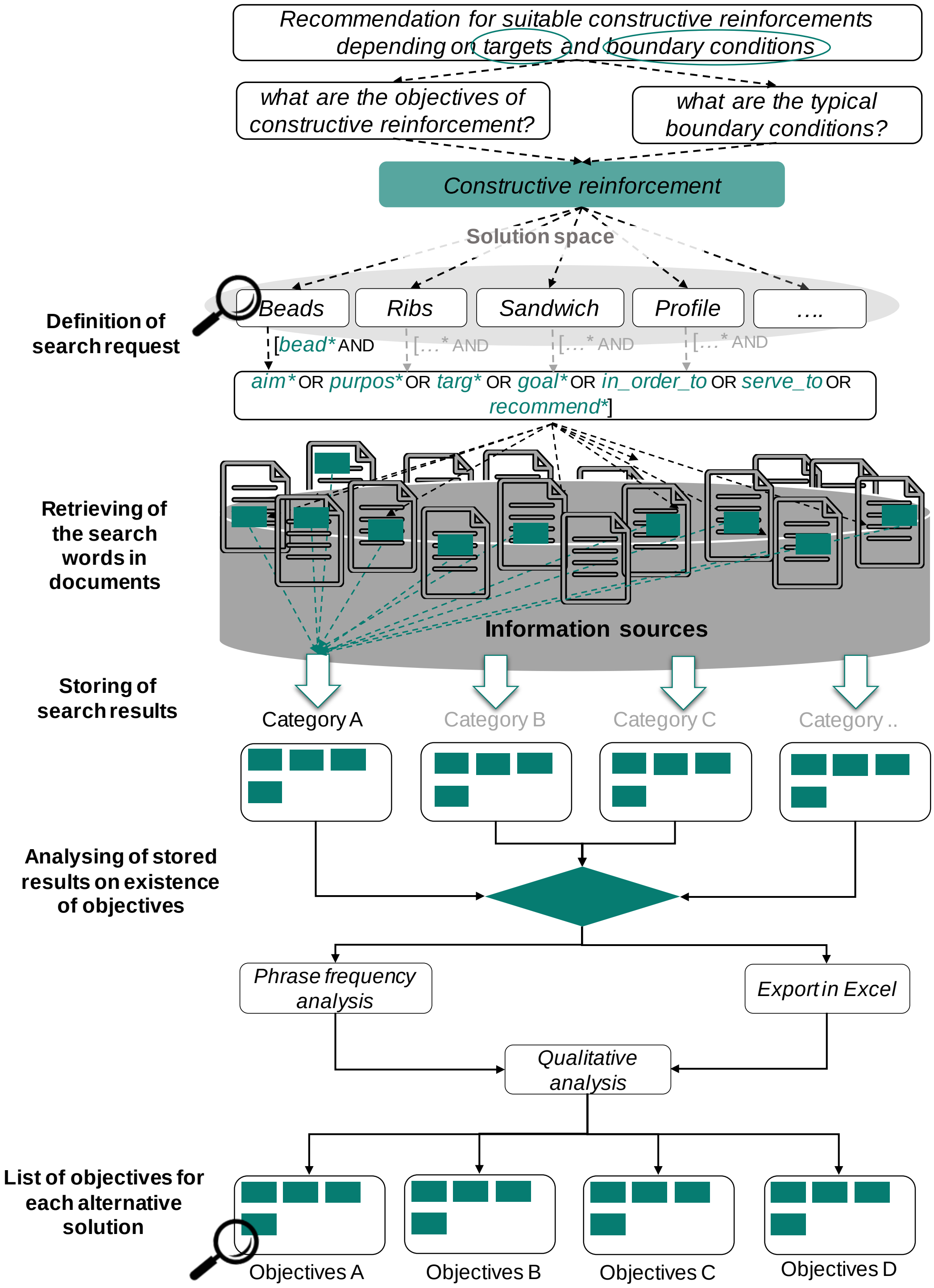


Figure 95: Approach for identifying objectives using the data-mining tool

A frequency analysis is helpful for larger data sets, as it allows all words to be grouped according to their occurrence frequency.

An example of the results achieved by a search with the data-mining tool is provided in Figure 96. The first column contains an excerpt from the original source of information, while the second column represents the derived targets, the third indicates the constructive elements that favor the achievement of the goal, and the last contains origin sources that could be helpful for later analyses.

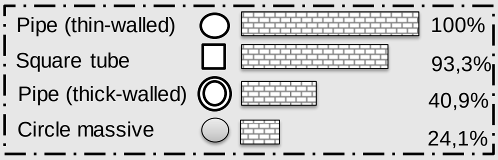
Information	**Objectives**	**Constructive elements**	**Source**
Beads serve to increase the **bending stiffness** in a limited range. It is disadvantageous that, in the case of the usual bead shape, the **tensile stiffness** across the bead is reduced.	Increase bending stiffness	Beads	H. Schürmann, 2007
In order to **increase bending stiffness** and strength particularly well, local sandwich cores can be integrated.	Increase bending stiffness	Sandwich cores	H. Schürmann, 2007
In order to **increase torsion stiffness** on wave-shaped components, the fibre arrangement of ± 45° is recommended. For **additional bending stresses**, either 0° layers or a crossing angle of less than 90° can be used (e. g. ± 15° to 30°).	Increase torsion stiffness Increase torsion + bending stiffness	Fiber arrangement by wave-shape components	VDI-Richtlinien, 2014
By torsion loading the thin-walled, closed circular cross sections are recommended. The cross-section has a great influence on **torsional stiffness**. 	Increase torsion stiffness	Cross-section form - (thin/thick-walled) - round/angular - open/closed	G. Ehrenstein, 2007

Figure 96: An example of information analysis adapted from Butenko and Albers (2019, p. 283)[150]

Definition of decision-relevant criteria: As described in Section 2.4, the criteria are important in order to assess the contribution of the solutions (here design guidelines) to the achievement of the defined objectives (Adem Esmail & Geneletti, 2017). The criteria can be defined within a bottom-up or top-down approach. In the top-down approach, criteria are defined based on an analysis of subordinate objectives, and in the bottom-up approach, they are defined based on alternative solutions (here, design guidelines). Alternatives are analyzed in terms of their strengths and weaknesses, and as a result, criteria are derived on the basis of identified differences. (Eisenführ & Weber, 1999, pp. 61–63; Marsh et al., 2016)

If a data-mining tool was used in the previous step, reusing the stored search results and analyzing the differences between the design recommendations to identify the possible criteria is advisable. These differences can easily be determined by the factors that influence the final embodiment design, which are usually explicitly mentioned in the text. Figure 97 exemplarily demonstrates how the criteria can be recognized in design guidelines.

[150] Text of design recommendations is adapted from (Schürmann, 2007, p. 638), (Ehrenstein, 2007) and (Verein Deutscher Ingenieure, 2014). The text is translated from German to English.

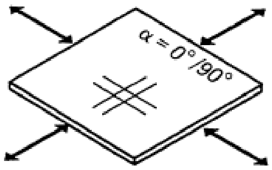
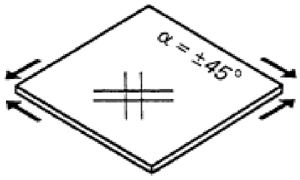
Recommendation I	**Recommendation II**
A favorable fiber arrangement of 0° / 90° for tensile and compression loads is recommended for planar structural elements. 	A favorable fiber arrangement of ± 45° for shear loads is recommended for planar structural elements. 

Figure 97: Deriving the criteria by the analysis of design guidelines[151]

In the first and second examples, the acting force is the influencing factor whose characteristics (tension, compression and shear) have an impact on the final fiber arrangement. Therefore, the characteristic of the acting force is one of the criteria that influences the final constructive solution.

Based on the result of the analyses, various criteria can be collected and brought into a hierarchy structure, as exemplified in Figure 98 for the topic recommendation of suitable constructive reinforcements depending on targets and boundary conditions.

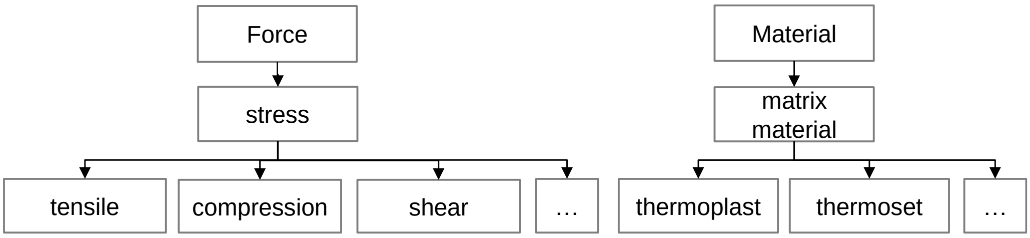


Figure 98: Example of the hierarchical tree of criteria

The first level represents a general collective term. The second is a sub-criterion that belongs to the first. The sub-criterion, in turn, can be concretized according to the specific characteristics that describe each criterion more clearly. For example, stress can be differentiated in tensile, shear, compression, flexure, torsion and combined stresses (Altenbach, 2016, pp. 3–7). It is important that the resulting criteria meet the requirements described in Section 2.4.3 which are based on Dodgson et al. (2009, pp. 35–39), Wang et al. (2009) and Keeney (1992).

It is always important to keep remember that the design guidelines and other information in the solution space are checked on the basis of defined criteria for their suitability to contribute to the achievement of objectives.

151 Text and images are adapted from (Verein Deutscher Ingenieure, 2014)

To summarize: The objectives and criteria are essential to describing situations of product developers. The more precisely the situation can be described, the better the support that can be given by the provision of relevant content.

The main results of this stage are summarized in Figure 99.

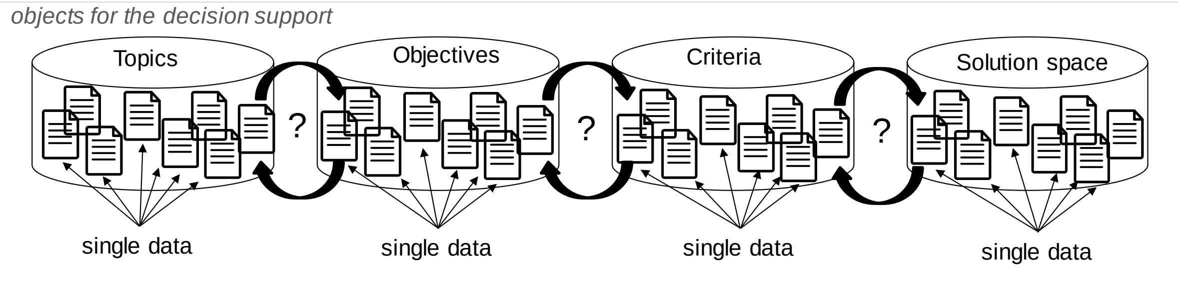
- List of topics for which support is needed
- List of requirements for the documentation of information in design guidelines
- List of requirements for searching and providing of information
- List of relevant decision-relevant objectives and criteria

Figure 99: Main results of the second phase

6.1.3 Development of information model for the decision support

The term “information modelling” is used to describe a system representation on an abstract level from the implementation considerations. The information model describes the properties and objects in a particular subject area, with a data model mapping this information model to a concrete implementation (Löschner & Menzel, 1993, p. 23).

The results of the previous stage represent general objects (e.g., topics, objectives) that form a basis for the conception of the information model necessary for the development of the method. Each of these objects initially represents only a single data collection, which is worthless without the context, as exemplified in Figure 100.



Legend:

Topics	indicate the areas where support is needed (a single data represents one topic e.g. ‘**Recommendation for suitable solutions to increase stiffness**’)
Solution space	represents the content required in design guidelines for certain topics (a single data stands for one specific issue e.g. ‘**Rib arrangement for increasing torsional stiffness**’)
Objectives	represents all relevant objectives (a single data stands for one obejctive e.g. ‘**Increasing torsional stiffness**’)
Criteria	collection of all criteria for the evaluation of issues in the solution space with regard to the achievement of objectives (a single data stands for one criterion e.g. ‘**shear acting force**’)

Figure 100: Basic elements for the conception of the information model

All these single objects must be processed, linked and put into context in order to create the information model. Three basic approaches are available in the literature to develop the models: bottom-up, top-down and middle-out approaches. (Eisenführ & Weber, 1999, pp. 61–63; Marsh et al., 2016) The bottom-up approach is a modeling strategy from specific to general. In this case, modelling begins with the solution space (design guidelines and other relevant information) and is described up to the product engineering phases. The top-down approach involves modeling from general to specific. The description of the highest level takes place first and is concretized step by step by the lower levels. For example, modeling begins with the phases of product engineering. In the middle-out approach, the modeling of the most conspicuous areas begins and is continued by combining the top-down and bottom-up approaches.

Selection of the modeling strategy: The top-down approach allows the characteristics of the solution space to be determined in a targeted and demand-oriented manner that improves the quality of decision support. In addition, the number of iterations is significantly reduced, since modeling takes place from the demand situation to the necessary solution for it, and not vice versa. If the bottom-up approach is chosen, a difference becomes visible at the latest modeling stage when items in the solution space must be assigned to the topics. Several iteration loops are often required to compensate for the differences. Therefore, the top-down approach is more appropriate for the creation of the information model in the context of the given situation.

Modeling of the access part: Since the top-down approach is chosen, the information and data model of the access part is initially the starting point, as visualized in Figure 101. The access part has an interaction with stakeholders (the users of the method) on one side and with other parts of the method on the other side.

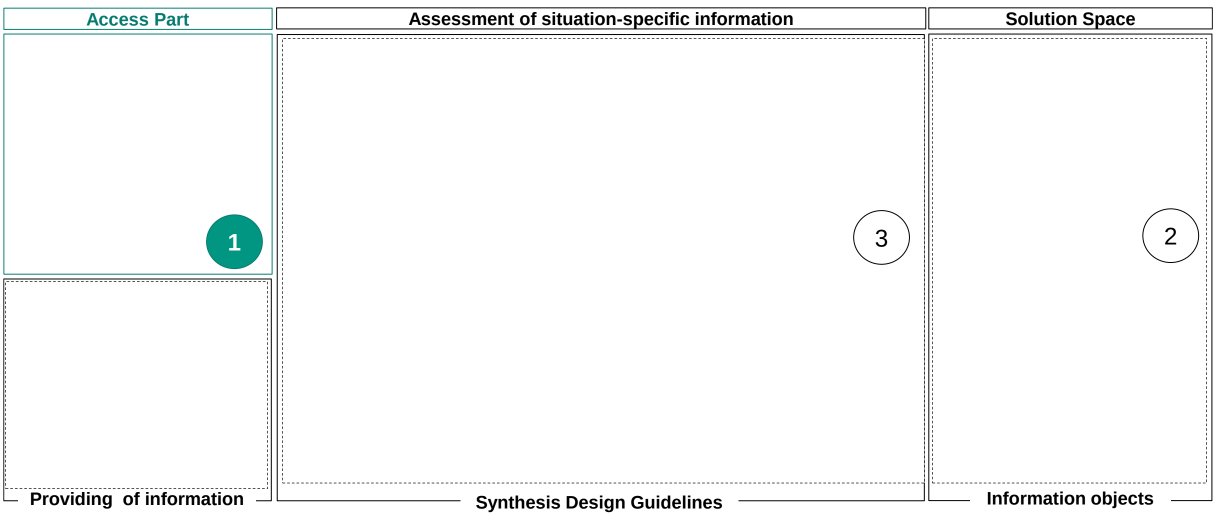


Figure 101: Generic overview (access part on the left side)

First drafts for creating of the access part structure were performed by Nicolini 2017.[152] It is important to focus only on the phases and activities of product engineering that are defined in previous steps and that are relevant for the development of the method. In the first step, each phase of product engineering should be described by the relevant activities. The assignment can be defined by answering the following question: Is activity X relevant in phase Y? If the answer is yes, then the activity is assigned to the phase, as exemplified in Figure 102.

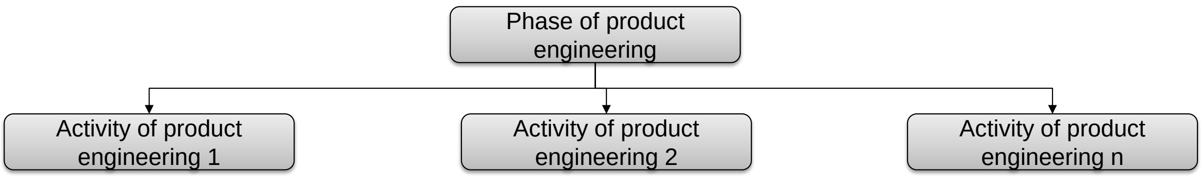


Figure 102: Modeling of the phases and corresponding activities of product engineering

In the next step, the topics identified as a result of performed surveys must be assigned to the corresponding activity. If one topic can be assigned to several activities, then its assignment should be specified, for example, by the reformulation or division into further sub-topics. The well-defined formulation of topics is important so that the target group can also clearly interpret them by selection later in the decision support system. The assignment is defined by answering the following question: Is topic X relevant in activity Y? A positive answer leads to the assignment of the topic to the corresponding activity, as exemplified in Figure 103.

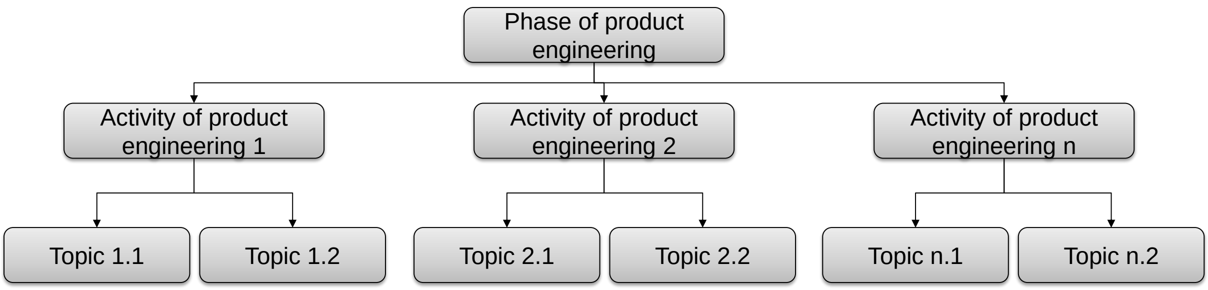


Figure 103: Modeling of phases, activities and topics

Next, the objectives identified need to be assigned to the certain topics, as illustrated in Figure 104. The assignment is defined by answering the following question: Is objective X relevant for topic Y?

[152] Co-supervised bachelor thesis

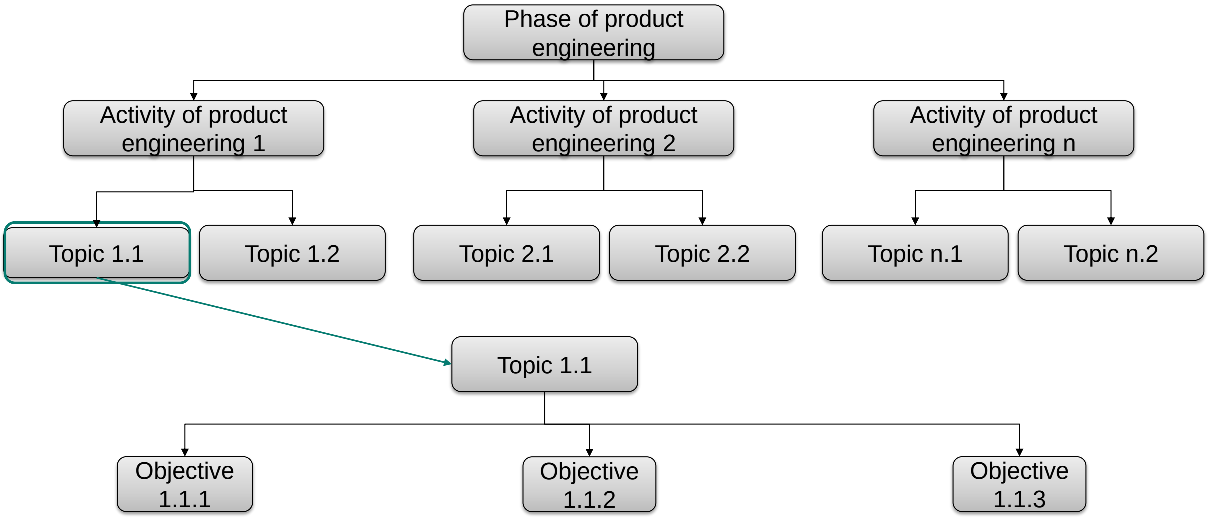


Figure 104: Assignment of objectives to the topic

The next step is to assign the identified criteria to the objectives. If some criteria remain unassigned to the objectives, then closer consideration with two alternatives is possible: 1) define a further objective specifically for the unassigned criteria or 2) exclude the unclassifiable criteria from further consideration, as exemplified in Figure 105. The review can be established by answering of the following question: Is criterion X relevant for the specification of objective Y? If the answer to this question is positive, then the criterion cab be assigned to objective in question.

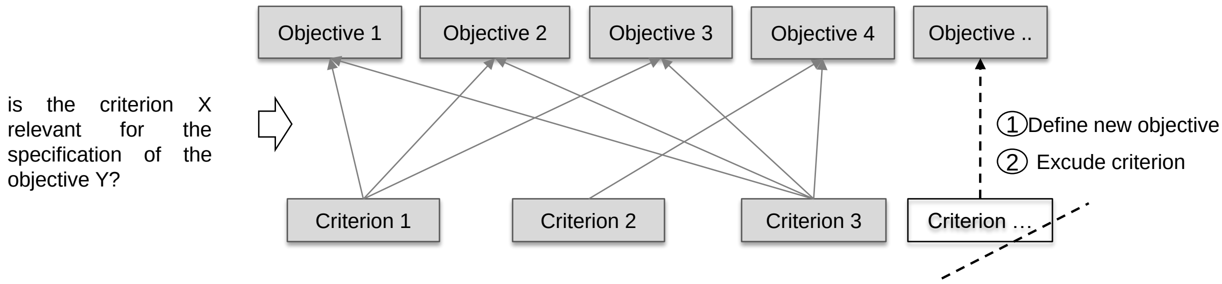


Figure 105: The review of criteria

It is important to discuss the criteria and their assignment to the objectives with the target group. The final decision as to whether further objectives must be defined to cover the unassigned criteria should be made together with that group. An example of the assignment of the criteria to the objectives is visualized in Figure 106.

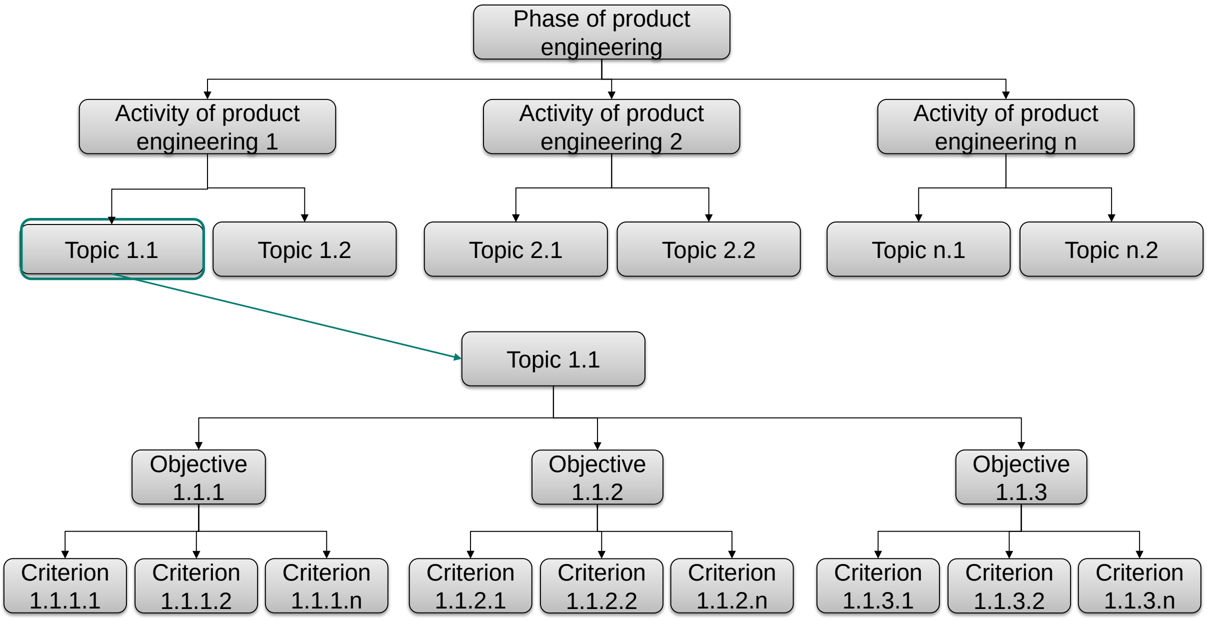


Figure 106: Assignment of criteria to objectives

These five levels – phase of product engineering, activity of product engineering, topic, objectives and criteria – serve to concretize the user situation, and they can be designated as an access part. Initially, all potential user situations are available. These situations are then filtered in five steps to achieve one appropriate situation for which support is needed. Therefore, each option in one level can be imagined as a tree structure consisting of a root node, any number of inner nodes and at least two leaves. Each node represents a logical rule, which links to the next relevant options on the next level.

Modeling of the solution space: Once the modelling of the access part is completed, the modeling of the information objects in the solution space occurs, as depicted in Figure 107. As information objects, certain design guidelines are designated, and the aim of the modeling is to clearly define and specify their attributes that are required for information purposes, their relationships among different information objects and their interrelation to objects in the access part.

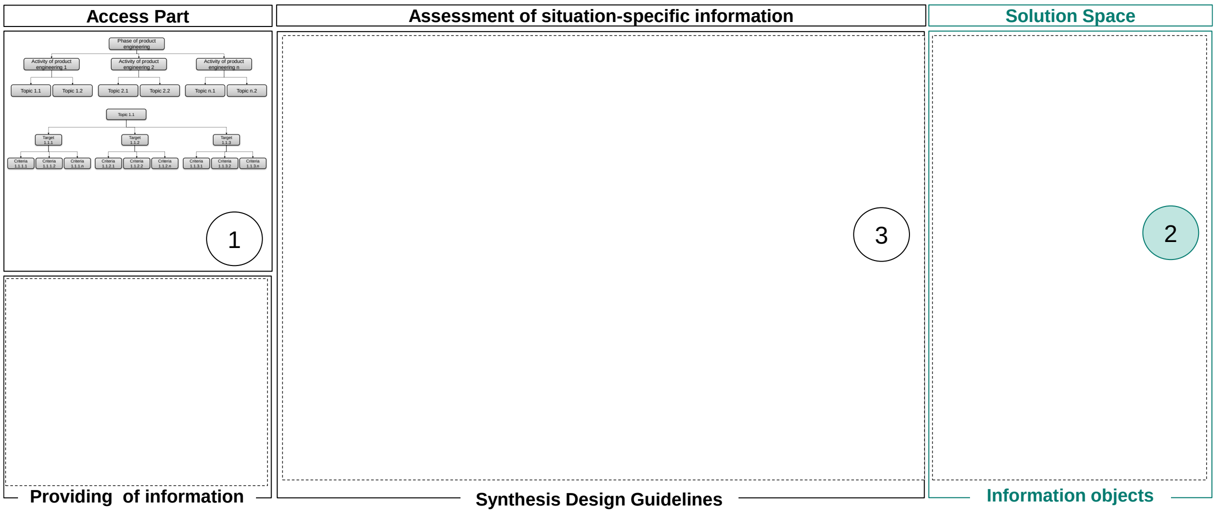


Figure 107: Generic overview (solution space on the right side)

The documentation of information, whether in the form of design guidelines, lessons learned or recommendations, always takes place in the context of certain objectives, with the aim of providing information and drawing attention to specific aspects. Therefore, the modeling of information objects in the solution space should also be done in the context of specified objectives in the previous steps. As input, serve the analyses performed in the previous stage either through the data-mining tool or through other methods. This time, however, it is not a matter of extracting objectives and criteria, but of analyzing which design characteristics relate to the achievement of certain objectives. As result, a transparent overview of correlations between objectives and design characteristics can be created. Figure 108 presents an example of how this correlation can be derived and visualized in a simple model. On the left side design recommendations for SMC material which contain information about objectives and related rib design characteristics are presented. The lower part presents the two exemplary objectives (avoid sink marks, ensure proper demolding) associated with ribs as a structural component. The upper part features the design characteristics of a rib such as rib radii, rib draft angle and rib thickness for which the recommendations on the left side are given. The design of these elements depends on the objectives and can be additionally influenced by other factors such as certain criteria[153]. Based on the information on the left side, it is apparent that avoiding sink marks can be influenced by the interaction of three design characteristics such as radii, draft angle and rib thickness. Ideally, design guidelines should provide information on all design elements that may favor or disadvantage the achievement of a certain objective. Therefore, it is important that the information and data model transparently captures all relevant relationships.

[153] More information on the influence of criteria is provided later

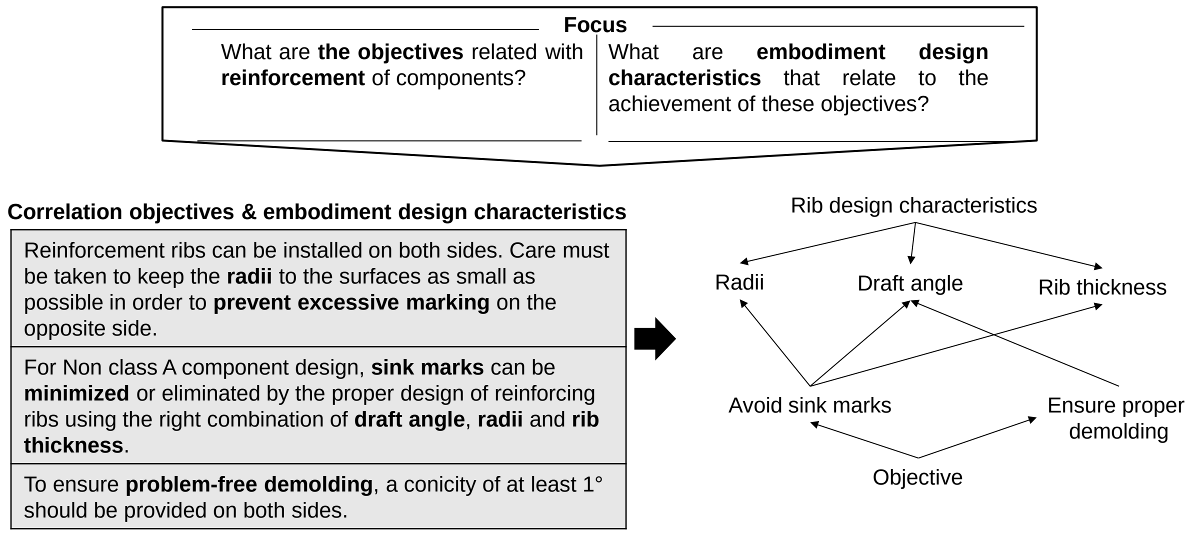


Figure 108: Correlations between objectives and design characteristics[154]

As the analysis progresses, the models gain in information content, as visualized in Figure 109. First, visualizing the relationships between objectives and design characteristics of a certain structural component, demonstrates how diverse the relationships are and that same design characteristic can be related to several objectives simultaneously. For example, a different rib arrangement is needed to increase the flexural stiffness than to increase torsional stiffness. In addition, warpage can also be influenced positively or negatively by the rib arrangement (BASF SE, 2014).

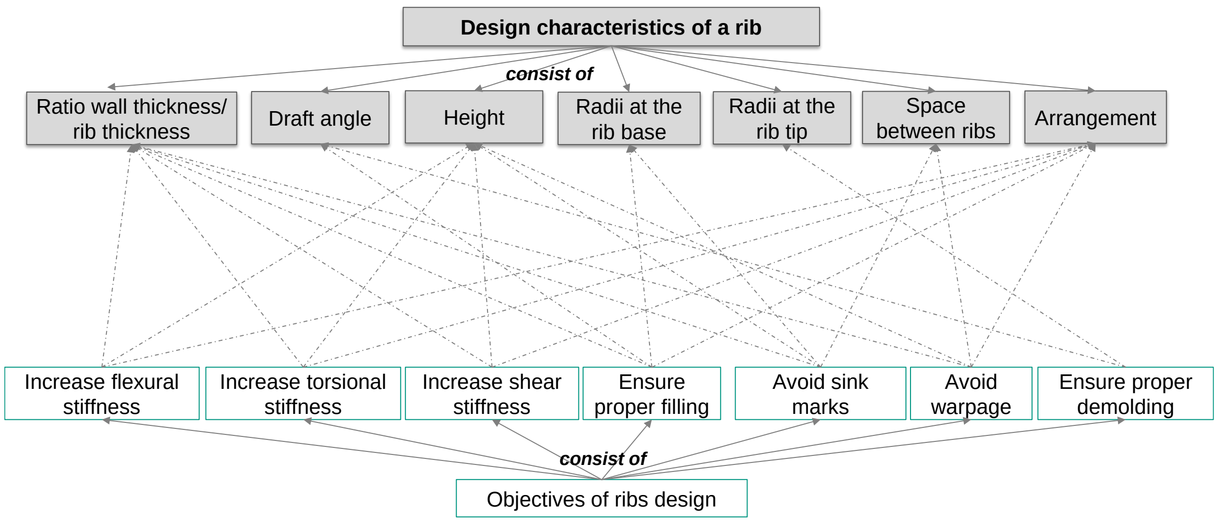


Figure 109: Model draft – an example of the rib design characteristics based on Butenko and Albers (2019, p. 284)

[154] Text on the left side is adapted from 1) Wernli (1998, p. 49), 2) European Alliance for SMC/BMC (2007), 3) AVK – Industrievereinigung Verstärkte Kunststoffe e. V (2013, p. 421). Text is translated from German to English.

Such models should be created for all topics and related objectives. This is time-intensive work but is an absolute prerequisite for the provision situation-specific information in design guidelines. All information models should be discussed with experts to verify the correctness of the defined relationships and to revise the models if necessary.

Modeling of dependencies between criteria and information objects: As already mentioned, in addition to the objectives, the criteria[155] also influence the design characteristics of constructive elements. The consideration of criteria in the creation and description of design guidelines is decisive for their practical applicability. As described in Section 2.3.4, the existing recommendations barely consider design characteristics in connection with manufacturing and material influences, both of which are important when designing with certain FRP materials. Three simplified situations are used below to illustrate the influence of criteria on providing situation-specific design guidelines. Figure 110 shows on the left side an exemplary objective to be considered in the design of ribs. As visualized in Figure 109, the achievement of this objective relates to four design characteristics of the rib. Therefore, as a result, a design recommendation which contains information on this objective and these four design characteristics. However, if the focus is not on a specific material[156] and manufacturing process, then no concrete design information, but rather general information about the role and influences of these four design characteristics on the achievement of the specified objective, can be provided. On the right side, the result is symbolically provided in a so-called "static block," which means that the content is generic and independent of the certain material or manufacturing process parameters. It is important that even if there is no concrete material in focus, a clear framework for the applicability of provided information be defined, because the field of FRPs is wide and it is impossible to define general information that applies to all FRP materials. However, for the certain material types such as SMC, BMC, LFT and so on, general information can be defined. This works better because such material types are roughly clustered by resins, fiber materials, fiber length range and manufacturing process[157].

[155] Material and manufacturing process are one example for the criteria.

[156] Specific material is understood to refer to the concrete designation of resin type, fiber material and length, fiber volume content and so on.

[157] An example of clustering: SMC is a class of materials based on thermoset resins that can be reinforced with glass or carbon fibers. The fiber's length can vary between 25 and 50 mm, and the typical fiber volume content is between 25% and 30% of weight, but can also be adjusted to up 60%. Compression molding is commonly used as a manufacturing process.

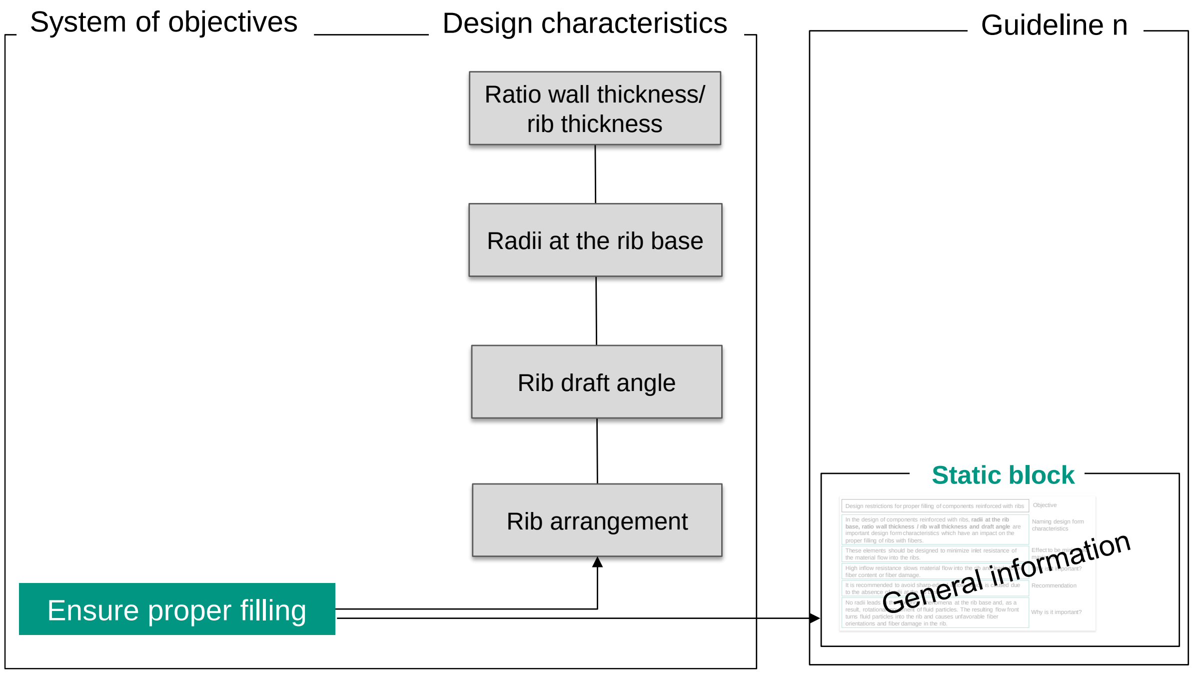


Figure 110: Influence of criteria on information providing – first case

A further situation is depicted in Figure 111, with the objective remaining the same but with a few certain criteria being defined in addition. These include a concrete material, fiber length and volume content and certain manufacturing process.

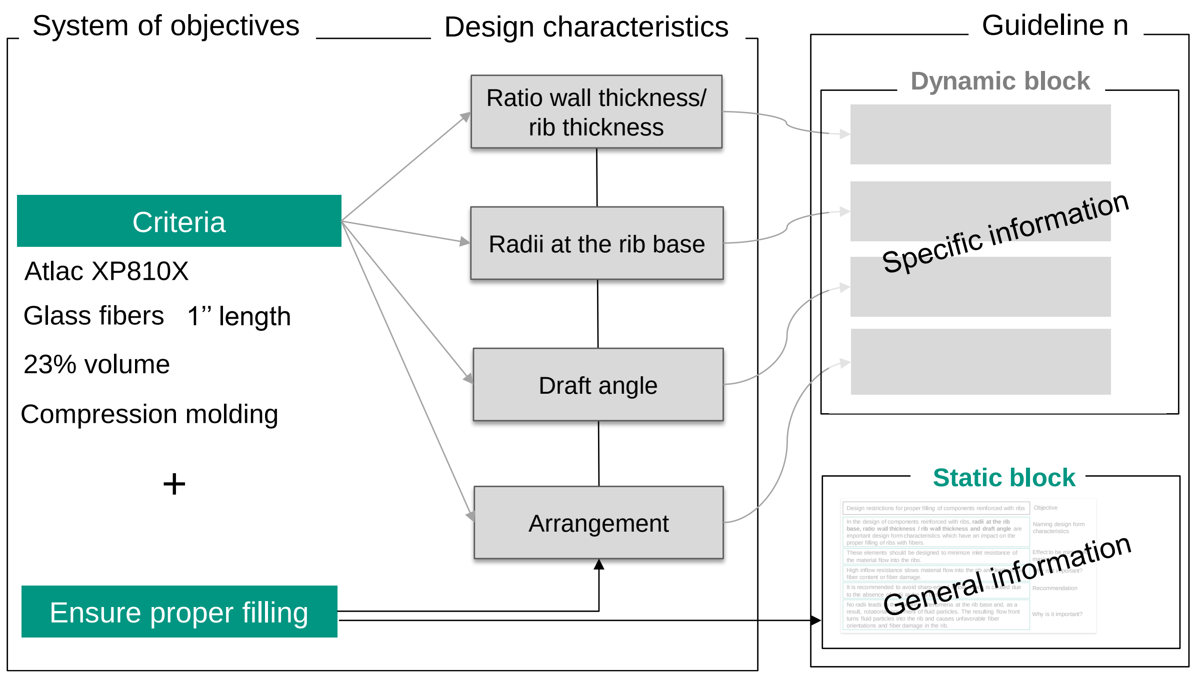


Figure 111: Influence of criteria on information providing – second case

On the level of design characteristic, the same four elements are relevant, as the objective remains un-changed. However, this time, the focus is not the generalized content, but rather specific design recommendations that consider the defined material, the manufacturing process and the objective. As result, the relevant information objects containing relevant recommendations are synthesized in a so-called dynamic block – final design guideline. The dynamic specifications are the contents in the dynamic block that change depending on the objective and criteria and therefore cannot be generalized.

As described in the state of the art, SMC materials can be reinforced with glass or carbon fibers (AVK – Industrievereinigung Verstärkte Kunststoffe e. V., 2013, p. 245). In case of a change in the material system components specified in the system of objectives,[158] it is possible for certain information objects in the dynamic block to remain valid despite this change and for others to need to be synthesized to new ones. As visualized in Figure 112, the specification of the information object for draft angles also applies to SMC material reinforced with carbon fibers, whereas three other recommendations are modified accordingly to the change in the criteria.

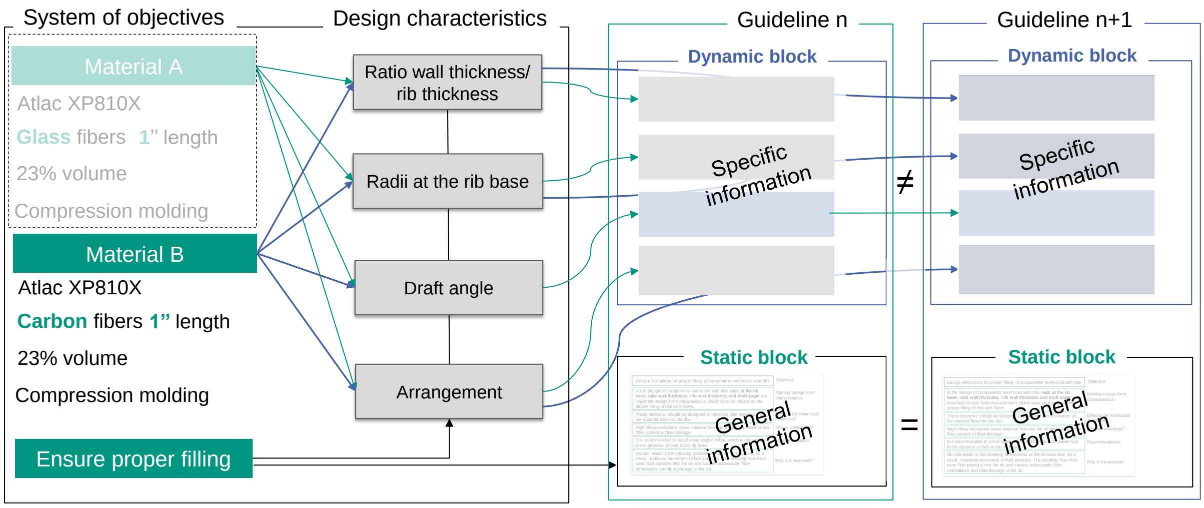


Figure 112: Influence of criteria on providing information – third case

Each of the design characteristics can be specified by certain dynamic and static specifications. The description of the dynamic specification is done in relation to the certain objectives and criteria, with the static specification needing the description in relation with the certain objective. One design characteristic can have a number of dynamic and static specifications, as exemplified in Figure 113 using the example of some recommendations for a draft angle. Here, the specific recommendations for the suitable draft angle for the different materials represents the dynamic specifications. A general explanation for why draft angles are important belongs to the static specification.

158 Objectives and criteria form together a system of objectives

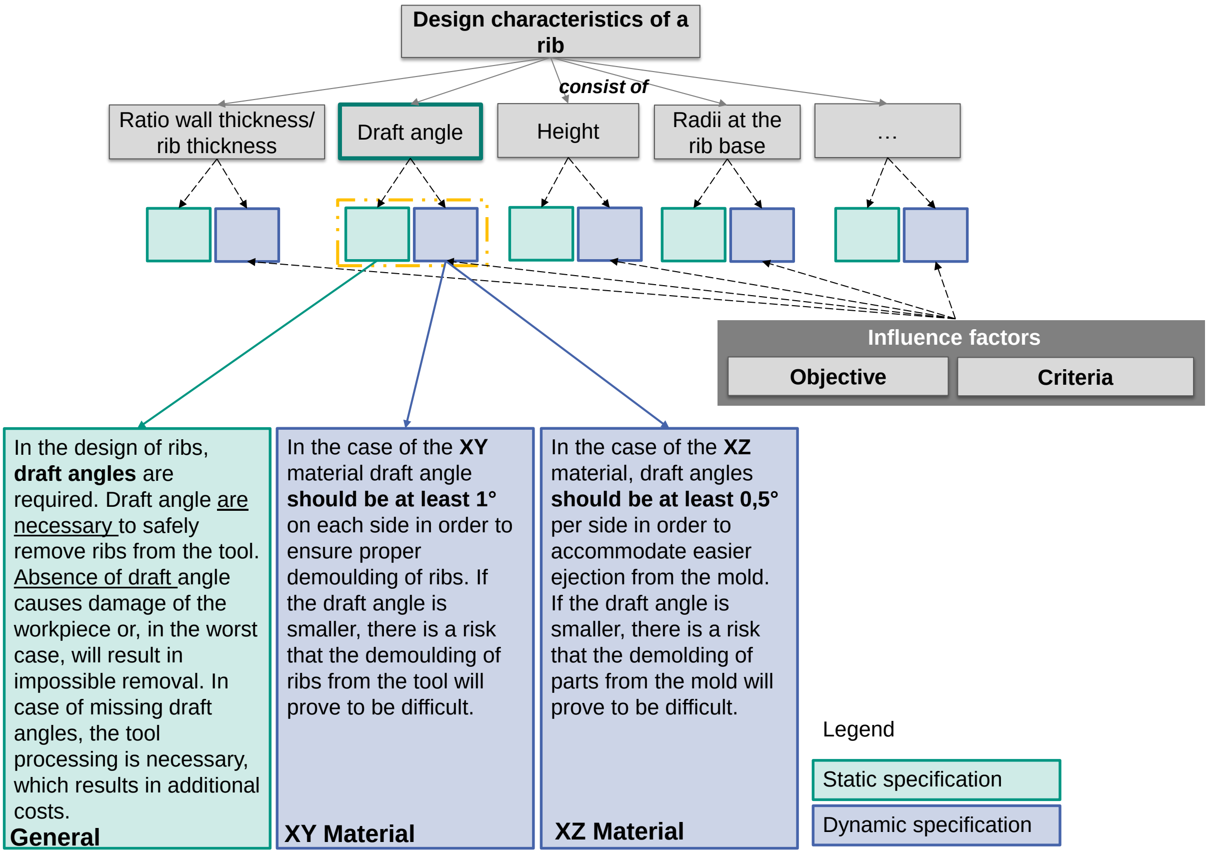


Figure 113: Static and dynamic design specifications based on Butenko and Albers (2019, p. 285)

Creating and describing information in the solution space: The situation-specific provision of information in a design guideline means that a design guideline synthesized as a result only has relevant content with regard to the objectives and criteria in focus. However, for such a synthesis, a fulfillment of certain prerequisites is necessary; this is considered during the creation design guidelines: 1) transparency about clear criteria for the applicability of the design guideline and 2) one and not several objectives in focus. If several objectives are addressed in one design guideline, then a high number of relevant design characteristics are also affected. Consequently, however, the search for the certain design guideline of a concrete objective results in much more information that is irrelevant and may even lead to confusion. In summary, the process of creation design guidelines can be described as a modular system in which each recommendation contains information with regard to a certain design characteristic, certain objective and certain criterion, as presented in Figure 114. Such a structure allows the reusability of recommendations, for example, if they apply to different objectives and materials. A further advantage of the modular structure is that as soon as new design guidelines are created for a further material composition, on the one hand, the recommendations that are already created can be reused to a certain extent, and on the other hand, the structure[159] created can serve as a guide for the creation of new design guidelines. The described procedure applies only to the creation of design guidelines that are managed and provided by a tool-supported solution. The procedure is not suitable for documentation in books, as the complexity is too high.

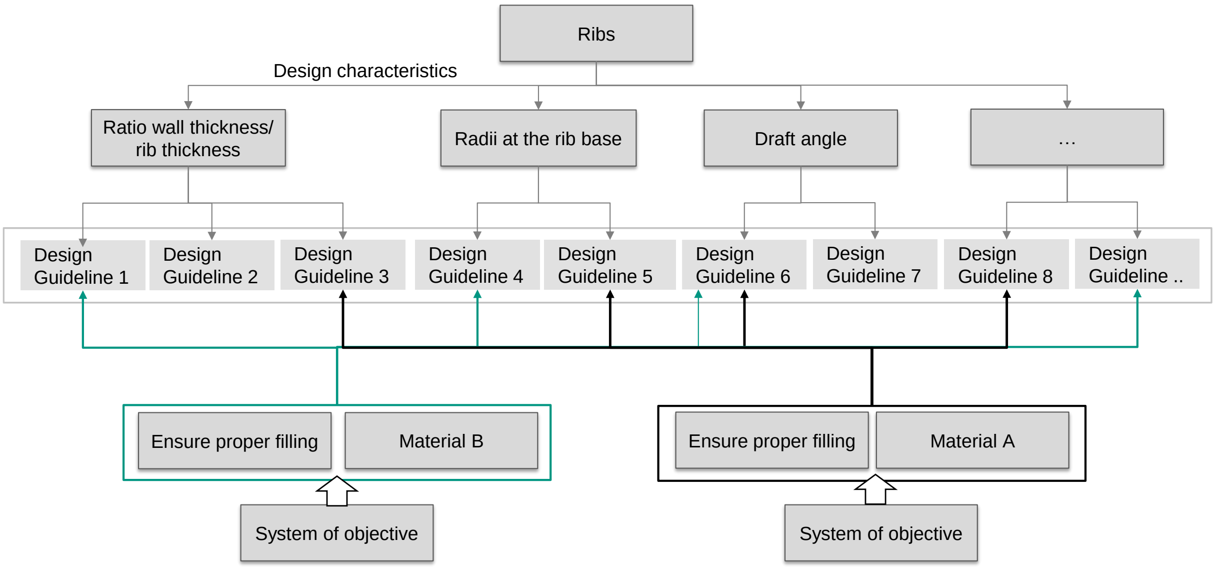


Figure 114: Modular structure of design guidelines

Process model for the targeted creation of the design guideline: Information and data in the solution space play an important role in decision support. The information model and the understanding of the interrelationships among the objectives, criteria and design characteristics of certain structure components established in the previous step enables the structured creation of new design guidelines or the reworking of existing guidelines. The formulation and structure of information in design guidelines to maintain proper quality and targeted documentation can be supported by following the created process presented in Figure 115. The creation of new design guidelines takes place in three stages:

1) Definition of the framework conditions for the design guideline application
2) Documentation of information in the design guideline
3) Visualization of information in the design guideline.

[159] As structure is understood created system of objectives, design characteristics of structural elements and their relationships

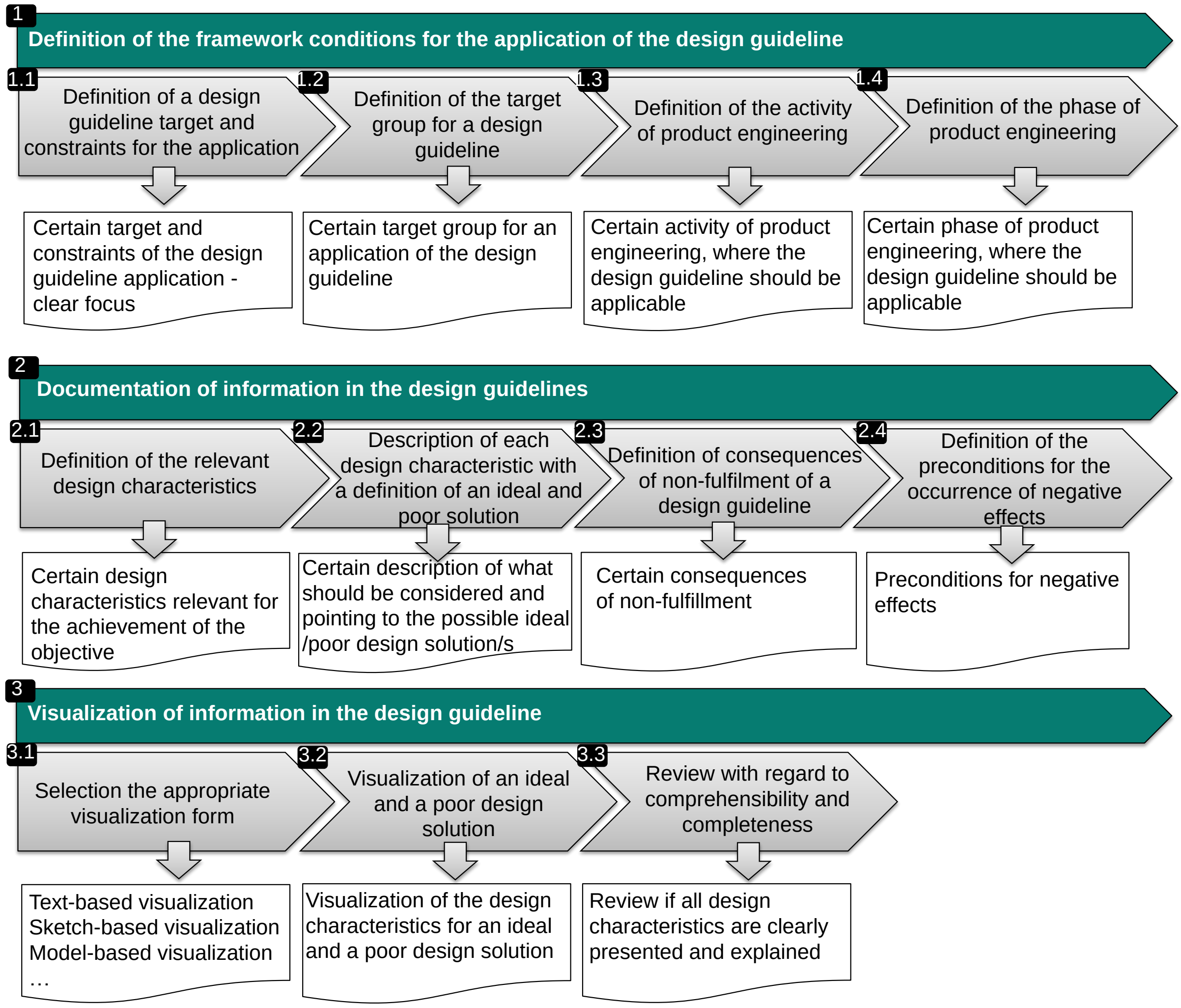


Figure 115: The process model for the targeted creation of the design guideline

The first step is a definition of the following:

- The objective and corresponding criteria for which the design guideline should be developed.
- The target group for the design guideline application.
- The phase and activity of product engineering, in which the design guideline can be applied.

The definition of objectives and criteria provides a clear focus for the creation of the design guideline. Knowing who the target group is and in which phases and activities of product engineering information is required is useful in the formulation of design guidelines. This clear assignment is also necessary to ensure mapping between the assess part and the solution space, as illustrated in Figure 116.

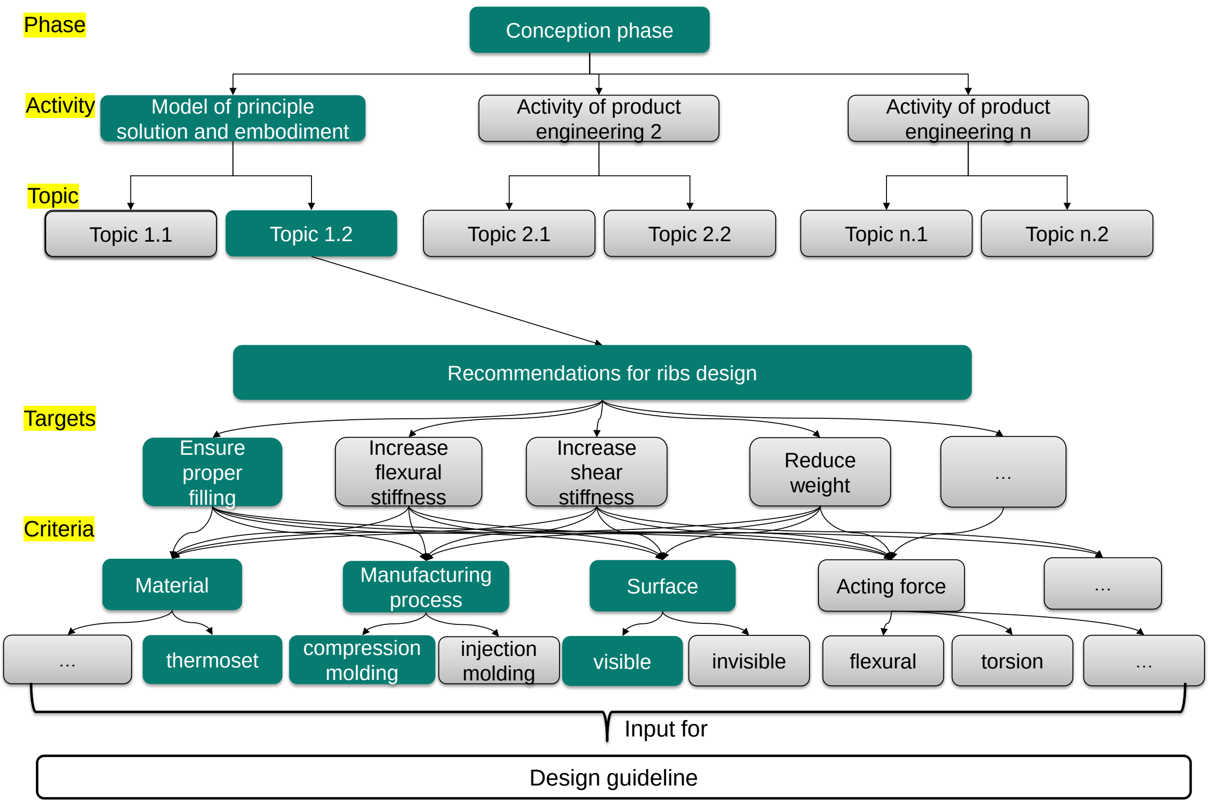


Figure 116: Definition of the framework conditions for the design guideline application and creation

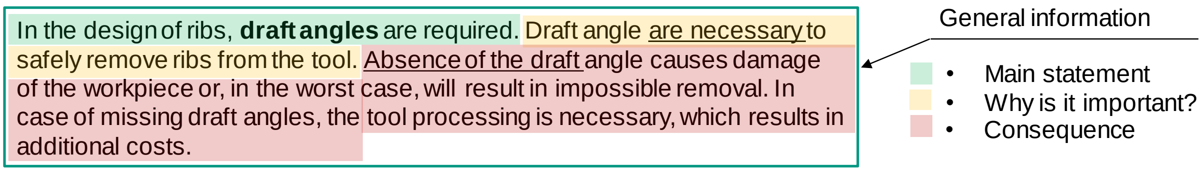
After clarifying the framework conditions for the design guideline application, the documentation of information takes place. The investigations in the study, described in Section 5.1, demonstrate that the information presented in different ways (text-based, ideal and poor solutions with brief text, and C&C²-based representation of ideal and poor solutions with brief text) can be assessed to be helpful in different ways to stakeholders with small and large experiments. However, creating different design guidelines for experienced and less-experienced stakeholders if both are the target group is not recommended, as such entails high effort in creation and maintenance. It is much more important to create design guidelines that are equally suitable for stakeholders with different levels of experience.

Documentation of information: As a first step it is important to define all design characteristics that relate to the achievement of the given objective. The model created to describe the relationships between objectives and design characteristics provides the basis for structuring. Once it is clear which design characteristics are in focus, starting to create the static block is recommended. Although the static block contains rather general information, it still has an important meaning, as it provides an overview of the relationships between a specific objective and the associated design characteristics. When designing with similar materials for which, for example, no specific information is available, the static block can be helpful, as it provides general information about what is usually relevant to consider[160].

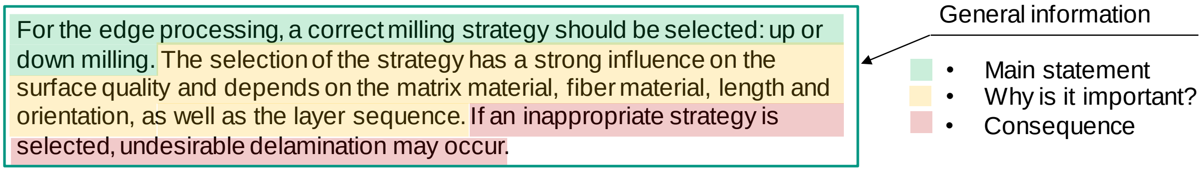
With regard to the description of general information, the aim is to inform about all relevant design characteristics following three rules:

- Description of the main statement.
- Explanation for why it is important to consider the provided information.
- Description of the consequences that can occur if the provided information is not considered.

Two simple examples of the description of general information are provided in Figure 117 (a) and (b).



(a) Manufacturing restrictions for the design of draft angles



(b) Milling strategy to avoid delamination

Figure 117: Example for the description of general information based on Butenko and Albers (2019, pp. 286–287)[161]

A dynamic block consists of information objects with specific information considering certain material, meaningful images and corresponding explanations. It is recommended that only one specific objective and one design characteristic be addressed in the certain information object. This is important in order to later enable an interactive, target-oriented compilation of information objects in a design guideline. In addition to the description, an ideal and a poor design solution for the relevant embodiment design characteristic should be visualized. The consequences of the unfavorable solution should be described explicitly, along with the prerequisites for the occurrence of negative effects. An example of the description of the specific information in one information object is provided in Figure 118.

[160] By designing the demonstrator described in Section 5.2, the available general information on relevant design characteristics (radii, wall thickness etc.) was quite helpful to gain first ideas on design draft.

[161] (a) and (b) figures are slightly modified and presented in a short version in this thesis.

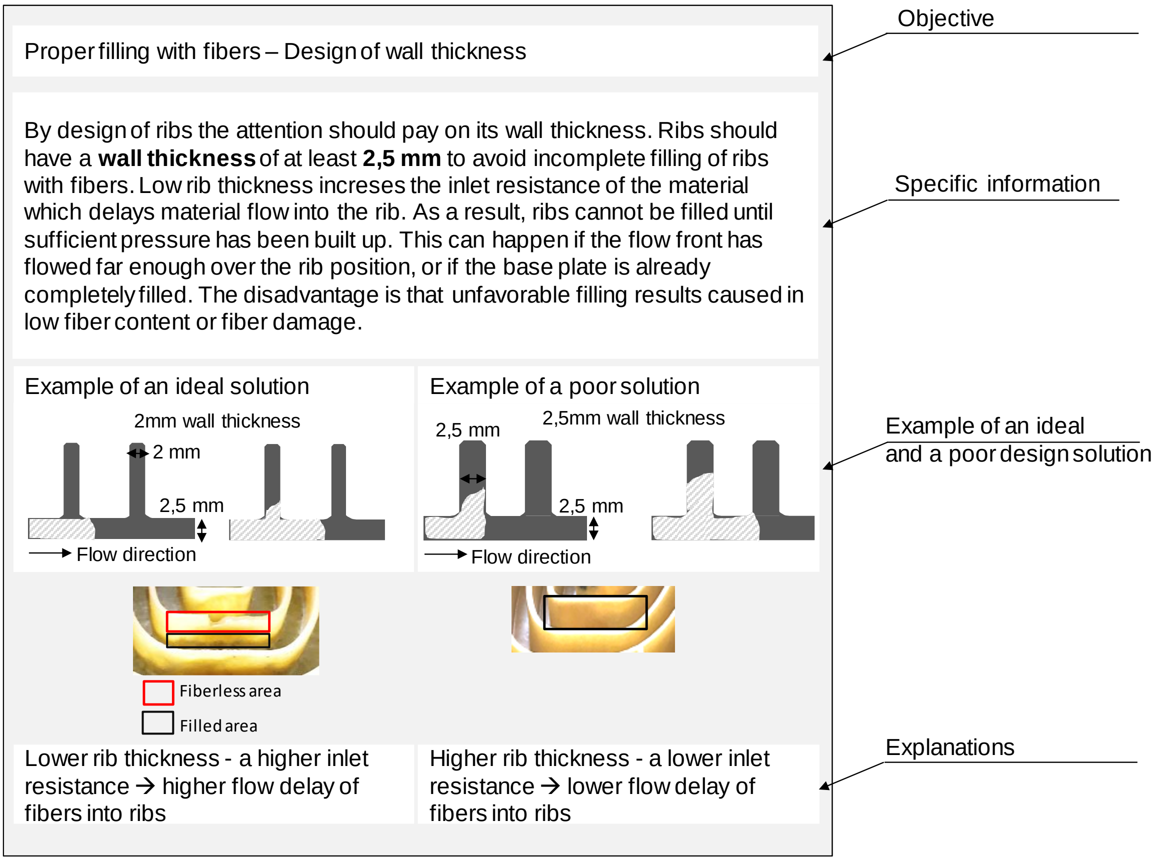


Figure 118: Example of the description of specific information

The structure presented for documentation is based partly on the work of Albers et. al (2009) and partly on the exchange with the industry representatives provided in Section 4.2.5. The use of both text and graphics, for example model-based visualization and sketch-based visualization to explain the essential details, is generally recommended and desired by industrial representatives, as described in Section 5.1.

The final step is to review the created recommendation with regard to its comprehensibility and completeness. For this purpose, the checklist provided in Figure 119 can be used on the one hand, and review by technical experts on the other.

- Content of the recommendation is clearly linked to the objective of the recommendation
- Concrete recommendation on “what should be considered” is provided
- Explanation “why it is important to follow the recommendation” is described
- Consequences “what can happen in case if the given recommendation is not taken into account” are stated
- Effects that lead to the negative consequences are described
- Visualization of ideal and poor solutions is provided with a short explanation.

Figure 119: Checklist for checking design guidelines regarding the completeness of described contents

6.1.4 Developing decision matrix and their validation

After defining all relevant objectives and criteria for the access part and information objects for the solution space, the development of decision matrices takes place, as illustrated in Figure 120. The aim is to define rules for evaluation of information objects stored in the solution space regarding their suitability to support users in different situations.

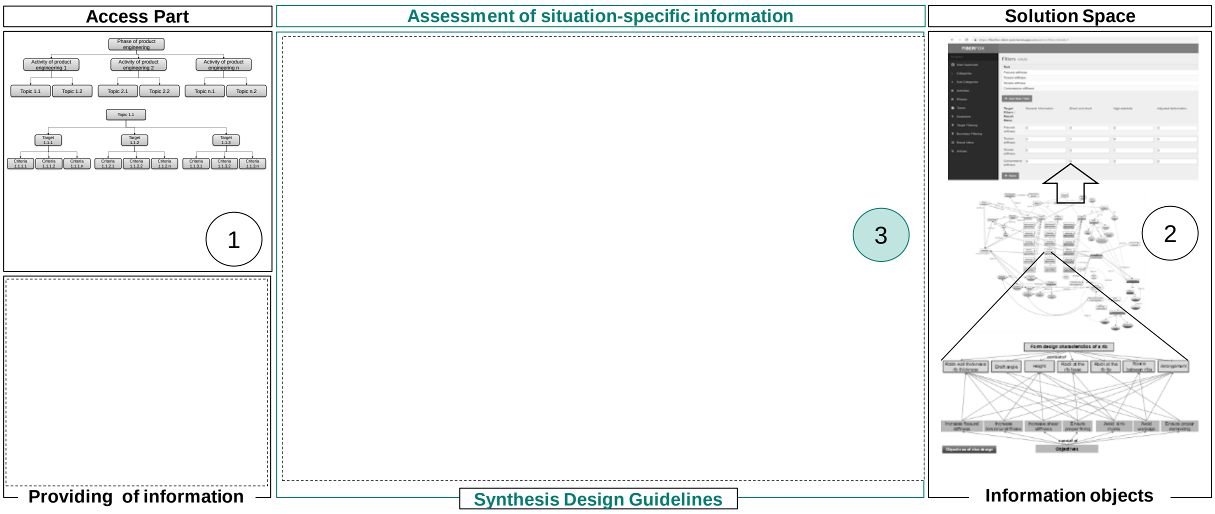


Figure 120: Generic overview (assessment of situation-specific information in the middle)

Scoring on information objects with regards to criteria and objectives: The scoring on the information objects provides information about their performance in relation to each relevant criterion and objective. The preference expression shall be as follows: 1) adapted to information type, 2) comfortable for a decision maker to use, and 3) applicable to a decision situation (El Amine et al., 2014). A number of methods, such as subjective, objective, or combined methods and rules, for their selection exist in the state of the art and are described in Section 2.4. However, since each information object only contains information for a certain objective and certain criteria, the assessment can be performed only in terms of the possession or non-possession of a particular characteristic on a nominal scale using the simplest densitometric variable. Therefore, the weighting can be evaluated as follows: a 0 value for non-possession and a 1 value for possession of a particular characteristic, as illustrated in Figure 121. Information object 1 is suitable, for example, for material XY, so the criterion is assigned a value of 1, and the criterion “material XZ” receives 0 in the assessment matrix. By assessing of information objects relating to the objectives, the 0 evaluation can be done if the information object does not contribute to the fulfillment of the objective, and the evaluation with value 1 can be done if the information object contributes to the objective. The evaluation can be carried out objectively by the qualitative comparison of information in the information objects with defined criteria/objectives or with the support of experts in the corresponding area if the assignment is not clear. The filled performance matrix is the result of this step.

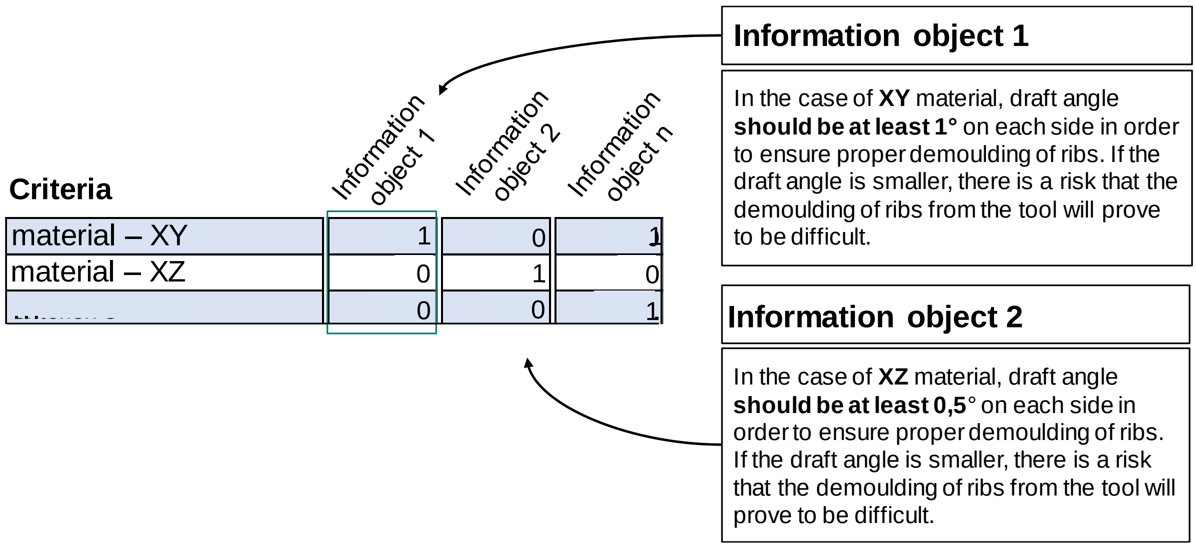
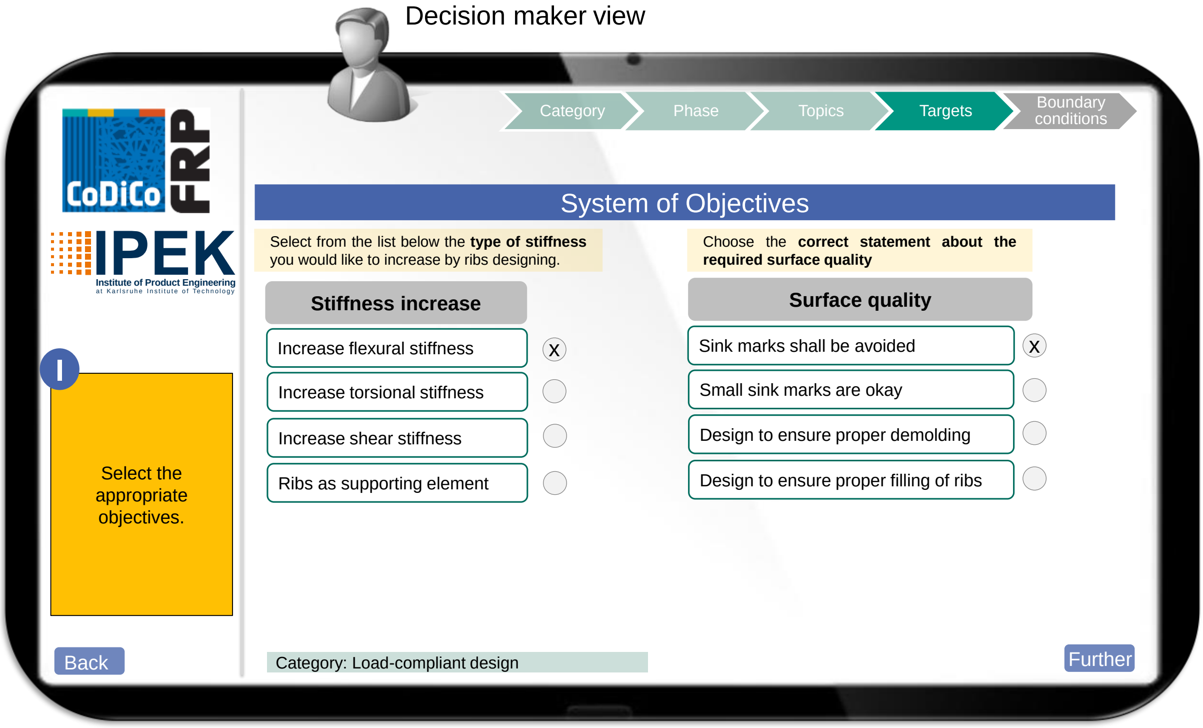


Figure 121: Evaluation of information objects with regard to criteria on the nominal scale

Scoring on criteria and objectives: A scoring on criteria and objectives indicates how important they are to users in terms of finding a solution to their certain situation. The scoring of values by a decision maker has advantages, as assigning the importance can be performed interactively during the definition of his or her actual situation. This procedure allows users to individually prioritize their objectives and criteria to be achieved. Figure 122 illustrates the procedure for the conversion of selected objectives into numerical values. In the upper part, view of the user (the interface between any user and user interface) is displayed, and the lower part depicts the interaction between the user interface and the database. Once an objective is selected, the appropriate decision matrix is activated in the background and an active value[162] is assigned. The value 0 is assigned to objectives and criteria that are not selected.

Decision maker view



Transformation of the selected objectives in background

Objectives		Information object 1	Information object 2	Information object 3
Increase flexural stiffness	3			
Increase torsional stiffness	0			
Increase shear stiffness	0			
Sink marks shall be avoided	3			

Figure 122: Interactive weighting of the objectives by the decision maker during the definition of his or her situation

Calculation of overall performance: The overall performance of each information object is measured according two values: (1) the relevance of the information object with regard to prioritized objectives and (2) the relevance of the information object with regard to prioritized criteria. The first value is calculated by the multiplication of each prioritized objective weight (t) on each related information object (a) and the total of all results as performance value $p_t(a_1) = (t_1{*}a_1) + (t_2{*}a_1) + (t_3{*}a_1) + \ldots (t_n{*}a_1)$; $p_t(a_2) = (t_1{*}a_2) + (t_2{*}a_2) + (t_3{*} a_2) + \ldots (t_n{*}a_2)$, as seen in Figure 123.

162 In the provided example, a value of 3 is assigned to the active objectives. The choice of whether this value should be 1, 3 or some other number can be made by the developer of the method.

	Topic: Recommendations for Rib Design							
		Weighting	ID-Nr of information objects					
			a1	a2	a3	a4	a5	a..
	Objectives		IO1	IO2	IO3	IO4	IO5	IO..
t1	Increase flexural stiffness	**3**	0	0	0	**1**	0	**1**
t2	Increase torsional stiffness	0	0	**1**	0	0	0	0
t3	Increase shear stiffness	0	**1**	0	0	0	0	0
t4	Ensure proper demolding	**3**	0	0	**1**	0	**1**	0
t5	…	0	…	…	…	…	…	…
	Result		0	0	3	3	3	3

Figure 123: The calculation of the performance value in relation to defined objectives[163]

A similar procedure is needed for the calculation of the performance of the information objects with respect to the relevant criteria. The calculation is realized by multiplying each related criteria weight *(c)* with each information object *(a)* and the total of all results as the performance value $p_c(a_1) = (c_1*a_1) + (c_2*a_1) + (c_3*a_1) + \dots (c_n*a_1)$; $p_c(a_2) = (c_1*a_2) + (c_2*a_2) + (c_3* a_2) + \dots (c_n*a_2)$, as seen in Figure 124.

	Topic: Recommendations for Rib Design							
		Weighting	ID-Nr of information objects					
			a1	a2	a3	a4	a5	a..
	Criteria (Material)		IO1	IO2	IO3	IO4	IO5	IO..
c1	Material System (Atlac XP810X)	**3**	**1**	**1**	0	**1**	0	**1**
c2	Material System (Atlac XP810Y)	0	0	0	**1**	0	**1**	**1**
cn	…	0	…	…	…	…	…	…
	Result		3	3	0	3	0	3

Figure 124: The calculation of the performance value in relation to defined criteria

Finally, the overall performance value is calculated by multiplying resulting performance value of each information object on prioritized objective ($p_t(a)$) with the performance value of each information object on prioritized criteria ($p_c(a)$), as seen in Figure 125. By multiplying the final values, the irrelevant results can be excluded. If, for example, the information object is suitable for the defined material but has a

163 Various performance values between 0 and 9 were investigated by Nicolini 2017, co-supervised bachelor thesis. At that time, design guidelines were not specified as information objects and described by their dynamic and static characteristics. Therefore, it was not possible to describe their performance by using only the 0 and 1 values. The applicability of the design guideline was described, as for example, 3-partly applicable or 9-very well applicable and so on. Dealing with the values and assessing their applicability became increasingly complicated and strongly influenced by subjective opinions of decision makers.

different objective than the prioritized one in focus, then the result of the overall performance is the value 0. Vice versa, if the information object contributes to the achievement of the objective but focuses on other material, the overall performance of the information object is also set to 0. In the case of static information objects, only the calculation of the prioritized objective weight (t) on each related information object (a) is performed.

		ID-Nr of information objects					
		a1	a2	a3	a4	a5	a..
		IO1	IO2	IO3	IO4	IO5	IO..
Result (Performance on objectives)	pt(a)	0	0	3	3	3	3
Result (Performance on criteria)	pc(a)	3	3	0	3	0	3
Overall Performance	p(a)	0	0	0	9	0	9

Figure 125: Calculation of the overall performance value

6.2 CoDico-FiberFox

CoDico-FiberFox represents the knowledge management–based decision support tool developed to support product developers in the early phases of product engineering through the provision of situation-related design guidelines and other information specific to these activities.

The solution uses the iPeM[164] as a basis and supports users during two activities: (1) idea detection and (2) model principle solution and embodiment, as illustrated in Figure 126. Dark green highlighted are the fields that are considered in the development of the method, while the fields with the light green color points to the fields in which the method can be extended in future work.

In the activity idea detection, the support is foreseen in the form of a search for possible solutions and the evaluation of alternatives in terms of their suitability for fulfilling the defined objectives. In this activity, however, no concrete design guidelines can be provided. In the activity “modeling of principle solution and embodiment,” concrete design recommendations, examples of ideal and poor design solutions, manufacturing restrictions with regard to defined materials, geometry, and manufacturing processes are foreseen as support. Therefore, there are generally three scenarios in which users can receive support:

1) Providing general information (A-scenario)

[164] iPeM is introduced in Section 2.1.1

2) Providing alternative solutions (B-scenario)

3) Providing design guidelines (C-scenario).[165]

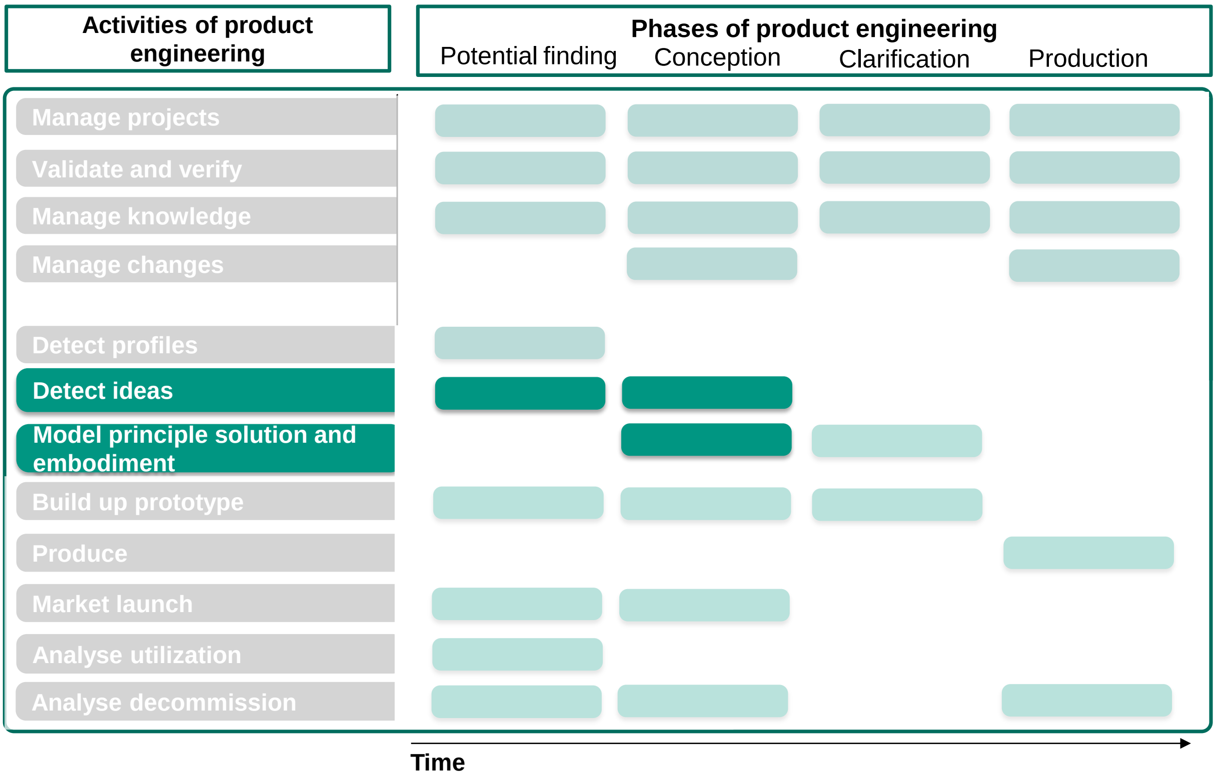


Figure 126: Allocation of the method to the corresponding activities and phases of product engineering using the iPeM[166]

The simple representation of the CoDico-FiberFox operating principle is illustrated in Figure 127. On the right is the system's user, who is asked various predefined questions to understand his or her situation. Depending on his or her needs, the algorithm calculates the suitability of various information objects stored in the database in relation to the identified situation and provides them on the results page.[167]

[165] According to Butenko and Albers (2018)
[166] Based on iPeM
[167] According to Butenko and Albers (2018)

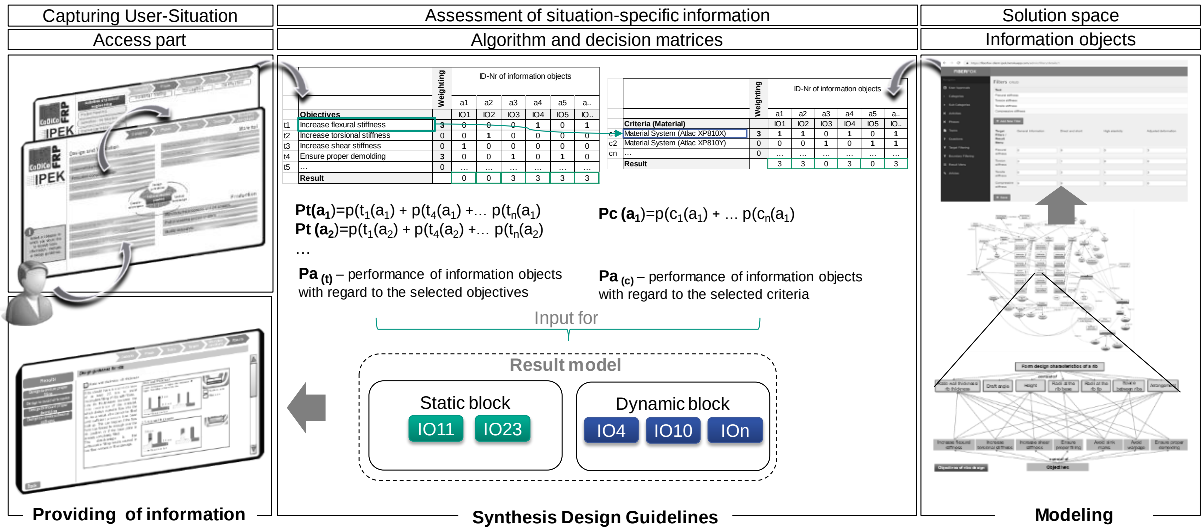


Figure 127: Operating principle of the CoDico-FiberFox

6.2.1 Front-end of CoDico-FiberFox

A front-end is an application with which users interact directly. The CoDico-FiberFox front-end is implemented as a website browser–based system[168] to avoid dependency on any operating system. The front-end provides a group of questions that serve to capture users' situations. The identification of users' situations can be imagined as a branching tree, with the user being presented with a single- or multiple-choice question, the answer to which leads to the next page of the front-end.

The sequence of questions and first mock-up structure was partly designed in a framework of a co-supervised bachelor's thesis[169] and was continuously improved through individual discussions with scientific staff members of the research groups working at the IPEK. The main points of the discussions were as follows:

1) The sequence of the first questions to be asked.

2) Elements of the iPeM that should be retained or reduced in the CoDico-FiberFox application.

The first discussion point focused on clarifying which questions should be presented to the users first: the selection of a specific phase and activity of product engineering or a list of superordinate categories that allows a first classification into the searched topic. Both possibilities were modeled as mock-ups in PowerPoint and discussed in the form of individual discussions. It was quickly revealed that starting with phases and activities became confusing, as many topics and associated system of objectives were assigned to them. As result users were overtaxed by many information entries in the

[168] According to Butenko and Albers (2019, p. 292)
[169] Nicolini 2017 (co-supervised bachelor thesis) p. 70-73

step after selecting the phase and activity. The advantage to first selecting a superordinate thematic category was that most of the topics and corresponding objective systems could be sorted at the beginning. The subsequent selection of the respective phase and activity in the next step resulted in the continuous restriction of the user situation.

With regard to SPALTEN, the decision was made not to integrate it into CoDico-FiberFox, because on the one hand, the modeling and handling of the access part became more complex, and on the other hand, it did not offer additional value to the users. Figure 128 illustrates the first request in the front-end that is provided to CoDico-FiberFox users. The number of topics collected in the interview study with industry representatives denotes the thematic categories[170] that serve to organize the subject content.

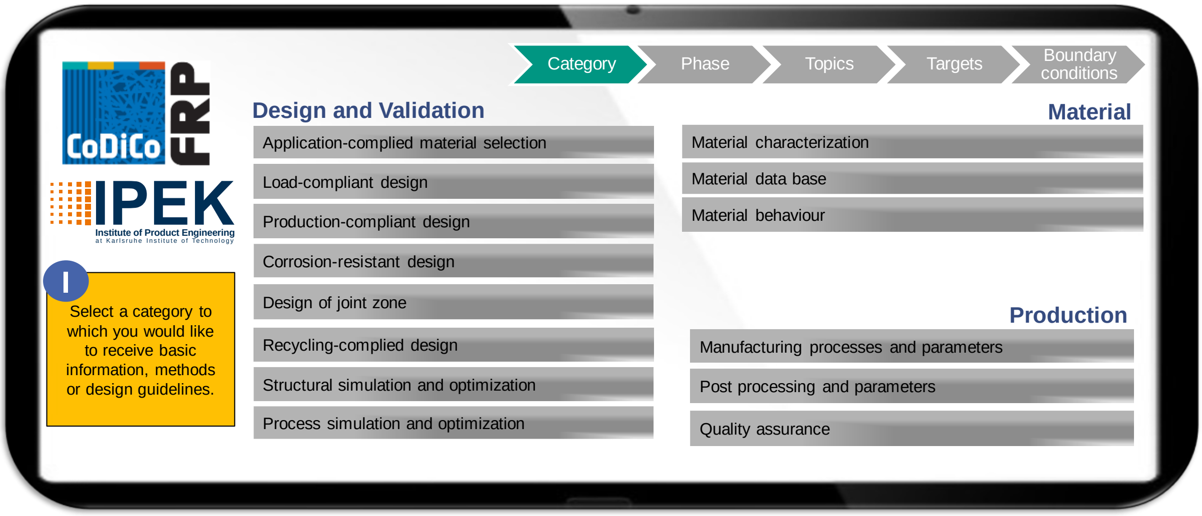


Figure 128: Front-end of CoDico-FiberFox

After selecting the relevant thematic category, the next step is to specify the corresponding phase and activity in which users are situated. In the current version, support is offered during the first two phases: potential finding and conception. In the potential finding phase and the activity “product idea detection,” users can obtain an overview of the advantages, disadvantages, or descriptions of various methods, manufacturing processes and materials or other relevant information related to the selected thematic category. In the conception phase and the activity “modeling of principle solution and embodiment,” users are provided with design guidelines on selected topics in the thematic category. Figure 129 presents the second request in the front-end, which is provided to users after selecting the thematic category.

[170] The explanation of each thematic category is introduced in Chapter 4

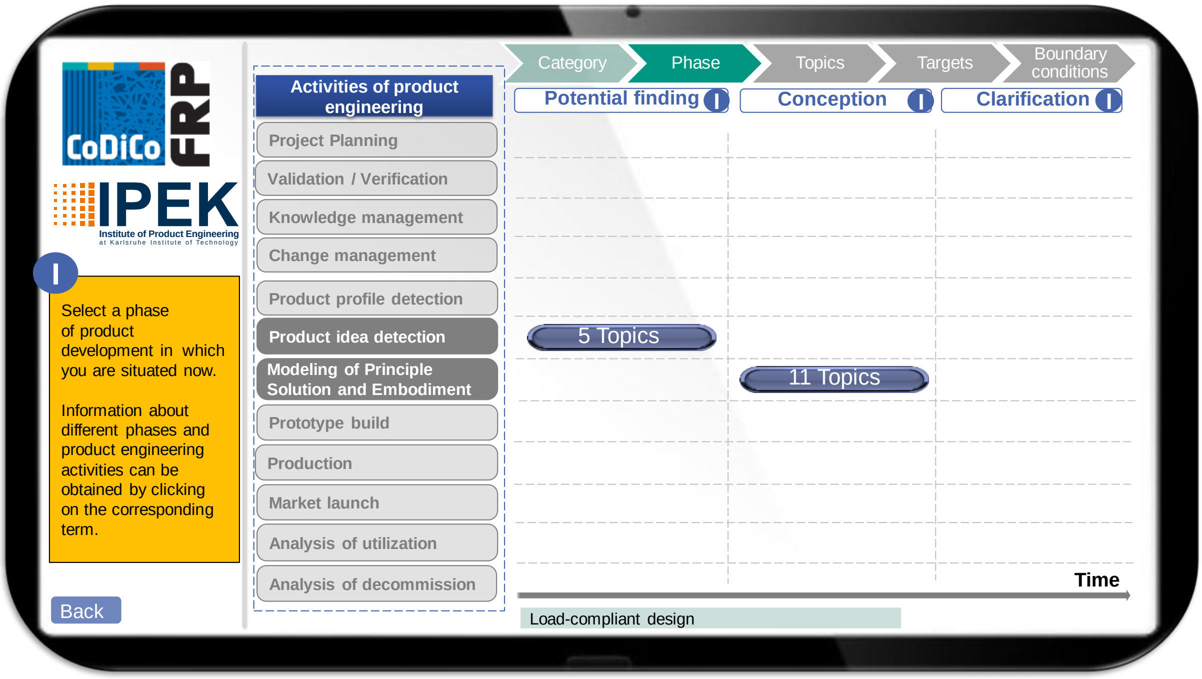


Figure 129: Selecting the activity and phase of product engineering in CoDico-FiberFox

The blue bars represent the number of topics that are subordinate in the given category, phase and activity. Depending on the selected bar, users are redirected to the next page, on which a relevant topic can be selected from the provided list. Figure 130 presents topics for the load-compliant design category, conception phase, and "modeling of principle solution and embodiment" activity. Notably, the aim here is to provide design recommendations for various topics with a focus on load-compliant design.

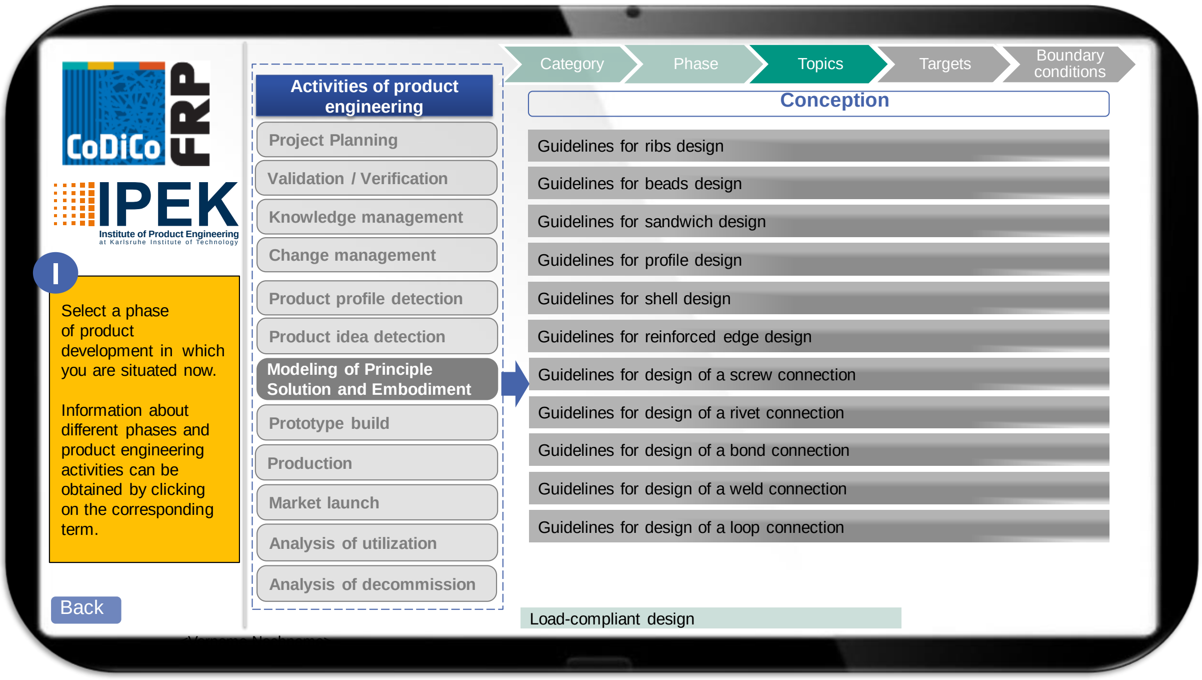


Figure 130: Selection of topics in CoDico-FiberFox

After selecting one topic from the list, users are then forwarded to another view, which involves the definition of relevant objectives. The selection of objectives is important to compile relevant information objects in a synthesized design guideline as a final result. Each topic has its own system of objectives. Figure 131 illustrates objectives on the topic "guidelines for ribs design" in CoDico-FiberFox. Once the corresponding objectives are set, the next step is to specify the relevant criteria, which belong to the system of objectives and serve to specify the current situation of users.

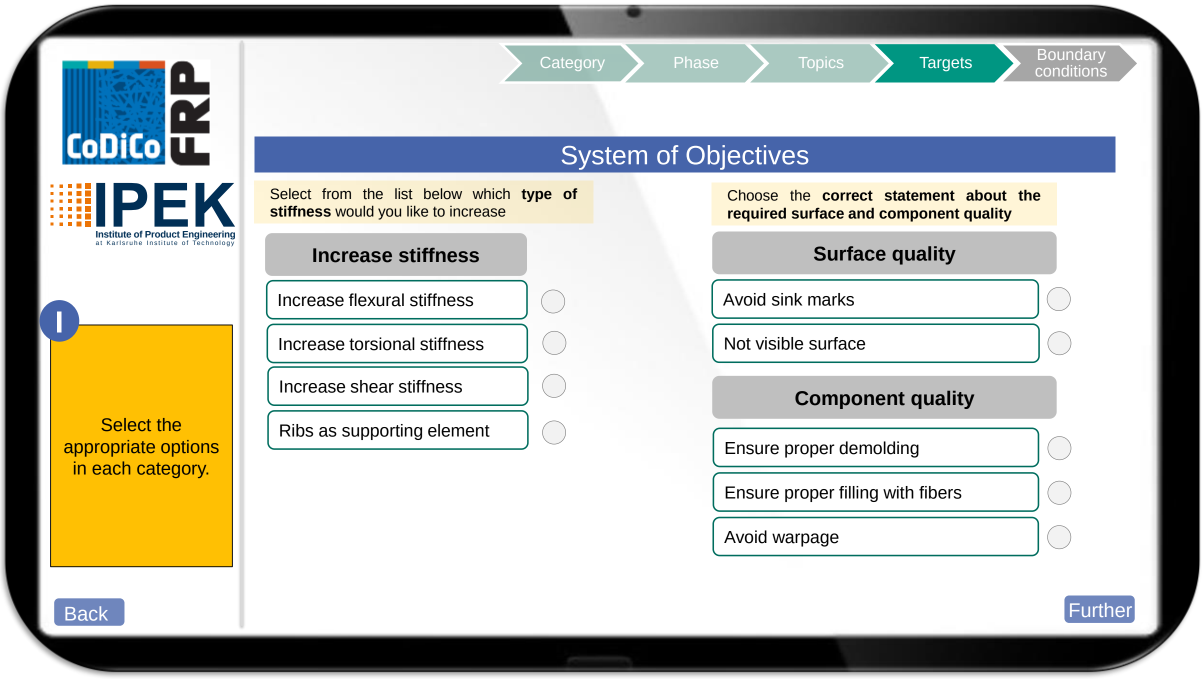


Figure 131: Specification of objectives in CoDico-FiberFox

When general information is needed, then the potential finding phase and "idea finding" activity are selected after specifying the appropriate category. With reference to the specified category, a list of topics is offered, from which one can be selected, as seen in Figure 132 using the example of the quality assurance category.

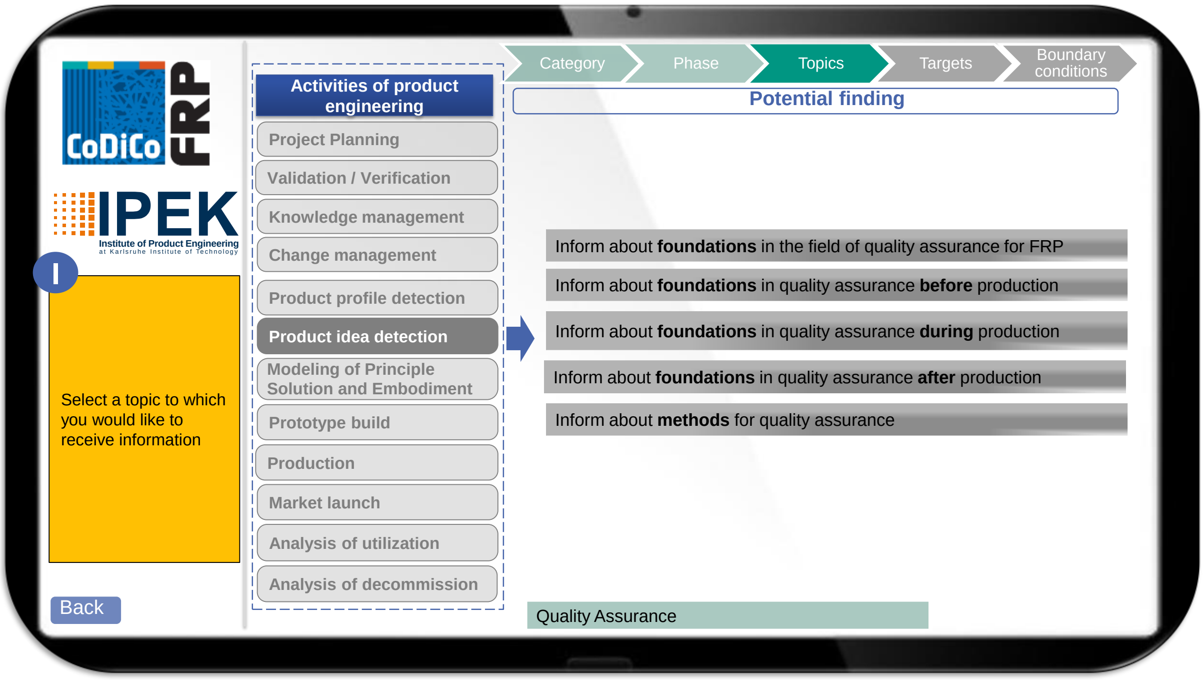


Figure 132: Search for general information in the potential finding phase and “product idea detection” activity

Depending on categories, phases, and activities of product engineering, other topics, objectives, and criteria are of relevance and are listed for selection in the front-end of CoDico-FiberFox.

6.2.2 CoDico-FiberFox – Dashboard

The front-end of CoDico-FiberFox is managed in the form of a dashboard implemented with the support of a student assistant. The main function of the dashboard is the effortless administration of information in the front-end. This function includes the following:

- The insertion, deletion, or renaming of objects (such as categories, phase, activities, topics, objectives, and criteria) in the front-end.
- The creation, deletion, or content modification of information objects stored in the database.
- The determination of relationships among information objects.
- The management of user accounts (such as the approval of new users).
- The scoring of information object performance against objectives and criteria.

Figure 133 presents a screenshot of the created dashboard. The left side displays a navigation bar in dark blue, which includes various fields such as user approvals, categories, activities, and phases. Each of these fields contains information on the corresponding thematic category. The field “user approvals,” for example, contains all requests from external users to access CoDico-FiberFox with brief information about their username, company, email address, and experience with FRPs. The field “category” includes information on the superior categories, including 1) design and validation, 2) material, and 3) production, to which a further 14 subcategories are assigned, as seen in Figure 134. Figure 128, introduced previously, illustrates the result of the relations described in the dashboard between categories and their sub-categories. If a new sub-category is to be introduced, then this is done in the dashboard simply by clicking on "add" button and entering the name and assignment to appropriate superordinate category, so that where the new subcategory appears in the front-end is clearly defined.

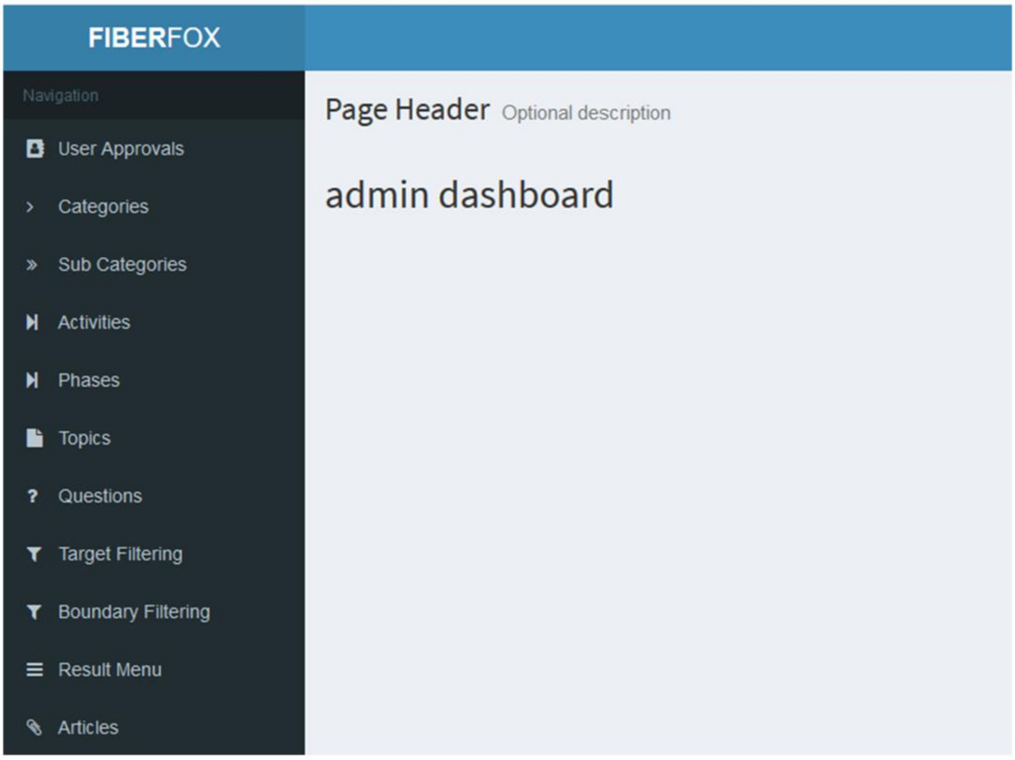


Figure 133: A screenshot of the navigation bar in the dashboard

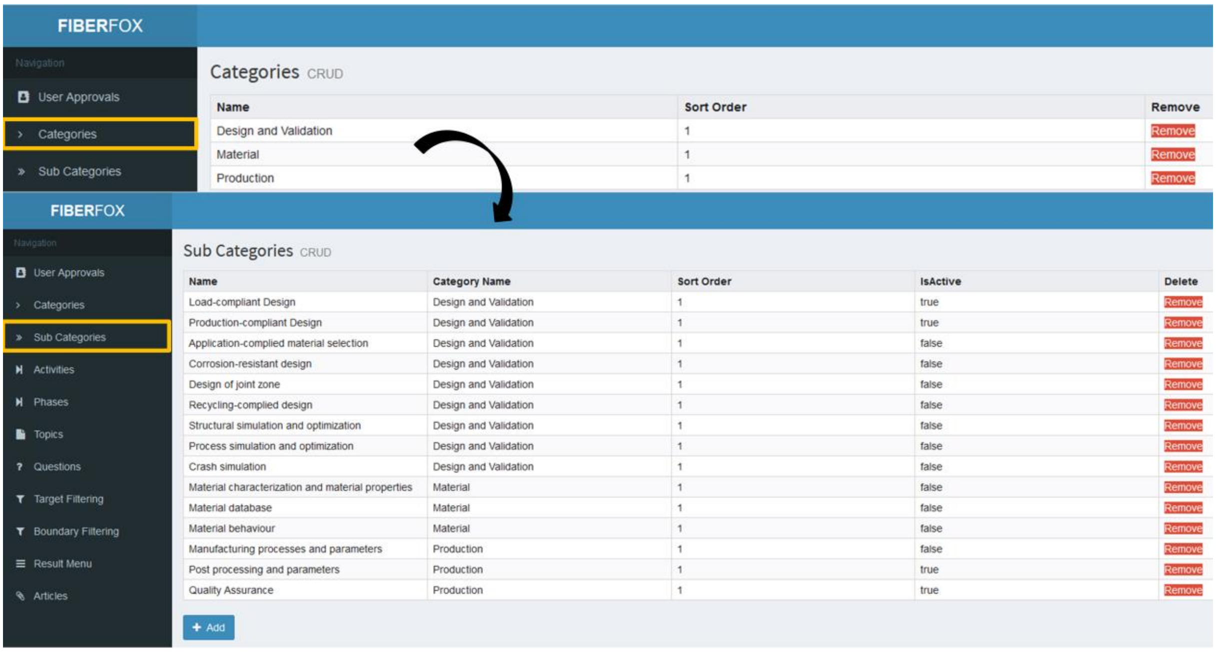


Figure 134: A screenshot of categories and sub-categories

The fields such as activities, phases and topics include a corresponding list of terms and their relation to each other. Figure 135 presents a list of topics in the first column and their assignment to the corresponding category, phase, and activity in the subsequent columns. The column "active" indicates whether content on the topic already exists in the database. If no content is currently available, the topic is displayed in the front-end, but in a gray color, and is inactive (unclickable). The column “has question(s)” indicates whether the topic belongs to the A-scenario (without specifying objectives and criteria) or to the other B- or C-scenarios. A positive answer in the column means that a page with further questions should be displayed in the front-end in order to concretize the need for general information to be provided. All these corresponding questions are stored in the navigation bar "question" on the left side. The columns “has target filtering” and “has boundary conditions” contain information about whether another page is required in the front-end to define objectives or criteria for a certain topic.

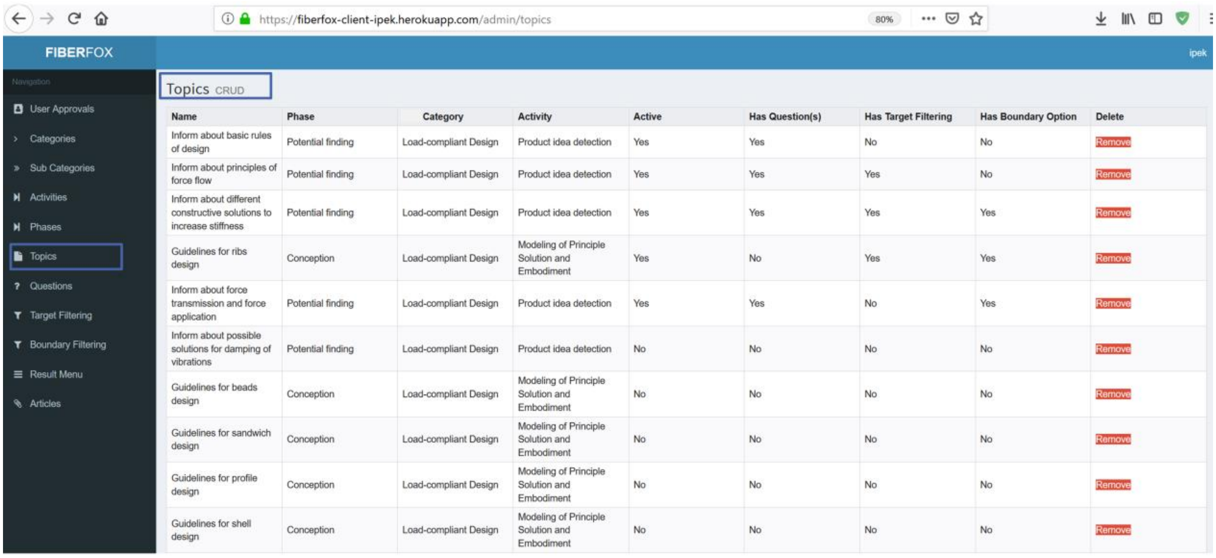


Figure 135: A screenshot of the dashboard for managing the topics in the CoDico-FiberFox front-end

Figure 136 presents an example of stored articles[171] consisting of four columns. The articles contain all static and dynamic characteristics of the stored information objects. The column “ID” denotes the ID of the respective information object. In the column "description," the respective text is filed in HTML format, and the column “result menu” describes a subject and what the information object is about in order to gain a rapid overview.

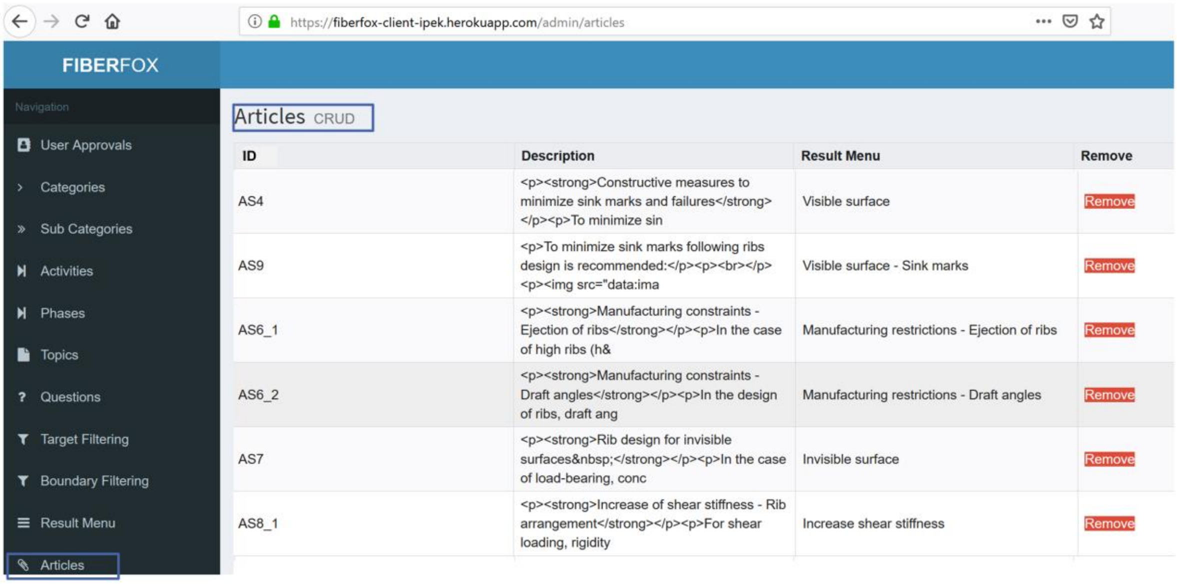


Figure 136: A screenshot of the dashboard for managing the information objects in CoDico-FiberFox

[171] Article containing a list of information objects with static and dynamic characteristics.

If a revision of any information object is required, the corresponding field should be double-clicked, in response to which a new window opens that allows all necessary changes to be performed, as exemplified in Figure 137.

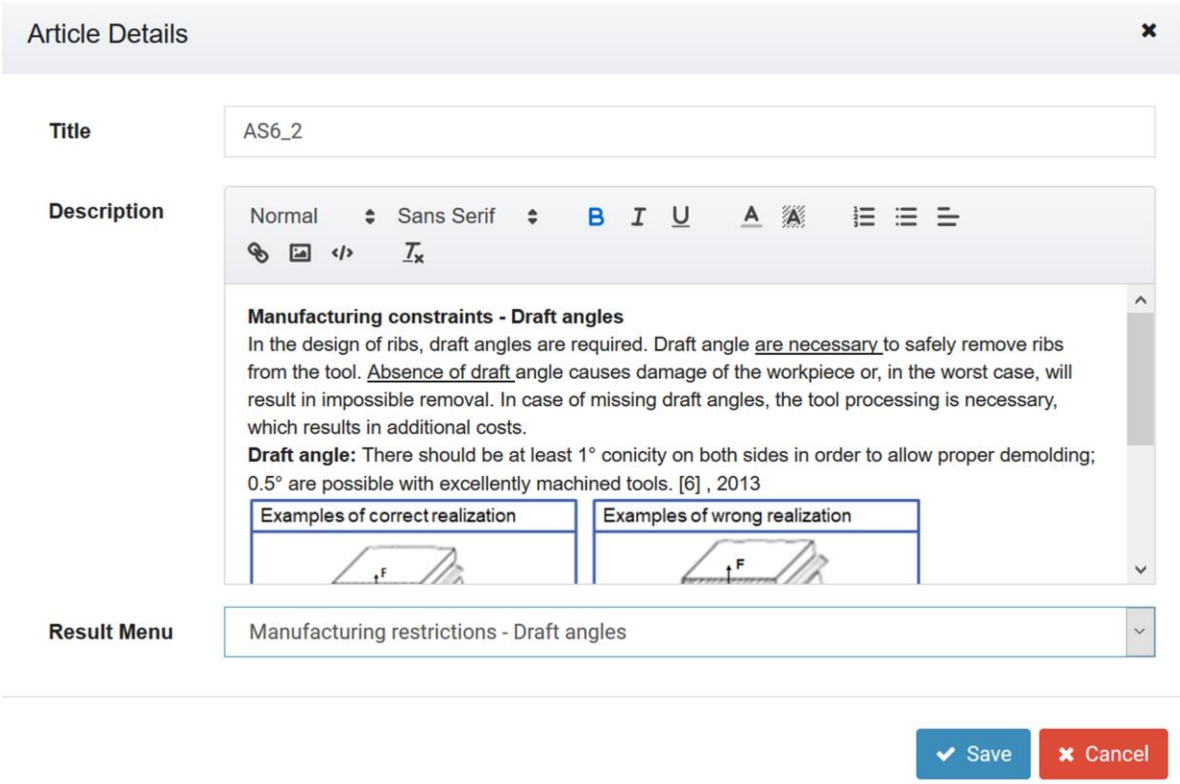


Figure 137: Revision of information objects in the dashboard

The scoring on the performance of the information object against the objective and criteria is also managed in the dashboard, under the navigation field "target filtering." Each information object can be scored directly in the provided decision matrix, as illustrated in Figure 138. The same procedure applies to the scoring of the information objects against the criteria and can be carried out under the navigation field “boundary filtering.”

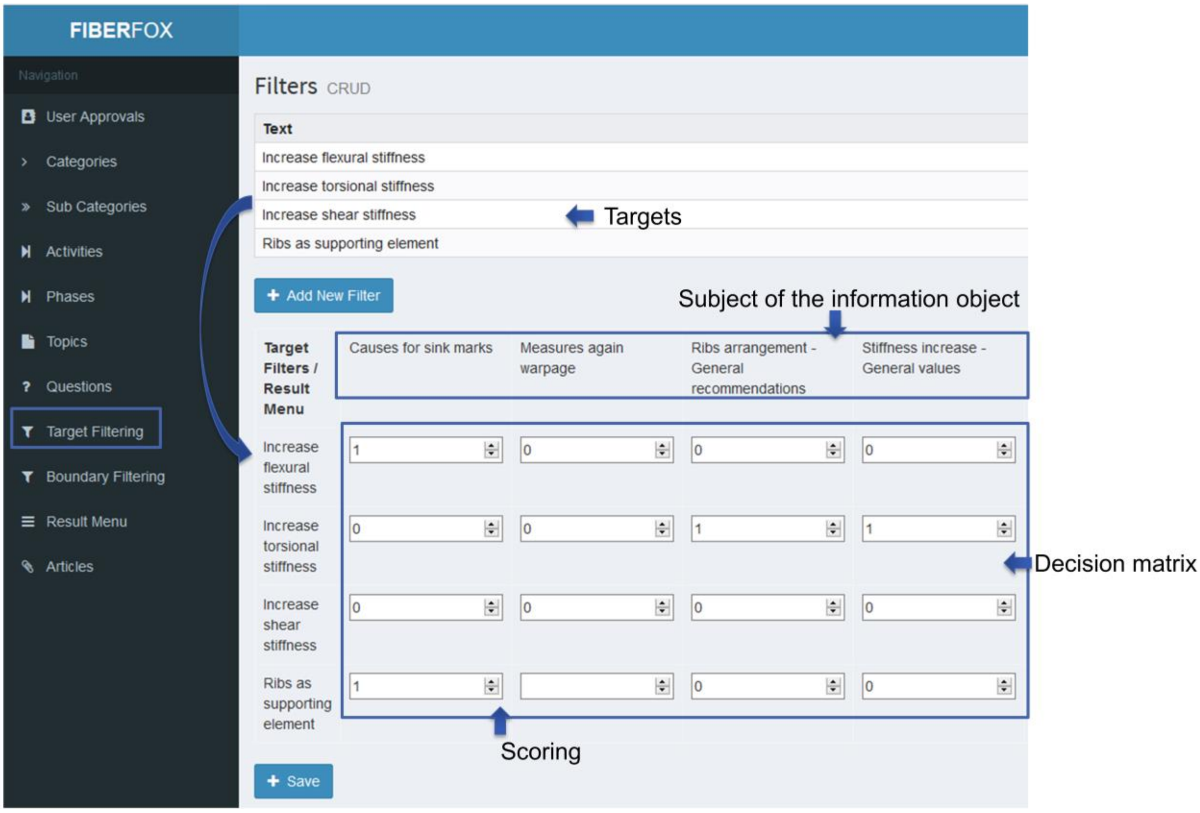


Figure 138: Scoring on the performance of design guidelines against objectives

The navigation field “result menu” is used to manage how the information objects are provided on the results page to answer the user request.

7 Validation of the developed approach

The validation of the method developed for providing situation-related information in design guidelines is intended to demonstrate that the application of the method leads to more efficient and effective identification of relevant information and thus contributes to decision support.

The following research question is the focus of the validation study:

> How efficient is the use of a decision-support method to search for and identify situation-relevant design guidelines in comparison to searching without such a method?

Two studies with a total of 24 participants were carried out to prove this fact. In the first case study with 10 participants, the utilization potential and the added value were examined from the perspective of the industry participants. In the second study with 14 study participants, a comparison was made between the time required to find relevant information using the method implemented in CoDico-FiberFox and that without its use. The participants of the second study were mainly students from the mechanical engineering faculty at the Karlsruhe Institute of Technology.

7.1 First validation study – study design

The study was carried out as part of a trade fair event at a German premium automobile manufacturer. The aim was to examine the utilization potential and the added value of the developed solution from the perspective of the industry participants. The method implemented in a web-based solution was presented to 10 people in individual interviews. The individuals involved had the opportunity to receive the views of the different functionalities of the developed method. Four case situations were prepared, and corresponding information, as were design guidelines stored in CoDico-FiberFox to increase the likelihood that the interviewees would be able to choose the topic with which he or she was familiar. At the beginning, a brief introduction to the IRTG project and the motivation for the development of the method was provided. Thereafter, the introduction to CoDico-FiberFox took place. The participants had the opportunity to test the interactive provision of information and design guidelines on the selected case situation. In the end, the relevance and benefits of the presented methodological approach for the provision of situation-related information were discussed.

The study participants were active in various fields and had various levels of professional experiences in terms of years. Figure 139 illustrates the fields of activity indicated by the participants.

Activities of participants	Years of experience
Connectivity between vehicles	2
Planning and design of test benches	3
Final contour-related revision of vehicle modules	3
Weight management	4
Design and implementation of test experiments	4
Manufacturing of door systems	6
Execution and validation of quality control tests	6
Conception and validation of rear lights	8
Conception of door systems	10
Planning of roof systems	15

Figure 139: Activity fields of participants

7.1.1 Four case situations

In preparation for the study, four situations were prepared for two activities of product engineering: 1) idea detection and 2) modeling of principle solution and embodiment.

First case situation: You are working as a design engineer and have just received a new project that involves approaches to increasing the bending stiffness of a flat sheet. You cannot change the material; the aim is rather to increase the stiffness of the sheet by using the appropriate structural elements. Use CoDico-FiberFox to get first ideas.

Second case situation: You work as a design engineer in a large company and develop a demonstrator for a new component. The main aim of the new demonstrator is weight optimization and an increase in torsional stiffness. To this end, you have decided to use ribs as a reinforcement element. A sheet molding compound is set as the material type, but it remains to be clarified whether glass or carbon fibers should be used. CoDico-FiberFox is the knowledge management tool used in your company. Use this tool to find out what should be considered in rib design to avoid sink marks and to achieve a homogeneous fiber filling.

Third case situation: You are working as a production engineer and are familiar with the post-processing of SMC materials. You receive a new order for the milling of a serial part. The applied material is the SMC material with the upper- and lower-layer carbon unidirectional fibers and the middle-layer SMC reinforced with glass fibers. Use

CoDico-FiberFox to identify suitable process parameters to mill SMC materials to avoid the occurrence of delamination.

Fourth case situation: You are working as a quality assurance engineer in a quality department that deals with FRPs. Several times already, the produced parts have had some quality issues. The topic of the discussion in one meeting is which methods are suitable for the quality assurance of carbon-fibers-reinforced SMC material to detect resin inhomogeneity and air inclusion. Use the CoDico-FiberFox tool to pre-select suitable methods for quality assurance.

The prepared case situations were briefly presented to the participants and they could choose which situation they would like to run with CoDico-FiberFox. All four situations were selected at least once.

7.1.2 Main results

Each conversation took between 20 and 30 minutes. Almost all participants displayed great interest in the methodical approach and the final results in the form of CoDico-FiberFox. The only exception was the study participant who dealt with autonomous driving, who found the approach generally interesting, but not useful for his daily tasks. When asked whether the test persons saw a benefit in the presented solution in their daily work, all other participants answered clearly with "yes." The provision of information depending on the phases and activities of product development was especially appreciated by the participants. The interactive provision of information was also found to be helpful and relevant:[172]

“This approach is relevant in the production and design phase because a lot of 'dead knowledge' is stored in books, and mistakes are still made in design solutions because there is no time to search for the information in such books.” (Butenko & Albers, 2019, p. 293)[173]

The participants also recognized that the methodological approach reduces the amount of work involved in the repeated search for information and is therefore conceivable in the idea detection and model principle solution and embodiment:

“This approach would be good suitable in the brainstorming and the conception phase.” (Butenko & Albers, 2019, p. 293)[174]

The transfer potential of the method to other areas was also quickly recognized. One of the participants active in the planning and design of test benches recognized this

[172] According to Butenko and Albers (2019, p. 293)
[173] Statement of one participant
[174] Statement of one participant

potential transfer to the topic of identifying relevant standards and norms depending on the targets of test benches:
“It would be very interesting for experiments, for example, for an overview of norms and standards that should be considered. However, this is also important for the reuse of knowledge in other areas of the company.”[175]

“I could imagine using this approach in the development of tailgates: First choose for which vehicle a tailgate should be developed, then narrow down the situation step by step so that only relevant information is supplied.”[176]

7.2 Second validation study – study design

In the second study, the increase in efficiency was measured through the application of the developed method. Two case situations were created for this purpose, each of which consisted of a situation description, defined objectives and subsequent questions. Based on the formulated tasks, the study participants were placed in a position to make a decision according to the outlined situation. To measure efficiency, the participants solved tasks similar in scope and complexity both with and without using the developed method. In both cases, the time taken by a participant to complete the task was measured and compared. The effectiveness was measured by the relevance of the identified information with and without methodological support. The study involved 14 selected students from the master’s program in mechanical engineering at the Karlsruhe Institute of Technology.

7.2.1 Two case situations

First case situation, in the field of constructive reinforcement: You work as a development engineer for a company that develops armrests for various OEMs. You have received a new order, and now you are working on the development of a new product generation. The product is to be optimized in terms of compressive and bending strength. The load- and production-compliant design of reinforcement ribs is part of your responsibility. The focus is on the hinged part.

[175] Statement of one participant
[176] Statement of one participant

Background:

It is known from previous cases that the hinged part does not have sufficient resistance. Bending and pressure loads occur during use.

The hinged part is covered with a fabric, so that the material is no longer in direct view. The manufacturing process is a compression molding.

The used material has the following specifications:

- The material is glass-fiber-reinforced epoxy with 40% fiber volume content
- The fiber length is approx. 25 mm
- The current wall thickness of the hinged part is 20 mm, its length is 160 mm and its width is 90 mm.

Folded condition[177]	Unfolded condition
	

Task:

You have chosen the rib structure as the stiffening element. Write down design elements that need to be considered in the rib design to meet the described requirements.

Second case situation, in the field of manufacturability: You are working as an engineer in the production of sheet molding compound parts. You participate in the meeting in which the final shape of the demonstrator is discussed. The colleagues from the design department ask your opinion regarding the manufacturability of the designed ribs. The main important point of the discussion is the manufacturability in terms of good quality (no sink marks on the surface), homogeneous filling with fibers and secure demolding from the tool.

[177] Images of the folded and unfolded armrest are taken from (Marlies Spangenberg GmbH & Co. KG, 2014)

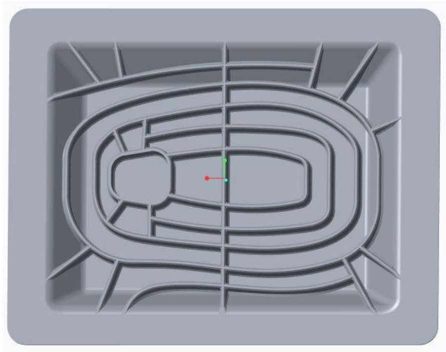
Background:

The material in focus is the SMC material, which is manufactured in the company.

The following material specification is in focus:

- Epoxy resin reinforced with carbon fibers
- Fiber length – 25 mm
- Volume content – 30%

- Demonstrator data:
- Ribs height – 17 mm,
- Ribs width – 1.5 mm
- Draft angle – 0.5°
- Radii at the rib base – 0.5 mm
- Wall thickness of the part – 2 mm


[178]

Task:

Provide your advice, regarding whether the design of ribs can work with the selected material. What should be improved?

At the beginning of the study, the method for the provision of situation-related information in design guidelines was briefly presented in the context of a CoDico-FiberFox web-based solution. Afterwards, the goals and the design of the validation study were explained, so that study participants understood the background of the study and did not regard it as an examination of their competencies. Each participant received two tasks in general. One task had to be solved using the developed method, to which end the participant was granted access to CoDico-FiberFox. The second task had to be solved without the help of CoDico-FiberFox. The participants received the second task as soon as they completed the first. The time it took each participant to complete each task was noted to later compare the time differences needed to complete the task with CoDico-FiberFox versus without CoDico-FiberFox. To solve the case study without access to the CoDico-FiberFox, participants were provided with the same information but in paper form. To be in line with reality, the information was distributed over several pages, just as it is in practice when reading books or

[178] 3D-Model was created in the framework of the IRTG project

publications, for example, and finding relevant information on a topic distributed over several resources. This means that generic information prepared in CoDico-FiberFox and provided in a "static block" about all relevant design characteristics in connection with a specific objective, was available in paper form but on different pages. The information was the same as formulated in CoDico-FiberFox in order to allow the comparability of the results. Altogether, 30 pages were prepared, which is still less effort compared to searching through different books for information.

The participants were divided into two groups consisting of seven people each. The task that the participants in the first group were supposed to solve without using CoDico-FiberFox was to be solved by the second group in reverse with the use of CoDico-FiberFox. To solve the second case situation, the participants of the first group were given access to CoDico-FiberFox, while the second group worked with paper-based information. There was no limitation in time for the solutions of the case studies. Two students assisted in the execution of the study. The focus was on noting the time required for task processing to ensure that there was no falsification in processing time if several study participants finished task processing at the same time.

7.2.2 Main results – assessment of the first case situation

Figure 140 illustrates the comparison values for the processing of the first case situation. The bar chart on the left side shows the results regarding the time needed to solve the case situation without using the CoDico-FiberFox, while the bar chart on the right side visualizes the results achieved using the tool. The numbers 1–7 and 8–14 stand for the designation of the study participants. It is evident that the study participants of the second group took significantly less time – between 3.38 and 5.17 minutes – to identify relevant information when using CoDico-FiberFox. In comparison, the first group took between 15 and 25 minutes to solve the same task, but searching themselves for the relevant information in documents that were provided. Not only time differences were noted in the processing of the tasks; the result itself was also different between the two groups. The main difference was the number of determined design characteristics. The group that solved the task without CoDico-FiberFox focused on the directly affected design characteristics such as the height of ribs, the wall thickness and the arrangement of ribs. The other group also included the radii of the ribs, the draft angle and the ratio between the ribs’ wall thickness and the wall thickness of the component. Comparing the maximum time it took the second group to solve the case study and the minimum time it took the first group, the result shows a threefold increase in efficiency.

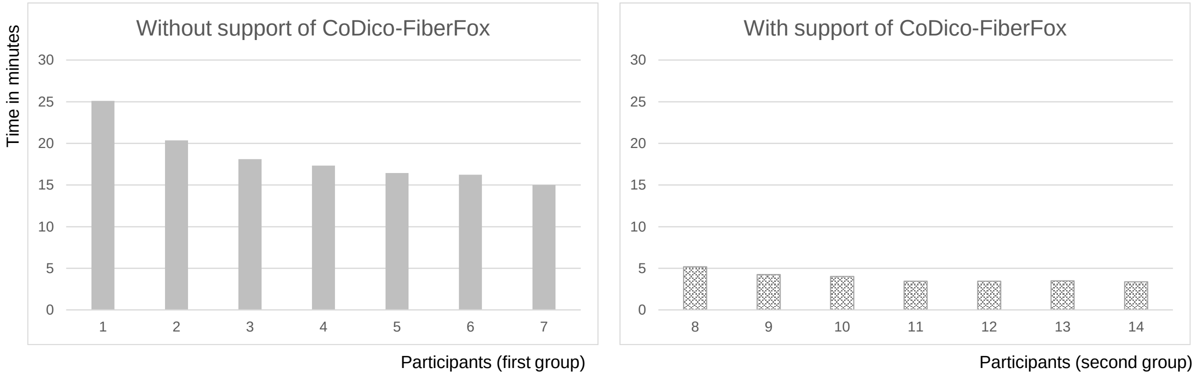


Figure 140: Comparison values between the two groups solving the first case study

Figure 141 provides the comparison values for the processing of the second case situation. This time, the first group used CoDico-FiberFox, while the second group received support in the form of prepared documents. The bar chart on the left side shows the time needed by the second group to solve the case situation without using CoDico-FiberFox, while the bar chart on the right side visualizes the results achieved by the first group with the use of the CoDico-FiberFox. A similar trend as in the first case study was observed in terms of time and completeness of results. Without using the tool, time range was between 15.2 and 20 minutes to solve the second case study. In comparison, support from the tool resulted in times between 4.28 and 6.4 minutes to solve the case study. The results provided by the second group focused mainly on increasing the ribs' wall thickness and draft angle. The first group also provided instructions on radii at the rib base, the orientation of ribs with respect to fiber flow direction and the minimum distance between two ribs.

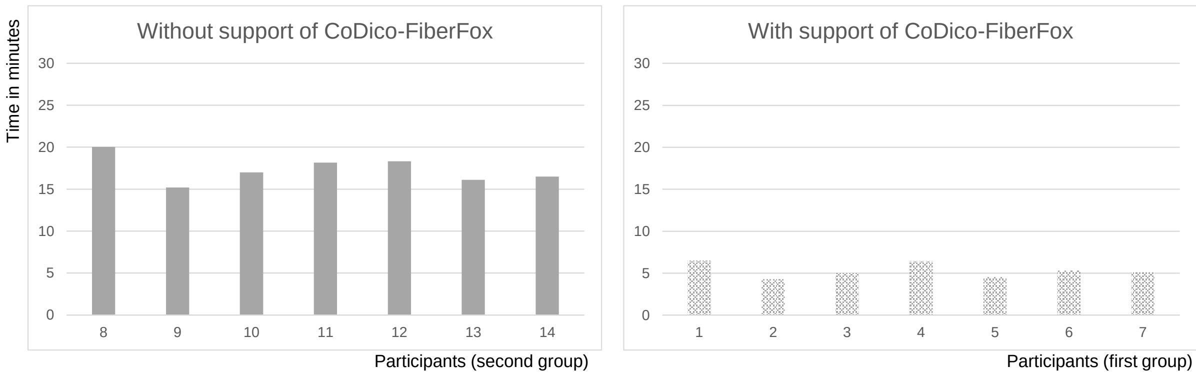


Figure 141: Comparison values between the two groups solving the second case study

Figure 142 summarizes the results of the two case studies for each group and shows on the left side the time it took the first group to complete the two case studies without and with CoDico-FiberFox and on the right side the results of the second group. The time difference in task processing can be determined according to certain participants, which can be observed by two bars placed next to each other.

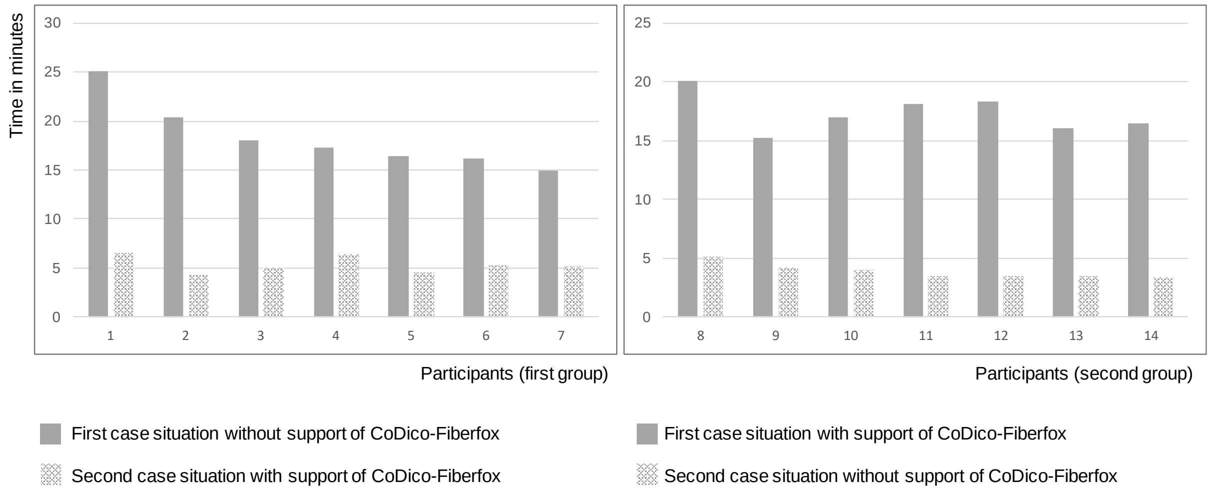


Figure 142: Comparison values between the two groups of participants solving the second task

In the study, simple case situations were used in comparison with real situations that arise during the development of products. The information provided in paper form was spread over a few pages, which is not comparable with the effort of searching in reality. It is expected that the efficiency will be even higher by applying the developed method in the real situation, since in most organizations, information is usually distributed in various documents and exists in different forms. The various studies show that the search for information is still time-consuming and costs employees time every day (Economic Times, 2019; Sabo, 2014).

8 Summary and outlook

8.1 Summary

In this work, an approach to support product developers in the early phases of product engineering with FRPs in the activities “detect ideas” and “model principle solution and embodiment” through the provision of situation-related design guidelines with a target-oriented documentation was developed, presented and validated.

The results of the analysis of the state of the art have shown that the content of most design guidelines for FRPs is rather short and mostly insufficiently supports the analysis and synthesis activities, which are important in product development (Butenko & Albers, 2018). The majority of design recommendations that were found hardly consider embodiment design in connection with manufacturing and material influences, both of which are important when designing with FRP materials. It was evident, that current design guidelines are simplifications of problems with an abstractly description to support easy understanding. However, reality has a clear problem definition and requires concrete information, resulting in the fact that the application of design guidelines in their current form is highly limited with regard to their transferability to real use cases.

Based on this motivation, qualitative and quantitative studies were carried out with industry representatives with the aim to find out what information should be included in the design guidelines for FRPs and how it should be documented to optimally support the design process. The results of the survey revealed that not only providing design recommendations on embodiment design, but also general technical information is necessary for optimal support. (Butenko & Albers, 2018)

Altogether, a need for 22 subject areas for design guidelines and 29 subject areas for technical information on 16 challenges associated with FRPs was determined. Within the findings gained in the qualitative and quantitative studies, it was clear that optimal support can not be garanteed by improving information documentation on relevant topics alone, but only in combination with a targeted provision of the necessary information avoiding the tedious search. For this reason, the developed approach not only deals with rules for the documentation and structuring of design guidelines, but also with prerequisites that must be fulfilled in order to ensure the provision of situation-specific information. Apart from prerequisites, such as clear definition of systems of objectives for which support in the form of design guidelines is necessary, it is also important to understand the correlations between the objectives, the criteria and the design characteristics of the certain structural elements. Objectives and criteria influence the design characteristics (e.g. radii, wall thickness, arrangement of ribs) and design charachteristics can contribute to the achievement of one or more objectives.

To enable situation-specific, targeted provision of design guidelines, their creation should therefore be defined as a modular structure consisting of various information objects described by static and dynamic specifications. The description of the dynamic specification shall be done in relation to the certain objective and criteria and contain specific information. The description of the static specification shall contain rather general information about the role and influences of the related design characteristics on the achievement of the specified objective. Furthermore, such a modular structure allows the reusability of recommendations to a certain extent, for example, if they apply to different objectives and materials.

The method developed was tested continuously in the framework of CoDico-FiberFox web-solution implemented as a website browser-based system. CoDico-FiberFox has primarily served as a test environment to test and optimize algorithms for providing situation-specific information. As the manufacturing tests in the IRTG project were carried out relatively late and there were some uncertainties in connection with the results obtained, requiring repeated tests, only limited design recommendations could be derived at that time. Therefore, the algorithm was tested mainly with available design guidelines in literature, which were slightly modified for this purpose. Nevertheless, CoDico-Fiberfox was designed in such a way that the access part can be supplemented/modified with a little effort and new findings/design recommendations from the second and third generation of the IRTG Project can be incorporated into the knowledge database.

The result of this thesis is the developed approach for the provision of situation-specific information in design guidelines. This approach was developed on the basis of the application fields collected from the industry surveys, existing knowledge from the state of research, and generated findings within the IRTG project. Furthermore, the approach developed enables the determination of relevant information objects and their output in a standardized form by an interactive limitation according to the activities and phases of the product development, and the system of objectives of the user. The validation of the approach demonstrated that the efficiency (effort in identifying relevant contents) and the effectiveness (number of certain relevant design characteristics) in searching and identifying relevant information is significantly improved.

8.2 Outlook

On the basis of the present work, the following connecting factors arise for further scientific work:

Integration of manufacturing guidelines for composite technologies.

The further development of the method to provide manufacturing guidelines is a consequent next step for which the first interfaces have been created in the context of this work and the algorithm and method developed here.

Integration of guidelines for the implementation of test procedures

The further development of the method to provide test methods for material characterization is also a further step to enable the completeness of the guidelines for the field composites.

Transfer of the method to conventional material technologies

The shown efficiency advantages of the developed method also hold potential for application in conventional material technologies or other novel lightweight design technologies. For example, the design and production with hybrid materials or on the basis of additive processes, but also the classical production technologies such as forming production processes could benefit from this.

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Bachelor- and Master thesis

The following theses were co-supervised by the author of this work at the IPEK - Institute of Product Engineering at the Karlsruhe Institute of Technology (KIT):

Wilwer 2016

Wilwer, J., Co-Supervisor: Butenko, V., Supervisor: Albers, A.: Development of a methodology defining the content of a dynamic construction guideline for fiber reinforced plastics. IPEK, Karlsruhe Institute of Technology (KIT), Bachelor thesis.

Nicolini 2017

Nicolini, M., Co-Supervisor: Butenko, V., Supervisor: Albers, A.: Development of a concept for design guidelines for load-compliant and production-oriented construction of fiber-reinforced plastics. IPEK, Karlsruhe Institute of Technology (KIT), Bachelor thesis.

Li 2018

Li, C., Co-Supervisor: Butenko, V., Supervisor: Albers, A.: Validation of a methodology for demand-oriented provision of design guidelines regarding the post processing and testing procedures. IPEK, Karlsruhe Institute of Technology (KIT), Master thesis.

Maurath 2018

Maurath, M., Co-Supervisor: Butenko, V., Supervisor: Albers, A.: Development of construction and design guideline focus on better knowledge transfer using the example of pressure compensation function. IPEK, Karlsruhe Institute of Technology (KIT), Bachelor thesis.

Zhang 2018

Zhang, L., Co-Supervisor: Butenko, V., Supervisor: Albers, A.: Development of a method to support the identification of target systems using Data-Mining approach. IPEK, Karlsruhe Institute of Technology (KIT), Bachelor thesis.

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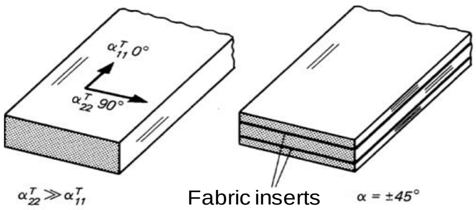
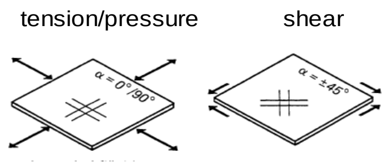
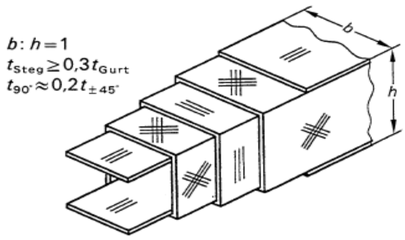
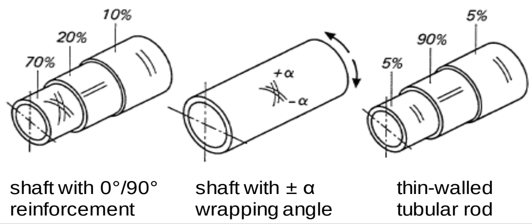
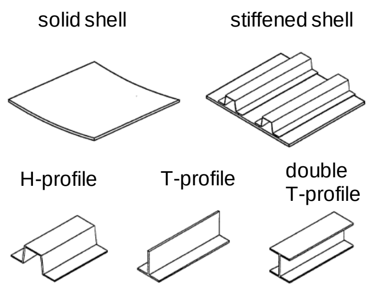
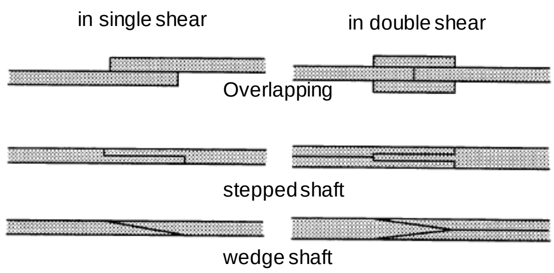
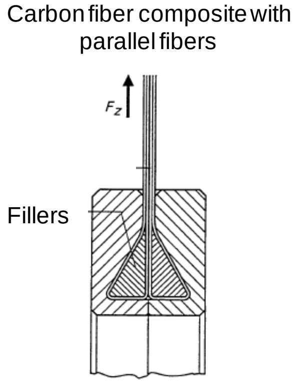
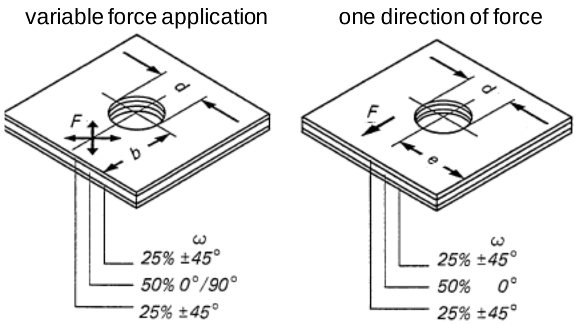
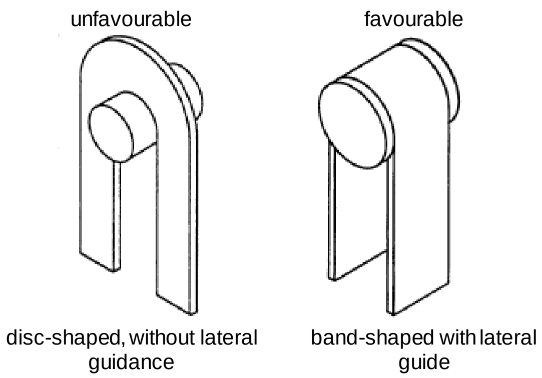
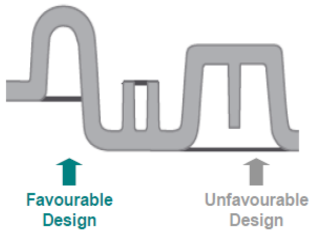
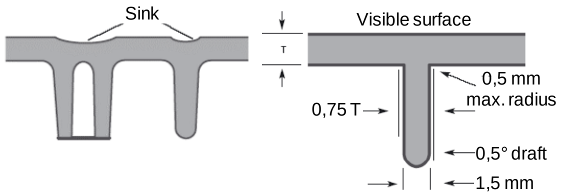
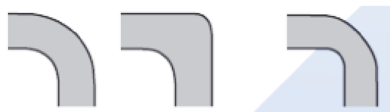
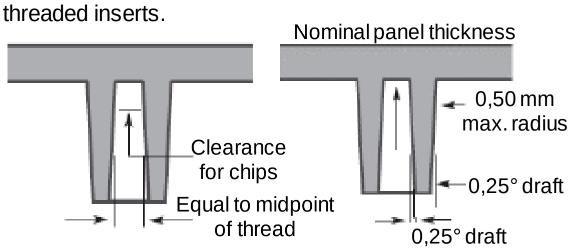
Annex

A. Overview of analyzed design guidelines

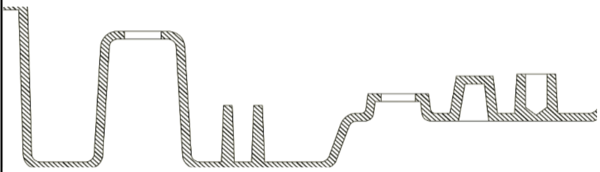
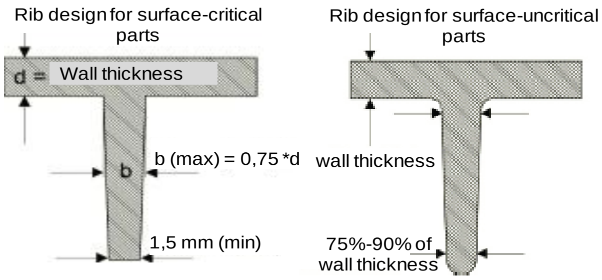
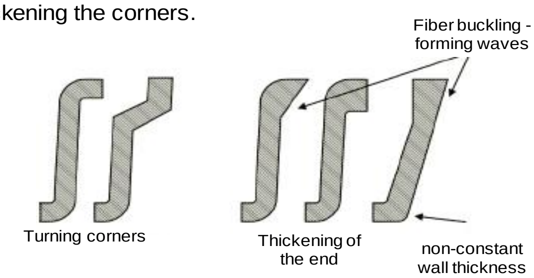
<table>
<tr><td colspan="4">VDI-Guidelines (2014) Development of FRP components (fibre-reinforced plastics), Concept and Design /
Entwicklung von Bauteilen aus faser-Kunststoff-Verbund, Konzept und Gestaltung, Beuth Verlag, Berlin, Germany</td></tr>
<tr><th>Objective</th><th>Considered factors</th><th>Material</th><th>Recommendation</th></tr>
<tr><td>Design of beam elements to avoid expansion differences</td><td>beam element</td><td>CoFRP</td><td>Parallel fibre composites are to be used for these elements. Reduction of the differences in elongation can be achieved by a transverse reinforcement of fabric layers.

</td></tr>
<tr><td rowspan="2">Design of surface elements to avoid warpage</td><td>surface elements (membran, disc, plate, shell)</td><td>CoFRP with fabrics reinforcement</td><td>Symmetry is required for layer composites reinforced with parallel fibre-reinforced individual layers</td></tr>
<tr><td>acting force: uniaxial; biaxial; surface elements (membran, disc, plate, shell)</td><td>CoFRP</td><td>The following favourable fibre orientation ratios are recommended for flat structural elements, depending on the main stresses:
- uniaxial - 95/0/5
- biaxial (tension-pressure) - 50/0/50
- biaxial (shear) - (0/100/0)

</td></tr>
<tr><td>Design of carrier-shaped component to distribute longitudinal forces evenly during bending</td><td>carrier-shaped elements</td><td>CoFRP</td><td>It is advisable to insert multiple webs or create a sandwich girder. Due to the high E/G ratios, it is important to distribute the longitudinal forces evenly during bending by homogeneous shear connection of the belts.

</td></tr>
<tr><td>Design of wavy and turbular rods increasing torsional and bending stiffness and the stiffness of the cross-section</td><td>wavy, turbular rods</td><td>CoFRP</td><td>The torsional stress prevails with shafts, which is why they are mainly designed in a'+-45° fibre arrangement. If the bending frequency is to be additionally influenced, either 0° layers can be added or a crossing angle smaller than 90° can be widened (e.g. +-15 to 30° for winding technology depending on the type of fibre). Approximately 10% of the wall thickness in 90° fibre arrangement ensures sufficient stiffening of the cross section with thin-walled shafts.

</td></tr>
</table>

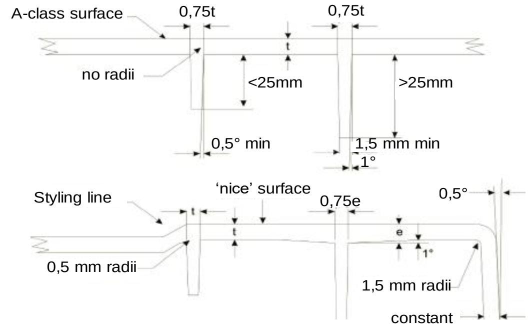
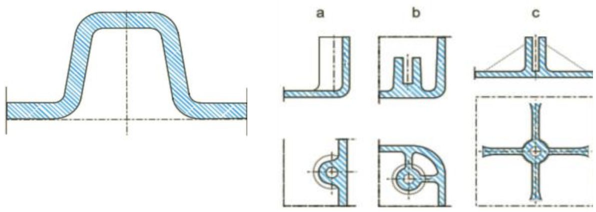
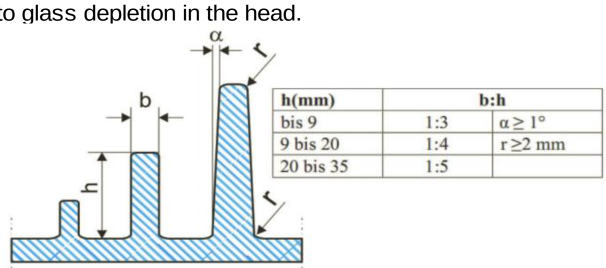
VDI-Guidelines (2014) Development of FRP components (fibre-reinforced plastics), Concept and Design / Entwicklung von Bauteilen aus faser-Kunststoff-Verbund, Konzept und Gestaltung, Beuth Verlag, Berlin, Germany			
Objective	**Considered factors**	**Material**	**Recommendation**
Design of shell-shaped components to avoide warpage	shell-shaped elements	CoFRP	Symmetrical profiles are preferred for stiffened shells (H-, double-T or I- profiles. Asymmetrical profiles such as L-, C- or Z-profiles can warp with temperature changes and result in a reduction of the limit loads. 
Design of shell-shaped components to avoide buckling	shell-shaped elements	CoFRP	The sandwich height and the stiffness of the surface course should be adapted to the spatial shape and load in order to be sensitive again buckling. The type of failure should be local creasing and not peeling of the top layers. A stiff surface layer requires a stiff and firm support material and a highly resilient adhesive. The design of the edges of sandwich structures must be observed due to the risk of injury and the brittle fracture behaviour.
Design for force transmission via bonding	prefabricated fabrics	CoFRP	Stepped mounting are ideal for the use of prefabricated fabrics. 
	combination of different materials	CoFRP	In case of a combination of different materials, a continuous preservation of the material is required for mounting of tensile stiffness.
	combination of FRP with metal	CoFRP	When connecting highly anisotropic FRP with isotropic materials such as metals, the different coefficients of thermal expansion and the stiffness of the materials to be connected must be taken into account.
	operating temperature of the components insignificantly above room temperature	CoFRP	For components whose operating temperature is only slightly above room temperature, preferably curing adhesives should be used.
	highly stressed joints with heat-curing adhesives	CoFRP	Highly stressed joints with hot-curing adhesives can often only be realized by additional measures such as the interposition of a rubber film in the adhesive gap or the partial adjustment of the coefficient of thermal expansion by local application of fabric or parallel fibre layers.

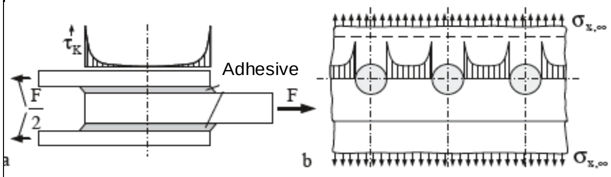
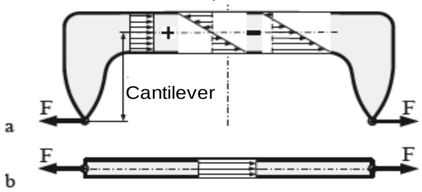
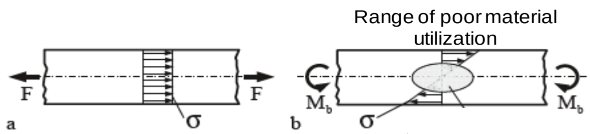
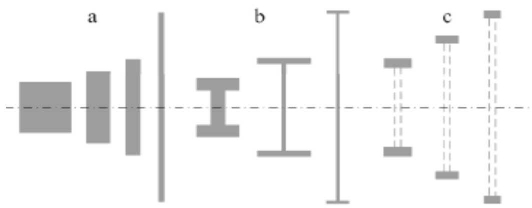
VDI-Guidelines (2014) Development of FRP components (fibre-reinforced plastics), Concept and Design / Entwicklung von Bauteilen aus faser-Kunststoff-Verbund, Konzept und Gestaltung, Beuth Verlag, Berlin, Germany			
Objective	**Considered factors**	**Material**	**Recommendation**
Design for transmission of force by friction	-	CoFRP	Force introduction by friction and clamping can only be found in very special applications due to the low stiffness and strength of the FRP across the grain direction and the relaxation tendency of the matrix. 
Design for force transmission of force through a hole in the body	-	CoFRP	If a variable force application angle is to be found at a bolt joint, a quasiisotropic SV with only one force direction (50/50/0)- Fiber arrangement recommended in the design. The application of force can be guided laterally over the bearing of the hole, e.g. by the use of rivet discs. 
Design for force transmission through loops	-	CoFRP	Contact surfaces of bolts and fittings with loops must be polished to prevent abrasion and thus premature failure. 

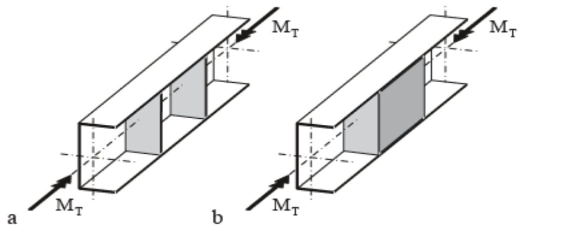
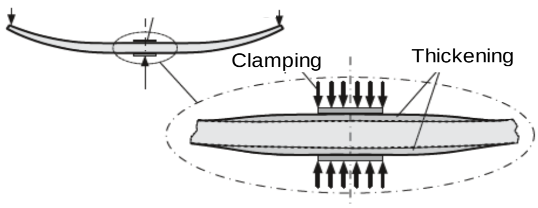
European Alliance for SMC/BMC (2007), Design For Success : A Design & Technology Manual for SMC/BMC			
Objective	**Considered factors**	**Material**	**Recommendation**
Design of wall thickness	-	SMC/BMC	Keep wall thicknesses constant to avoid thin to thick sections along material flow paths and at the end of the flow - so as not to impair excellent surface quality and isotropic properties. 
Design of rib to minimize sink marks	non A-class surface	SMC/BMC	For Non class A component design, sink marks can be minimized or eliminated by the proper design of reinforcing ribs using the right combination of draft angle, radii and rib thickness as indicated in the diagram opposite. 
Design of rib radii	-	SMC/BMC	The recommended radii is 2mm minimum for inside corner radii and 1.5mm minimum for outside corner radii.  The preferred design for outside radii. This design is not recommended
Design of rib draft angle	non-visible surface	SMC/BMC	return flanges 1.5°, rib - 1° per side
Design of rib draft angle	A-class surface	SMC/BMC	return flanges 1.5°, rib - 0,5° per side
Design of thinner wall thickness to reduce weight	-	SMC/BMC	Reduce overall component weight by diluting non-loaded areas. The larger the area, the less reduction there should be in wall thickness. Diluted thickness is approximately 75 – 80% of normal
Design of openings & holes	-	SMC/BMC	Holes are best achieved via a secondary drilling, punching, routing, or water-jet cutting operation. Larger openings require shear edged tools around their periphery.
Design of bosses to reduce the risk of bosses cracking	-	SMC/BMC	Bosses must be designed 25 % longer than the fastener; Boss diameter should be 2.5 times cored hole diameter; Torque and pull-out strength should follow suppliers recommendation; The specific design (asymmetrical thread, recessed thread root & special cutting notch) reduces the risk of bosses cracking and increases tightening, break-loose and pull-out forces. An assembly operation repeated more than five times will require threaded inserts. 

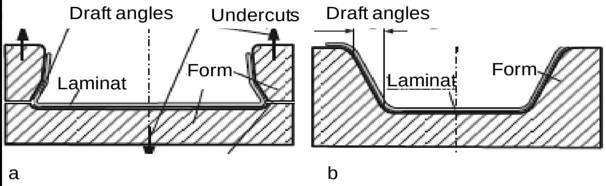
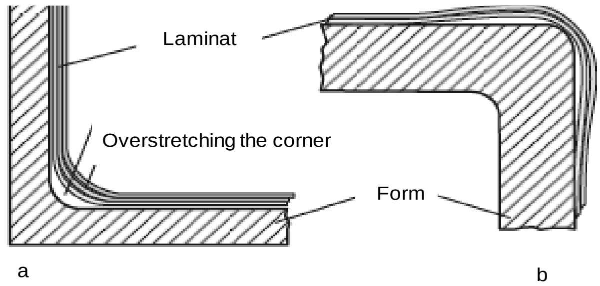
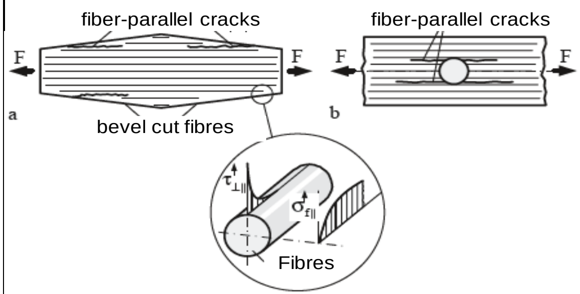
European Alliance for SMC/BMC (2007), Design For Success : A Design & Technology Manual for SMC/BMC			
Objective	**Considered factors**	**Material**	**Recommendation**
Design of inserts to prevent or minimize torque retention	-	SMC/BMC	require a definite clearance off the mould surface of typically 0.5mm to prevent or minimize torque retention. Moulded-in and standard inserts both require mechanical undercut conditions to achieve the necessary friction otherwise unobtainable with plain geometries.
Design of trimming to achieve smooth edges	structural parts and non-visible part	SMC/BMC	Structural parts and other non visible parts require a simple de-flashing operation to achieve smooth edges
	visible part	SMC/BMC	Visible parts like exterior body panels may require defined radii or minimal radii of ≥ 2.5 mm due to legal requirements.

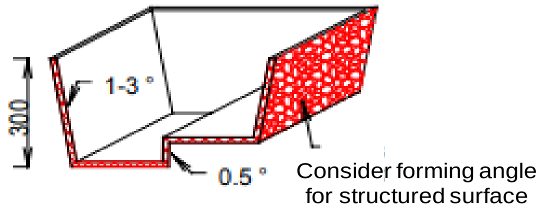
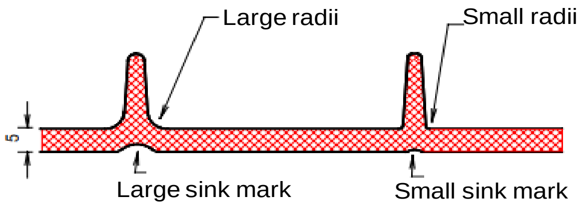
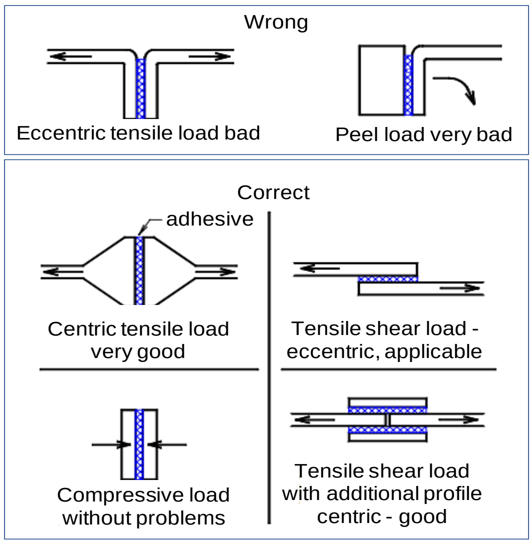
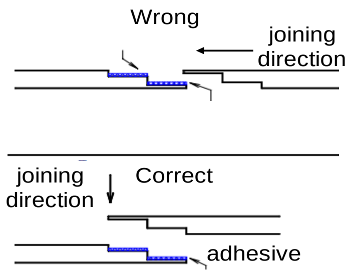
AVK – Industrievereinigung Verstärkte Kunststoffe e. V.(2013) Handbuch Faserverbundkunststoffe/Composites			
Objective	**Considered factors**	**Material**	**Recommendation**
Design of wall thickness	-	SMC	The aim should be to achieve as uniform a wall thickness as possible over the entire component. Wall thicknesses from 1.2 mm have proven themselves in pressing technology. Smaller wall thicknesses are possible, but usually problematic. 
Design of radii by ribs	good surface or optimal strength in focus	SMC	When designing the radii of the rib connection, it must be decided whether good surfaces or optimum strengths are important. The surface improves as the radius decreases, while the transverse strength of the rib decreases. 
Design of wall thickness jumps	-	SMC	Wall thickness jumps are possible at any time, but can have a negative effect on the surface in the transition area. A waviness often occurs in the area of the transition. The optical impression can be improved by deliberately inserting a shadow gap or other stylistic elements. When stiffening the edges, bending the corners is therefore preferable to thickening the corners. 

AVK – Industrievereinigung Verstärkte Kunststoffe e. V.(2013) Handbuch Faserverbundkunststoffe/Composites			
Objective	**Considered factors**	**Material**	**Recommendation**
Design of ribs	visible surface	SMC	At least 1° conicity should be present on both sides to allow perfect demoulding; 0.5° is possible with excellently machined tools. For surface critical parts, the rib thickness at the base should be less than the wall thickness of the part in a ratio of 3:4 and the cutting angle between two ribs or between a rib and other elements should not be less than 30°. 
Design of draft angles to enable good demolding	textured surfase	SMC	To ensure problem-free demoulding, a conicity of at least ½ ° must be provided for all areas of the pressed part. Regardless of formal aesthetic considerations, it is better to work with too much conicity than with too little. For textured surfaces, 1° conicity must be added for each 0.025 mm structure depth. This largely eliminates the risk of damage to the surface structure during demoulding.
Design of dome for compression mouldin	-	GMT/LFT	
Design of ribs for good filling with fibres	-	GMT/LFT	For a ribbed filling with good glass distribution, the geometries shown in Figure below are recommended. Ribs should preferably be placed on the "pressure side". Tensile stressed ribs can show considerable losses in strength due to glass depletion in the head. 
Design of edge stiffening	-	GMT/LFT	
Design of beads	-	GMT/LFT	

H. Schürmann (2007), Konstruieren mit Faser-Kunststoff-Verbunden			
Objective	**Considered factors**	**Material**	**Recommendation**
General consideration regarding joints	-	General for FRP	Joints must be avoided or their number must be kept low. They entail increased production costs and additional weight. In addition, there are multi-axes and voltage superelevations, so that joints are often the failure triggers.  Disadvantages of joints: the material doubling of the necessary overlap - riveted or glued - causes additional weight. Excessive stresses at the beginning of an overlap bond (a) or at the edge of the drill hole (b) are usually the starting point for cracks and joint failure.
General consideration regarding force flow	-	General for FRP	Force flows are to be conducted directly. Otherwise, considerable additional burdens occur, which cause additional weight.  (a) Force diversions cause additional bending moments and thus require significantly higher material costs. (b) Forces transmitted directly only require simple components with favourable material utilization.
General consideration regarding cross-sections	-	General for FRP	In lightweight construction, thin-walled hollow cross-sections are used, not full cross-sections. In the case of solid cross-sections, the material inside the cross-section is only low used for bending and torsion.
General consideration extremely loaded structures	-	General for FRP	Constant stress distributions must be set above the wall thickness. Extremely loaded structures should therefore be designed as single axis loaded bars or double axis loaded discs and not as beams or plates. In this way, uniform material utilization and optimum light-weight grades are achieved.  A bending load (b) has the disadvantage of poor utilization of the material in the middle area of the beam compared to the rod or disc load (a).
General consideration by bending load	bending load	General for FRP	If there is a bending load, material should be saved in the area of low stresses around the neutral plane. This leads, for example, to the I-beam or sandwich construction. Comparison of different profile dimensions (a) rectangular profiles (b) I-profiles (c) cross-section resolved into tension and compression bar; this can be realized in the sandwich  Required cross-section A relative to the full square cross-section in %. 100 67 50 25 60 30 20 17 12 10

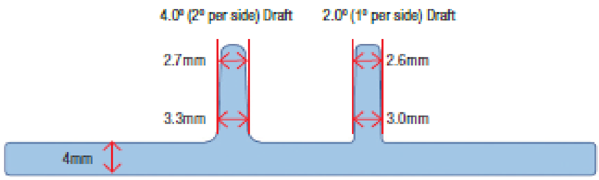
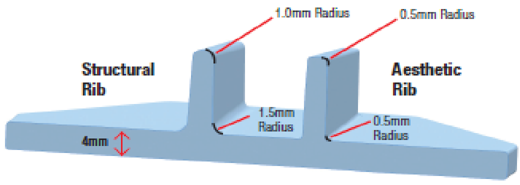
H. Schürmann (2007), Konstruieren mit Faser-Kunststoff-Verbunden			
Objective	**Considered factors**	**Material**	**Recommendation**
General consideration to achieve high torsional stiffness	torsional load, profiles	General for FRP	If high torsional stiffness is required, it is essential to use a closed hollow cross-section with the largest possible enclosed area A and the smallest possible circumference. Thin-walled circular cross-sections are ideal. However, if there is only an open profile cross-section, the torsional stiffness, which is almost negligible compared to closed profiles, can be slightly increased by a high arch stiffness. Open profiles with higher arch stiffness are the U, Z and I profiles (UZI), whereby the Z profile has the highest arch stiffness. Another possibility is to close open profiles at least locally.  Increase of torsional stiffness of an open U-profile: (a) The setting of bulkheads brings only a minimal improvement. (b) It is very effective to close the open profile at least partially.
General consideration to design torsionally soft	torsional load, profiles	General for FRP	If, on the other hand, torsionally soft construction is required, open profiles are recommended. They should also be free of curvature. Suitable are the T- and the cross profile. If a closed profile is to be assumed, the middle, enclosed area A should be kept small.
General consideration for force transmission	-	General for FRP	In the area of force transmissions, stiffness transitions lead to the additional stresses. To avoid failure always growing out of the force introduction, a simple design rule is applied: the stress level is lowered by changing the geometry. In the simplest case, one deviates from the light construction-optimal contour and increases the wall thickness. Force introduction via clamping  Since force introductions usually involve complex, multi-axis stress states, it is recommended to reduce the stress level in the force introduction area. In the example this occurs around the clamping force introduction through a section by section higher overall height.
General consideration for force transmission	-	General for FRP	Force transmissions should not be placed near cut-outs so that the voltage surges do not overlap there.
General consideration for avoiding of notching	-	General for FRP	Notching and the resulting local voltage surges must be avoided at all costs. It is almost always possible to achieve a significant reduction in mass if stress curves can be smoothed and a component no longer has to be dimensioned to local, high notch stresses!
General consideration for avoiding of buckling	-	General for FRP	Thin-walled, free edges buckle even at very low pressure loads and must therefore be stiffened. These local stiffeners are particularly easy to integrate with FKV. A sensible measure is to flange the edges. The flare height must not become too high, otherwise the flare itself becomes a free edge at risk of buckling.

H. Schürmann (2007), Konstruieren mit Faser-Kunststoff-Verbunden			
Objective	**Considered factors**	**Material**	**Recommendation**
General consideration in manufacturing	-	General for FRP	Composite fibre components are usually produced in negative moulds. Firstly, undercuts must be avoided. Secondly, it is essential to provide draft angles on all sides. This applies in particular to thick-walled, rigid components. Thin-walled structures can be bent easily and just peel it out of the mould. On this and on a careful treatment If the mould is not treated with release agents, the component remains locally adhered to the mould and is damaged during forcible demoulding.  Design to choice, if undercuts in the manufacturing tool are un-avoidable. Sufficiently large draft angles shall be provided for easy demoulding.
General consideration sharp corners	-	General for FRP	Sharp corners are to be avoided. There are two reasons for this. The semi-finished textile products have low bending stiffness. When pressureless hardened, they stand out from corners. Since there is no tool contact, bad surfaces remain in the corners, which must be reworked. More serious, however, is that the laminate is inadequately compacted there and consequently the interlaminar strengths are reduced. The problem can be alleviated by selecting large corner radii and pressing the semi-finished product into the corner under pressure.  Corners must be designed with large radii. (a) The semi-finished product spans one to sharp internal corner. (b) In narrow outer corners, the areas next to the corner are insufficiently compacted.
General consideration for post-processing	-	General for FRP	The fiber composite designer must consider the subsequent post - processing when selecting the fiber orientation. Avoid machining the edges of highly loaded structures - tension rods, leaf springs, etc. - and cutting fibres with them. Already after a few load changes, shear cracks would occur between the fibres.  (a) Shear cracks occur at cut edges of UD layers which run into the layer parallel to the fibres. The reason for this is the shear stress peak at the fiber edge in the fiber matrix interface, via which the fiber stress increases from zero to the effective stress in the undisturbed area. (b) Typically, this is also found with fiber ends cut through holes.

Wernli, R. (1998) Konstruieren mit faserverstärkten Duroplaste			
Objective	**Considered factors**	**Material**	**Recommendation**
Design of draft angles	structured parts	SMC	The better the mould surface, the smaller the draft angle can be. The draft angle depends very much on the height of the component. 1 to 3 ° are the rule, small surfaces can also be shaped with an angle of less than 1 °. For structured surfaces, the draft angle depends on the depth of the structure etching. 
Design of ribs to prevent sink marks	-	SMC	Reinforcement ribs can be installed on both sides. Care must be taken to keep the radii to the surfaces as small as possible in order to prevent excessive marking on the opposite side. 
Possible radii	-	SMC	Radii from approx. 1 mm are possible. For static reasons, however, large radii should always be used wherever possible for plastic parts (with the exception of ribs and reinforcing eyes).
Possible wall thickness	-	SMC	The wall thicknesses can vary. Partial additional roving pre-preg's are possible.
Design of bonding connections	-	thermoset	
Design of bonding connections	-	thermoset	

Clarke J. (1996) Structural design of polymer composites, Euroomp Design Code and Handbook			
Objective	**Considered factors**	**Material**	**Recommendation**
General consideration - screws	structural parts	FRP	Screws are not recommended if the primary role of the joint is structural, because both self-tapping screws and tappedhole screws cause extensive damage to the laminates. If screws are to be used for structural applications, it should be possible to cast metal blocks into the composite at the time of manufacture or to mount metal blocks on the composite and then to drill and tap into them in the conventional way.
General consideration - rivets	laminate	FRP	Because the process of forming the rivets involves applying a lateral pressure to the composite, there may be cases in which the riveting operation causes damage to the laminate, especially when using blind rivets. The clamping force exerted by the rivets also affects the strength of the joint.
General consideration - screws to ensure a smooth surface	smooth surface	FRP	If countersunk screws are to be used to ensure a smooth external surface, they must not be allowed to cut completely through the laminate. This will generally imply a restriction in the minimum thickness of the composite. Care must be taken in tightening joints to avoid driving washers into and crushing the laminate, particularly in the case of sandwich panels. But, provided excessive overtightening if the joint does not take place, no damage should be done to the composite during assembly.
General consideration - position of holes to avoid failure during assembly	-	FRP	It is important to locate accurately the relative positions of the holes in the composite materials to be joined, so that high stresses leading to premature failure during assembly are avoided, either by accurate templates, clamping the units to be bolted together and drilling them in the workshops or drilling and bolting as one operation on site.
General consideration - reduce the long term creep	-	FRP	Long term creep in the structure could reduce the initial tightening of bolted joints and this should be considered in the design.
General consideration - spacing between bolts to eliminate lapping	-	FRP	Large washers are sometimes required from design considerations, and the designer and fabricator must provide sufficient spacings between bolts that lapping of washers is eliminated.
General consideration - bolt hole size	close tolerance	FRP	Bolt hole sizes should not be specified smaller than necessary and the use is of large washers recommended. Where close tolerance bolts are specified, holes must not be enlarged beyond the specified size.
General consideration - bolts, fixings, metal inserts	-	FRP	Bolts, fixings and metal inserts shall be of a suitable type of stainless steel, non-ferrous metal or FRP and shall be such as to avoid bi-metallic corrosion.
General consideration - bolted connections	-	FRP	Bolted connections shall be formed in such a way as to ensure that the load on the connection is properly distributed between the bolts without damage to the parts being joined, either during the forming of the joint or in service.
General consideration - holes for structural connections	structural connection	FRP	Holes for structural connections using bolts loaded in shear shall be formed so that each bolt is a close fit in the mating holes of the parts to be joined and so that no loads due to misaligned holes are imparted to either of the FRP laminates being joined.

Molded Fiber Glass Companies (2014), Designing with SMC

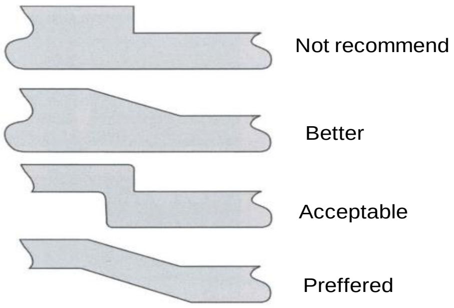
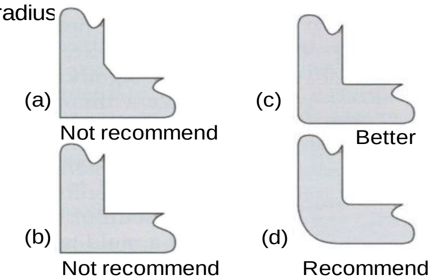
Objective	Considered factors	Material	Recommendation
Design guidance for incorporating ribs	A-class	SMC	To avoid sink marks on the surface, make sure the base of the rib is thinner than the nominal part thickness (3/4 of the wall stock). For example, a panel with a nominal thickness of 4mm will have ribs 3.0mm thick at the root, tapering toward the tip. This tapering is required to add draft to the rib. Ideally, minimum draft should be one degree per side to allow the compression molds to open and close without difficulty and completely “fill-in” the cross-section. 
	-	SMC	Overly deep ribs also create problems and are unlikely to properly fill with glass. A remedy to this is adding radius to the entrance, allowing for better flow of material into the rib. This adds thickness to the root of the rib, which would result in more shrink/show, but allows the glass fibers to fill in the depth, improving the strength. The deeper the rib, the less glass at the bottom – the more fiber orientation occurs – which can create problems. As with any material, glass-filled or not, adding radii to part geometry can improve flow - it’s simply easier for resin to move through curved radii and fillets than a sharp angle.  Example: An ideal design approach for a 4mm thick panel would be a smoothly transitioned fillet into a 3mm wide rib with a one degree draft (per side) down to 2mm that is about 28mm deep.

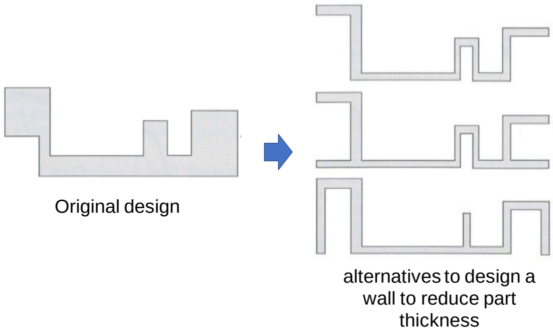
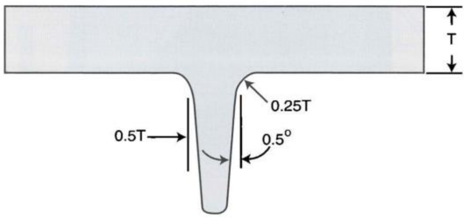
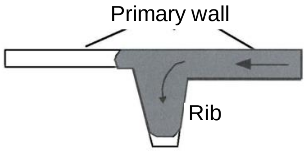
Campbell F. (2010) Design and Certification

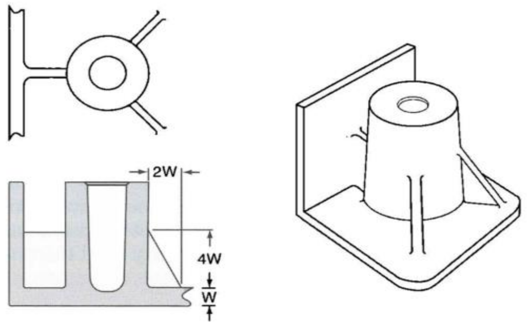
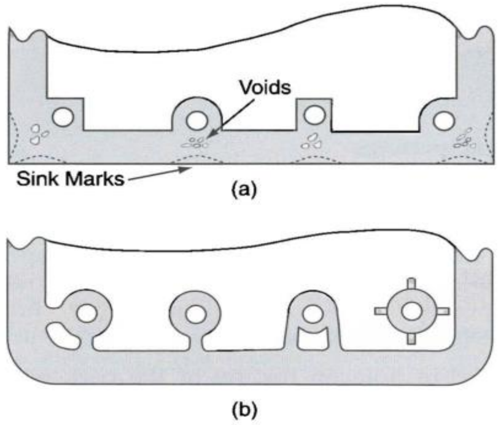
Objective	Considered factors	Material	Recommendation
General considerations	laminate	FRP	**Guidelines (G)** - Avoid or minimize conditions which cause peel stresses such as excessive abrupt laminate terminations or cocured structures with significantly different flexural stiffnesses. **Remarks (R)** - Peel stresses are out-of-plane to the laminate and hence, in its weakest direction.
General considerations	laminate	FRP	**(G)** - Buckling or wrinkling is permissible in thin composite laminates provided all other potential failure modes are properly accounted for. In general, avoid instability in thick laminates. **(R)** - Significant weight savings are possible with postbuckled design.
General considerations	laminate	FRP	**(G)** - Locating 90° and +-45° plies toward the exterior surfaces improves the buckling allowables in many cases. Locate 45° plies toward the exterior surface of the laminate where local buckling is critical. **(R)** - Increases the load carrying capability of the structure.

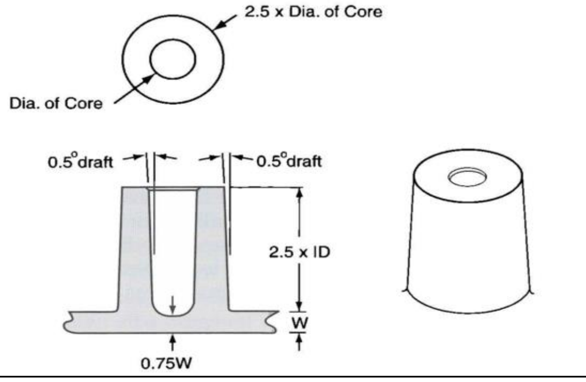
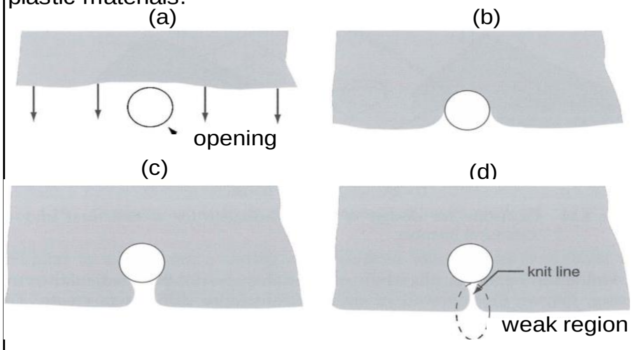
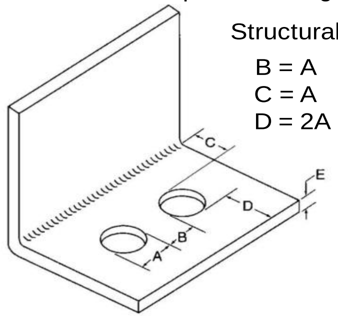
Campbell F. (2010) Design and Certification			
Objective	**Considered factors**	**Material**	**Recommendation**
General considerations	laminate	FRP	**(G)** - When adding plies, maintain balance and symmetry. Add between continuous plies in the same direction. Exterior surface plies should be continuous. **(R)** - Minimizes warping and interlaminar shear. Develops strength of plies. Continuous surface plies minimize damage to edge of ply and help to prevent delamination.
General considerations	laminate	FRP	**(G)** - Never terminate plies in fastener patterns. **(R)** - Reduces profiling requirements on substructure. Prevents delamination caused by hold drilling. Improves bearing strength.
General considerations	laminate	FRP	**(G)** - Stacking order of plies should be balanced and symmetrical about the laminate midplane. Any unavoidable unsymmetric or unbalanced plies should be placed near the laminate midplane. **(R)** - Prevents warpage after cure. Reduces residual stresses. Eliminates "coupling" stresses.
General considerations	laminate	FRP	**(G)** - Use fiber dominated laminate wherever possible. The [0°/+-45°/90°] orientation is recommended for major load carrying structures. A minimum of 10% of the fibers should be oriented in each direction. **(R)** - Fibers carry the load; the resin is relatively weak. This will minimize matrix and stiffness degradation.
General considerations	laminate	FRP	**(G)** - When there are multiple load conditions, do not optimize the laminate for only the most severe load case. **(R)** -Optimizing for a single load case can produce excessive resin or matrix stresses for the other load cases.
General considerations	laminate	FRP	**(G)** - If the structure is mechanically fastened, an excess of 40% of the fibers oriented in any one direction is inadvisable. **(R)** - Bearing strength of laminate is adversely affected.
General considerations	laminate	FRP	**(G)** -Whenever possible maintain a dispersed stacking sequence and avoid grouping similar plies. If plies must be grouped, avoid grouping more than 4 plies of the same orientation together. **(R)** - Increases strength and minimizes the tendency to delaminate. Creates a more homogeneous laminate. Minimizes interlaminar stresses. Minimizes matrix microcracking during and after service.
General considerations	laminate	FRP	**(G)** -If possible, avoid grouping 90° plies. Separate 90° plies by a 0° or +-45° plies where 0° is direction of critical load. **(R)** - Minimizes interlaminar shear and normal stresses. Minimizes multiple transverse fracture. Minimizes grouping of matrix critical plies.
General considerations	laminate	FRP	**(G)** -Two conflicting requirements are involved in the pairing or separating of +-0° plies (such as +-45°) in a laminate. Laminate architecture should minimize interlaminar shear between plies and reduce bending/twisting coupling. **(R)** - Separating +-0° plies reduces interlaminar shear stresses between plies. Grouping +-0° plies together in the laminate reduces bending/twisting coupling.
General considerations	laminate	FRP	**(G)** - Locate at least one pair of +-45° plies at each laminate surface. A single ply of fabric will suffice. **(R)** - Minimizes splintering when drilling. Protects basic load carrying plies.

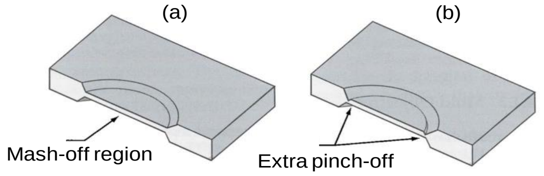
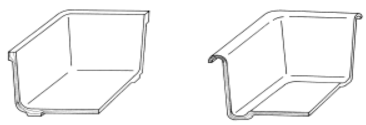
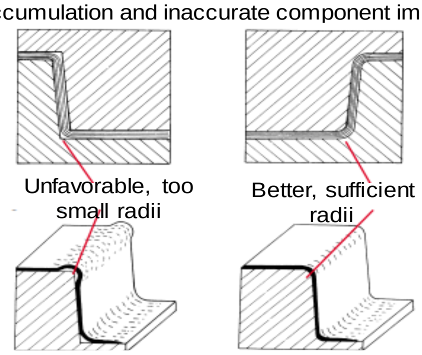
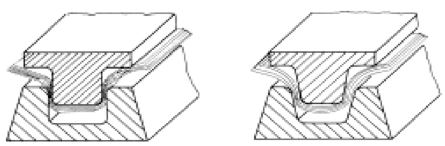
Campbell F. (2010) Design and Certification			
Objective	**Considered factors**	**Material**	**Recommendation**
General considerations	laminate	FRP	**(G)** - Avoid abrupt ply terminations. Try not to exceed dropping more than 2 plies per increment. The plies that are dropped should not be adjacent to each other in the laminate. **(R)** - Ply drops create stress concentrations and load path eccentricities. Thickness transitions can cause wrinkling of fibers and possible delaminations under load. Dropping nonadjacent plies minimizes the joggle of other plies.
General considerations	laminate	FRP	**(G)** - Ply drop-offs should not exceed 0.010 in. thick per drop with a minimum spacing of 0.20 in. in the major load direction. If possible, ply drop-offs should be symmetric about the laminate midplane with the shortest length ply nearest the exterior faces of the laminate. Shop tolerance for drop-offs should be 0.04 in. **(R)** - Minimizes load introduction into the ply drop-off creating interlaminar shear stresses. Promotes a smooth contour. Minimizes stress concentration.
General considerations	laminate	FRP	**(G)** - Skin ply drop-offs should not occur across the width of spars, rib, or frame flange. **(R)** - Provides a better load path and fit-up between parts.
General considerations	laminate	FRP	**(G)** - In areas of load introduction there should be equal numbers of +45° and -45° plies on each side of the mid-plane. **(R)** - Balanced and symmetric pairs of +-45° plies are strongest for in-plane shear loads which are common at load introduction points.
General considerations	laminate	FRP	**(G)** - A continuous ply should not be butt-spliced transverse to the load direction. **(R)** - Introduces a weak spot in the load path.
General considerations	laminate	FRP	**(G)** - A continuous ply may be butt-spliced parallel to the load direction if coincident splices are separated by at least four plies of any orientation. **(R)** - Eliminates the possibility of a weak spot where plies are butted together.
General considerations	laminate	FRP	**(G)** - The butt joint of plies of the same orientation separated by less than four plies of any direction must be staggered by at least 0.6 in. **(R)** - Minimizes the weak spot where plies are butted together.
General considerations	laminate	FRP	**(G)** - Overlaps of plies are not permitted. Gaps shall not exceed 0.08 in. **(R)** - Plies will bridge a gap, but must joggle over an overlap.

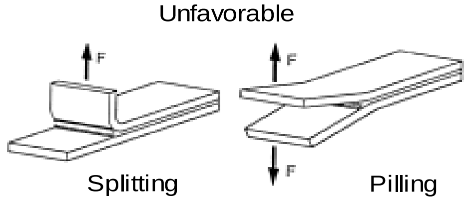
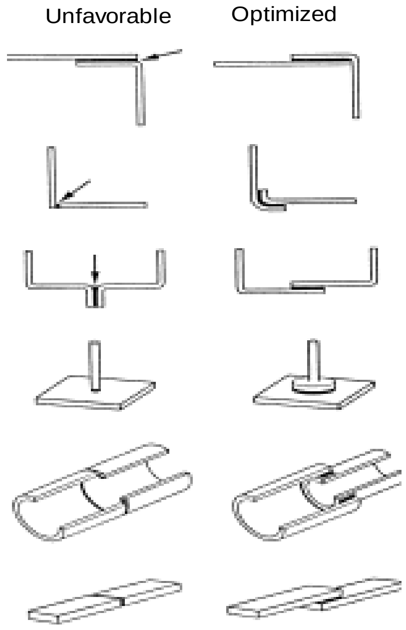
Davis B. et al (2003) Compression Molding			
Objective	**Considered factors**	**Material**	**Recommendation**
Design of wall thickness	Compression molding	SMC	One of the most important guidelines when designing a plastic component for any manufacturing process is maintaining a uniform wall thickness in the part. Varying wall thickness creates regions with different degrees of shrinkage, structural performance and stress concentration. When a change in thickness is required, gradual transitions are recommended. Figure demonstrates how the thickness or position of the wall should change. Gradual change with no thick region is preferred. Abrupt changes in wall thickness can also affect how material flows through the mold cavity. During mold filling the resin will tend to flow easier into thicker regions than in thinner regions. This may give undesirable mold filling patterns, which could lead to weld or knit lines, gas entrapment, or less than optimal fiber orientation. One should remember that in compression molding the cavity's thickness is changing throughout the molding processes. 
Design of corner or part radius	Compression molding	SMC	When designing a corner or part radius it is also important that a constant wall thickness be maintained to avoid material flow and solidification problems. Figure (a) illustrates a poorly designed corner, though the inside corner is made for easy mold release. This corner design will have an excess amount of material creating potential problems during solidification. These problems could include material shrinkage, excess heat due to cure, under-cure, and void formation. In addition, the 90° angle at the outside corner will be difficult to fill with material during molding. Sharp corners should be avoided because they are easily damaged. The corner shown in Figure (b) will have similar problems. Also, the 90° angle at the inside corner will make it more difficult to extract the part from the mold. Figure (c) illustrates a much better design and avoids some of the problems that would be seen with the two previous designs. To avoid problems, Figure (d) shows a preferred corner design with a large inside and outside radius 

Davis B. et al (2003) Compression Molding			
Objective	**Considered factors**	**Material**	**Recommendation**
Minimize wall thickness	Compression molding	SMC	Wall thickness plays an important role in how material flows through the cavity, how fast heat flows into and out of the part during molding, how part solidification takes place, overall cycle time, and structural response of the part. Clearly, wall thickness also dictates the part weight. If part thickness is too large, the strength-to-weight advantage is lost. At the same time, if wall thickness is too small part structural integrity may be jeopardized. The goal should be to design a part with the minimum wall thickness that satisfies the part's structural requirements. 
Rib design to avoid sink marks and flow anomalies	Compression molding	SMC	An important advantage when designing with plastic is the ability to incorporate ribs and bosses directly into the part. Care needs to be taken when using these features due to problems they can create, such as sink marks and flow anomalies. To help avoid this problem, the following dimensional rules may be useful. The base of the rib (point where rib attaches to primary wall) should be 50-75% of the thickness of the primary wall. The radius at the attachment point should be a minimum of 0.25 times the primary wall thickness. The height of the rib should never be more than 2.5 to 5.0 times the thickness of the primary wall. A minimum taper of 0.5 degrees is required for easy part removal from the mold. Figure below demonstrates a common rib geometry.  A problem that can occur if the thickness of the rib is similar or greater to the primary wall thickness is a flow divergence phenomenon. Instead of the material flowing along the primary wall it will flow into and along the rib, as shown in Fig. below. This can cause problems down stream with knit line formation, gas entrapment, or fiber matrix separation 

Davis B. et al (2003) Compression Molding			
Objective	**Considered factors**	**Material**	**Recommendation**
Design for the boss gusset	Compression molding	SMC	The typical function of a boss is to give a place for self-tapping screws and force fit pins to fasten to. They are also used for positioning and as stops. They may be designed to be hollow or solid, and can be free standing, attached to a side wall, or have small ribs attached to them called gussets, as shown in Fig. below. The height of the gusset should be approximately 4 times the thickness of the primary wall with the base 2 times the thickness. The thickness of the gusset should be limited to around 0.75 times the primary wall thickness. It is preferred that the boss not be attached directly to the side wall since this will create a thick region that is susceptible to sink marks, voids, and residual stresses. These residual stresses should be avoided since the boss will already be under a degree of stress from the fastener. An improved method is to attach the boss to the sidewall with a small rib or gusset. This small rib or gusset will improve the overall torsional and bending stiffness of the boss, which may be needed depending on the load that will be applied to the fastener.
			
			Examples of (a) bad and (b) good boss design 
			The dimensions of the boss should be specified so that it can withstand the assembly and service loads. Large wall thickness increases the structural properties of the boss. However, it is clear that excessive thickness can lead to cosmetic problems, as well as to an increase in part weight. There is a balance in thickness that results in a boss that performs well structurally while the surface quality of the part is not compromised. A standard recommended boss design is shown in Fig. below. The inside diameter of the boss is typically the pitch diameter of the screw, while the outer diameter is 2.5 times the inside diameter. The height of the boss should be no greater than 2.5 times the inside diameter. Similar to the design of a rib, the radius of the boss with the primary wall should be approximately 0.25 times the primary wall thickness.

Davis B. et al (2003) Compression Molding			
Objective	**Considered factors**	**Material**	**Recommendation**
Design for a standard boss	Compression molding	SMC	
Design of molded-in openings	Compression molding	SMC	Creating a molded-in hole on the top of the part, perpendicular to mold closing, seems quite trivial. However, the influence that the opening will have on the mold filling and ultimately the structural properties can be detrimental. During molding, material flow around an opening will inherently create a knit or weld line on the side opposite to where the material approached the opening. The knit or weld line that results can be quite severe depending on at what time during the process this occurs, how the material approaches and flows around the opening, what material is being processed, the amount of fiber reinforcement, along with several other variables. Figure below demonstrates a flow pattern in a mold where a knit or weld line forms as the material flows around the opening and reforms after flowing past it. This is very common occurrence when processing plastic materials. 
Design of hole placement for a structural and non-structural part	Compression molding	SMC	When designing the opening, its placement on the part should be considered. If the part is to be loaded, then the distance from the outer perimeter of the hole should be a minimum of two diameters away from the outside edge of the sidewall. The spacing between holes should be one diameter or greater. Openings that appear on non-loaded parts can be spaced twice the thickness of the part. The distance from the outside edge should also be a minimum of twice the thickness of the part. Structural analysis is recommended to better understand the stresses that are created with the specific loading and geometry.  Structural: B = A, C = A, D = 2A Non-Structural: B = 2E, C = 2E, D =2E

Objective	Considered factors	Material	Recommendation
Davis B. et al (2003) Compression Molding			
Design of molding of openings	Compression molding	SMC	When dealing with problems caused by the molding of openings, the compression molding process gives the molder some extra options that other processes do not. The first option is to incorporate a mash-off where the opening will eventually be.  Geometry of mash-off (a) conventional (b) extra pinch-off
Design to reduce thickness	Compression molding	SMC	Similar to a mash-off, a sliding core-pin fired after the mold is filled will also result in a reduction in part thickness where the pin and freshly molded part come in contact. One of the main differences between this method and a mash-off is that the sliding core-pin does not influence the mold filling, whereas the mash-off feature is in contact with the flowing material during the process and will influence how it travels in the mold.
Drechsler and Bockelmann (2016) based on RGF (2014)			
Design of wall thickness	-	FRP	Provide as uniform wall thicknesses in the component as possible in order to avoid resin accumulation and local differences in the fibre volume content and to enable a uniform force flow. Unfavorable Optimized 
Design of radii	-	FRP	Large radii should be provided in order to enable the fibres to be distributed as homogeneously as possible. Due to the bending stiffness of fibres, small radii lead to resin accumulation and inaccurate component impressions. 
Design of draft angles	Compression molding	FRP	Undefined distortion and displacement of individual fiber mats in automated draping processes. Easier demoulding of the cured part from the mould. This is particularly critical when processing is carried out under the influence of temperature due to the very low coefficient of thermal expansion of some types of reinforcement. Unfavorable Optimized 

Drechsler and Bockelmann (2016) based on RGF (2014)			
Objective	**Considered factors**	**Material**	**Recommendation**
Deisgn of bonding connections	-	FRP	Adhesives must be designed in such a way that the forces acting on them cannot lead to peeling or splitting in the adhesive layer: 
Deisgn of bonding connections	-	FRP	Constructive design of the joint for the - Enlargement of the adhesive surface - Avoidance of critical loads 

B. Questionnaire

(Questions are extracted from LimeSurvey)

The objective of this survey is to **raise requirements on design guidelines for fiber reinforced polymers** in order to develop a new concept for efficient support of engineers during the process of product development.

The idea is to develop the interactive design guidelines that provide relevant information regarding requirements on product.

The development of guidelines is carried out within the framework of a project called "**Integrated engineering of continuous-discontinuous long-fiber-reinforced polymer structures**" which is funded by **German Research Foundation** (DGF). The **research results** in this project will be subsequently transferred into the design guidelines and made **available to the industry**.

By participating in this survey, you will be able to **contribute** the development of future design guidelines and **specify your personal requirements**.

To the answer of the questions you need about 10-15 minutes.

The information provided by you will be held **totally anonymously**.

Our goal is to create an application-oriented design guideline for you. For this reason, we need to know information about your industry, department you work in and your experience level considering working with fiber-reinforced polymers.

[1] What industry are you employed in?

Please choose **only one** of the following:

- Automotive industry
- Aerospace
- Rail transport
- Shipbuilding
- Construction industry
- Electrical engineering
- Plant construction
- Mechanical engineering
- Other

[2] Which department do you work in?

Please choose **only one** of the following:

- Research and Development
- Planning
- Design
- Validation and Verification
- Production
- Market launch
- Other

Legend:

Research and development - You are involved in the development of new approaches, ideas, planning, implementation, interpretation, calculation and testing of various research and development topics.

Planning - The part of your task is to clarify the requirements, the objectives, the product functions, the resources and the data required for a project. You take care of a product from the idea to the commissioning.

Design - You are involved in the creation of mechanical structures, design calculations, design drawings, CAD designs, their analysis, planning, implementation, control and documentation.

Validation / verification - You carry out calculations and simulations for technical-physical systems, evaluate real systems and optimize developments based on the data obtained.

Production - You are responsible for production processes, their planning, optimization and order execution. You care for products and ensure their quality.

Market launch - You are responsible for the market introduction of products.

[3] How many years of professional experience do you have in the field of long- and endless-fiber-reinforced plastics?

Please choose **only one** of the following:
- No experience
- 1-2 years
- 3-5 years
- 6-10 years
- 11-15 years
- 16-20 years
- >20 years

[4] What material classes / manufacturing technologies do you work with?

(Only answer this question if the following conditions are met: Answer was '1-2 years' or '3-5 years' or '6-10 years' or '11-15 years' or '16-20 years' or '>20 years' at question '3 [3]' (How many years of professional experience do you have in the field of long- and endless-fiber-reinforced plastics?))

Please choose **all** that apply:
- Long-fiber-reinforced composites (SMC, LFT, BMC, etc.)
- Continuous fiber-reinforced composites (RTM, VARI, Prepreg, Wet presses, etc.)
- Hybrid technologies (combination of long fiber with continuous fiber in a single component)
- Hybrid technologies (Glass or carbon fiber-reinforced polymers + Metal)
- Other:

Current situation in the use of design guidelines / design rules

We want to capture the current situation in the use of design guidelines / design rules. Please let us know your experiences.

[5] Do you use design guidelines / design rules in your work?

Please choose **only one** of the following:
- Yes
- No
- Unsure

[6] The design guidelines / design rules that I use ...

(Only answer this question if the following conditions are met: Answer was 'Yes' at question '5 [5]' (Do you use design guidelines / design rules in your work?))

Please choose **all** that apply:

- Are available in the company
- Are from the literature / the internet
- Other:

[7] Do you see any disadvantages in the design guidelines / design rules you are using?

(Only answer this question if the following conditions are met: Answer was 'Yes' at question '5 [5]' (Do you use design guidelines / design rules in your work?))

Please choose **all** that apply:

- No, I am satisfied with design guidelines
- Yes, because the design guidelines are not state of the art
- Yes, because the design guidelines are only partially suitable for the application
- Yes, because the design guidelines are not sufficiently detailed
- Yes, because the design guidelines are confusing
- Yes, because the search for good design guidelines is too time-consuming
- Other:

[8] What are the reasons why you do not use design guidelines / design rules in your work?

(Only answer this question if the following conditions are met: Answer was 'Planning' at question '2 [2]' (Which department do you work in?) and Answer was 'No' at question '5 [5]' (Do you use design guidelines / design rules in your work?))

Please choose **all** that apply:

- For planning, I do not need any design guidelines
- The design guidelines are not state of the art
- There are no design guidelines for my area of responsibility
- The design guidelines are only partially suitable for the application
- The design guidelines are not sufficiently detailed
- The design guidelines are confusing
- The search for good design guidelines is too time-consuming
- Other:

[9] What are the reasons why you do not use design guidelines / design rules in your work?

(Only answer this question if the following conditions are met: Answer was 'Research and Development' at question '2 [2]' (Which department do you work in?) and Answer was 'No' at question '5 [5]' (Do you use design guidelines / design rules in your work?))

Please choose **all** that apply:

- In research and development, I am above the state of the art, so I do not need any design guidelines
- There are no design guidelines for my area of responsibility
- The design guidelines are only partially suitable for the application

- The design guidelines are not sufficiently detailed
- The design guidelines are confusing
- The search for good design guidelines is too time-consuming
- Other:

[10] What are the reasons why you do not use design guidelines / design rules in your work?

(Only answer this question if the following conditions are met: Answer was 'Design ' at question '2 [2]' (Which department do you work in?) and Answer was 'No' at question '5 [5]' (Do you use design guidelines / design rules in your work?))

Please choose **all** that apply:

- The design guidelines are not state of the art
- There are no design guidelines for my area of responsibility
- The design guidelines are only partially suitable for the application
- The design guidelines are not sufficiently detailed
- The design guidelines are confusing
- The search for good design guidelines is too time-consuming
- Other:

[11] What are the reasons why you do not use design guidelines / design rules in your work?

(Only answer this question if the following conditions are met: Answer was 'Validation and Verification' or 'Conception' or 'Production' or 'Market launch' or 'Other' at question '2 [2]' (Which department do you work in?) and Answer was 'No' at question '5 [5]' (Do you use design guidelines / design rules in your work?))

Please choose **all** that apply:

- I do not need any design guidelines for my job
- The design guidelines are not state of the art
- There are no design guidelines for my area of responsibility
- The design guidelines are only partially suitable for the application
- The design guidelines are not sufficiently detailed
- The design guidelines are confusing
- The search for good design guidelines is too time-consuming
- Other:

Main focus and content for a design guideline

An interactive design guideline should cover all relevant areas of interest. Help us to figure out what topics are important to you and what content you would like to find in design guidelines.

[12] Please specify the topics in working with fiber-reinforced plastics in which you would like to have a support in form of design guidelines. The topics are divided into four areas: material characterization, technology, simulation and design.

Please choose the appropriate response for each item:

	Strongly relevant	Moderately strong relevant	Little relevant	Not relevant
Material characterization:	☐	☐	☐	☐

Scattering material properties				
Inaccurate / missing material characteristics	☐	☐	☐	☐
Technology:				
Selection of appropriate manufacturing processes regarding requirements	☐	☐	☐	☐
Selection of appropriate post processing (milling, cutting etc.) and their process parameters	☐	☐	☐	☐
Selection of appropriate joining procedures	☐	☐	☐	☐
Effects of manufacturing on the resulting product quality	☐	☐	☐	☐
Influence of temperature and humidity during production storage	☐	☐	☐	☐
Simulation:				
Predicting crash and impact behavior of crash behavior of fiber-reinforced composite	☐	☐	☐	☐
Material models for structural simulation	☐	☐	☐	☐
Material models for process simulation	☐	☐	☐	☐
Design:				
Corrosion protection of metal inserts in FRP	☐	☐	☐	☐
Temperature and humidity effects on mechanical properties in the later application	☐	☐	☐	☐
Optimal utilization of anisotropic behavior of the fiber-reinforced composite	☐	☐	☐	☐
Load-compliant design of the fiber-reinforced polymers	☐	☐	☐	☐
Production-oriented design of components	☐	☐	☐	☐
Recycling-oriented design	☐	☐	☐	☐

Legend:

Not relevant – topic holds no relevance for my area of responsibility

Little relevant – topic holds only a small relevance to my area of responsibility

Moderately strong relevant – topic is relevant to my area of responsibility

Strongly relevant – topic is very relevant to my area of responsibility

[13] What other topics are particularly important in your area of responsibility?

Please write your answer here:

[14] What challenges do you see relating to the topic “scattering material properties of fiber-reinforced plastics”?

(Only answer this question if the following conditions are met: Answer was 'Strongly relevant' or 'Moderately strong relevant' at question '12 [12]' (Please specify the topics in working with fiber-reinforced plastics in which you would like to have a support in form of design guidelines. The topics are divided into four areas: material characterization, technology, simulation and design.))

Please choose **all** that apply:

- Missing approaches for predicting the scattering of material properties
- Missing approaches for prediction / consideration of the scattering in the behavior of components
- Incomplete exploitation of lightweight potential
- Other:

[15] What contents should be available in the design guideline on the topic of "scattering material properties"?

(Only answer this question if the following conditions are met: Answer was 'Strongly relevant' at question '12 [12]' (Please specify the topics in working with fiber-reinforced plastics in which you would like to have a support in form of design guidelines. The topics are divided into four areas: material characterization, technology, simulation and design.))

Please choose **all** that apply:

- Methods for prediction of the expected scatterings in the material properties
- Methods for prediction of component behavior based on scatterings in material properties
- Other:

[16] What challenges do you see relating to the topic “creating models for process simulation”?

(Only answer this question if the following conditions are met: Answer was 'Strongly relevant' at question '12 [12]' (Please specify the topics in working with fiber-reinforced plastics in which you would like to have a support in form of design guidelines. The topics are divided into four areas: material characterization, technology, simulation and design.))

Please choose **all** that apply:

- Missing or inaccurate material characteristics (matrix, fiber)
- Missing homogenization methods
- Missing or inaccurate models for the simulation of the draping process
- Missing or inaccurate models for the simulation of the extrusion process
- Missing or inaccurate models for simulation of curing and warping
- Other:

[17] What contents should be available in the design guideline on the topic of "creating models for process simulation"?

(Only answer this question if the following conditions are met: Answer was 'Strongly relevant' at question '12 [12]' (Please specify the topics in working with fiber-reinforced plastics in which you would like to have a support in form of design guidelines. The topics are divided into four areas: material characterization, technology, simulation and design.))

Please choose **all** that apply:

- Provision of material characteristics
- Approaches for defining the draping strategy
- Approaches for defining the insertion position during the mold filling process
- Approaches for defining the process boundary conditions during the mold filling process
- Approaches for determining the demolding strategy after production or other measures to avoid / minimize warpage
- Other:

[18] What challenges do you see relating to the topic “missing / inaccurate material characteristics”?

(Only answer this question if the following conditions are met: Answer was 'Strongly relevant' at question '12 [12]' (Please specify the topics in working with fiber-reinforced plastics in which you would like to have a support in form of design guidelines. The topics are divided into four areas: material characterization, technology, simulation and design.))

Please choose **all** that apply:

- Lack of knowledge about suitable innovative test methods for material characterization
- Choice of safety factors are unclear
- Other:

[19] What contents should be available in the design guideline concerning the topic of "missing / inaccurate material characteristics"?

(Only answer this question if the following conditions are met: Answer was 'Strongly relevant' at question '12 [12]' (Please specify the topics in working with fiber-reinforced plastics in which you would like to have a support in form of design guidelines. The topics are divided into four areas: material characterization, technology, simulation and design.))

Please choose **all** that apply:

- Recommendation of suitable test methods for material characterization
- Recommendations on safety factor choices
- Other:

[20] What challenges do you see relating to the topic “temperature and humidity effects on mechanical properties in the later application”?

(Only answer this question if the following conditions are met: Answer was 'Strongly relevant' at question '12 [12]' (Please specify the topics in working with fiber-reinforced plastics in which you would like to have a support in form of design guidelines. The topics are divided into four areas: material characterization, technology, simulation and design.))

Please choose **all** that apply:

- Creep and relaxation processes
- Influences on corrosive behavior
- Thermal distortion and thermal residual stresses
- Effect on mechanical properties and strength values
- Frost cracks caused by water deposits in pores / voids
- Mass increase due to moisture absorption
- Other:

[21] What contents should be available in the design guideline on the topic of "temperature and humidity effects in the later application"?

(Only answer this question if the following conditions are met: Answer was 'Strongly relevant' at question '12 [12]' (Please specify the topics in working with fiber-reinforced plastics in which you would like to have a support in form of design guidelines. The topics are divided into four areas: material characterization, technology, simulation and design.))

Please choose **all** that apply:

- Information about creep and relaxation processes, maximum application temperatures and maximum loads
- Information about influences of temperature on corrosion
- Calculation of thermal distortion / thermal stress
- Approaches for a desired heat conduction
- Calculation of the mass increase by moisture absorption
- Information about influences of temperature on conductivity
- Other:

[22] What challenges do you see relating to the topic "corrosion protection of metal inserts in fiber-reinforced plastic components"?

(Only answer this question if the following conditions are met: Answer was 'Strongly relevant' at question '12 [12]' (Please specify the topics in working with fiber-reinforced plastics in which you would like to have a support in form of design guidelines. The topics are divided into four areas: material characterization, technology, simulation and design.))

Please choose **all** that apply:

- Corrosion protection measures in joining zones (both with joining elements as well as with joining partners) are not always obvious
- Consequences of a possible corrosion are difficult to estimate
- Uncertainties in the selection of suitable material combinations
- Other:

[23] What contents should be available in the design guideline on the topic "corrosion protection of metal inserts in fiber-reinforced plastic components"?

(Only answer this question if the following conditions are met: Answer was 'Strongly relevant' at question '12 [12]' (Please specify the topics in working with fiber-reinforced plastics in which you would like to have a support in form of design guidelines. The topics are divided into four areas: material characterization, technology, simulation and design.))

Please choose **all** that apply:

- Approaches for good corrosion protection
- Support in the selection of suitable material combinations
- Treatment of corrosion-inhibiting / corrosion-promoting factors
- Information on the effects of corrosion
- Other:

[24] What challenges do you see relating to the topic "effects of the manufacturing process on the resulting component quality"?

(Only answer this question if the following conditions are met: Answer was 'Moderately strong relevant' or 'Strongly relevant' at question '12 [12]' (Please specify the topics in working with fiber-reinforced plastics in which you would like to have a support in form of design guidelines. The topics are divided into four areas: material characterization, technology, simulation and design.))

Please choose **all** that apply:

- Uneven fiber volume distribution
- Uneven fiber orientation distribution
- Occur of defects in the component (pores, voids, fiber ripples,..)
- Insufficient form filling
- High cost of quality assurance, many virtual tests are necessary because of insufficient virtual validation
- Reproducibility of the component quality is not always guaranteed
- Other:

[25] What contents should be available in the design guideline concerning the topic of "effects of the manufacturing process on the resulting component quality"?

(Only answer this question if the following conditions are met: Answer was 'Strongly relevant' at question '12 [12]' (Please specify the topics in working with fiber-reinforced plastics in which you would like to have a support in form of design guidelines. The topics are divided into four areas: material characterization, technology, simulation and design.))

Please choose **all** that apply:

- Recommendations on appropriate process conditions for a given material system to avoid production effects
- Information about typical manufacturing effects and their causes
- Information about influences of process boundary conditions on the occurs of production effects
- Information about influences of manufacturing effects on the component properties
- Information about suitable test methods for quality assurance
- Other:

[26] What challenges do you see relating to the topic “load-compliant design of fiber reinforced components”?

(Only answer this question if the following conditions are met: Answer was 'Strongly relevant' or 'Moderately strong relevant' at question '12 [12]' (Please specify the topics in working with fiber-reinforced plastics in which you would like to have a support in form of design guidelines. The topics are divided into four areas: material characterization, technology, simulation and design.))

Please choose **all** that apply:

- Lack of overview of the advantages and disadvantages of different structural reinforcements
- Unclear approach to structural stiffening - position, geometry, number of ribs / beads depending on different loads
- Influence of visible areas on the possible stiffening measures
- Uncertainties in the design of force transmission areas
- Local material properties are not known
- Absence of efficient and reliable failure criteria
- Other:

[27] What contents should be available in the design guideline on the topic of "load-compliant design of fiber-reinforced components"?

(Only answer this question if the following conditions are met: Answer was 'Strongly relevant' at question '12 [12]' (Please specify the topics in working with fiber-reinforced plastics in which you would like to have a support in form of design guidelines. The topics are divided into four areas: material characterization, technology, simulation and design.))

Please choose **all** that apply:

- Advantages and disadvantages of different structural reinforcements
- Covering many load cases and the possibility of defining load cases themselves in order to obtain a solution
- Approaches for stiffening of components in visible areas (choice of stiffening, avoiding insertion of ribs)
- Proposed design solutions for rib or bead (depending on applied loads and production methods)
- Information about failure models with application recommendations and their advantages/ disadvantages
- Recommendations for the detection of potential sources of damage
- Recommendations for damage progress calculation
- Other:

[28] What challenges do you see relating to the topic “structure simulation of fiber-reinforced components?

(Only answer this question if the following conditions are met: Answer was 'Strongly relevant' at question '12 [12]' (Please specify the topics in working with fiber-reinforced plastics in which you would like to have a support in form of design guidelines. The topics are divided into four areas: material characterization, technology, simulation and design.))

Please choose **all** that apply:

- Missing of material models
- Choosing the right material model is difficult
- Missing / Inaccurate material characteristics
- Results of the process simulation do not correspond to reality
- Other:

[29] What contents should be available in the design guideline on the topic of "structure simulation of fiber-reinforced components"?

(Only answer this question if the following conditions are met: Answer was 'Strongly relevant' at question '12 [12]' (Please specify the topics in working with fiber-reinforced plastics in which you would like to have a support in form of design guidelines. The topics are divided into four areas: material characterization, technology, simulation and design.))

Please choose **all** that apply:

- Provision of material characteristics for fiber materials, matrix materials and typical composite materials
- Listing of material models that describe the deformation and failure behavior
- Recommendations for selecting the appropriate material model
- Approaches to the consideration of process-dependent fiber orientations directly in the simulation
- Other:

[30] What challenges do you see relating to the topic “production-oriented design of fiber-reinforced components?

(Only answer this question if the following conditions are met: Answer was 'Strongly relevant' or 'Moderately strong relevant' at question '12 [12]' (Please specify the topics in working with fiber-reinforced plastics in which you would like to have a support in form of design guidelines. The topics are divided into four areas: material characterization, technology, simulation and design.))

Please choose **all** that apply:

- Geometric constraints are not always known /clear (rib design: minimum radii, rib thickness etc.)
- Results of the process simulation do not correspond with reality
- The feasibility of certain types of construction is not clear
- Other:

[31] What contents should be available in the design guideline on the topic of "production-oriented design of fiber-reinforced components"?

(Only answer this question if the following conditions are met: Answer was 'Strongly relevant' at question '12 [12]' (Please specify the topics in working with fiber-reinforced plastics in which you would like to have a support in form of design guidelines. The topics are divided into four areas: material characterization, technology, simulation and design.))

Please choose **all** that apply:

- Proposed design solutions for rib or bead depending on production restrictions
- Recommendation for the appropriate design (integral, differential, sandwich or hybrid) by taking into account production restrictions
- Other:

[32] What challenges do you see relating to the topic “predicting the crash and impact behavior of fiber-reinforced components”?

(Only answer this question if the following conditions are met: Answer was 'Strongly relevant' at question '12 [12]' (Please specify the topics in working with fiber-reinforced plastics in which you would like to have a support in form of design guidelines. The topics are divided into four areas: material characterization, technology, simulation and design.))

Please choose **all** that apply:

- Lack of material models
- Lack of damage models
- Prediction of the deformation behavior is difficult
- Other:

[33] What challenges do you see relating to the topic “selection of joining procedures”?

(Only answer this question if the following conditions are met: Answer was 'Strongly relevant' at question '12 [12]' (Please specify the topics in working with fiber-reinforced plastics in which you would like to have a support in form of design guidelines. The topics are divided into four areas: material characterization, technology, simulation and design.))

Please choose **all** that apply:

- Selection of the most suitable joining method is not always clear
- Difficulty dimensioning the joining zones
- Pretreatments must be considered

- Choice of suitable joining partners / connecting elements (galvanic corrosion, different thermal expansion) is not always clear
- Preload stress losses due to different thermal expansion coefficients are causing problems
- Other:

[34] What contents should be available in the design guideline on the topic of "selection of joining procedures"?

(Only answer this question if the following conditions are met: Answer was 'Strongly relevant' at question '12 [12]' (Please specify the topics in working with fiber-reinforced plastics in which you would like to have a support in form of design guidelines. The topics are divided into four areas: material characterization, technology, simulation and design.))

Please choose **all** that apply:

- Advantages and disadvantages of different joining processes
- Support in the selection of suitable joining partners / connecting elements
- Description of any necessary pretreatments
- Design note for joining zones
- Other:

[35] What challenges do you see relating to the topic "post processing of fiber-reinforced components"?

(Only answer this question if the following conditions are met: Answer was 'Strongly relevant' or 'Moderately strong relevant' at question '12 [12]' (Please specify the topics in working with fiber-reinforced plastics in which you would like to have a support in form of design guidelines. The topics are divided into four areas: material characterization, technology, simulation and design.))

Please choose **all** that apply:

- Possible delamination
- Uncertainties in choosing suitable processes for given material (sawing, milling, waterjet cutting etc.)
- Uncertainties in choosing suitable process variables (cutting speeds, drilling speeds)
- Uncertainties regarding the coating (pretreatments, required surface quality)
- Thermal influence on the component leads to local quality degradation
- Other:

[36] What contents should be available in the design guideline on the topic of "post processing of fiber-reinforced components"?

(Only answer this question if the following conditions are met: Answer was 'Strongly relevant' at question '12 [12]' (Please specify the topics in working with fiber-reinforced plastics in which you would like to have a support in form of design guidelines. The topics are divided into four areas: material characterization, technology, simulation and design.))

Please choose **all** that apply:

- Information about advantages and disadvantages of different post processing processes
- Recommendation of suitable post processing strategies including process parameters
- Recommendation for design of process zones
- Approaches against delamination for different procedures
- Information on surface pretreatment during coating (cleaning, influence of release agents)
- Information on heat removal during machining
- Other:

[37] What challenges do you see relating to the topic “recycling in connection with fiber-reinforced components”?

(Only answer this question if the following conditions are met: Answer was 'Strongly relevant' at question '12 [12]' (Please specify the topics in working with fiber-reinforced plastics in which you would like to have a support in form of design guidelines. The topics are divided into four areas: material characterization, technology, simulation and design.))

Please choose **all** that apply:

- Approach to recycling design unknown
- Recycling is only possible to a limited extent with the combination of different materials
- Pure separation of the matrix material is complex
- Deterioration of properties by recycling
- Recovery and reuse of the fibers
- Other:

[38] What challenges do you see relating to the topic “optimal utilization of anisotropic behavior of the fiber-reinforced composite”?

(Only answer this question if the following conditions are met: Answer was 'Planning' or 'Conception' at question '2 [2]' (Which department do you work in?) and Answer was 'Strongly relevant' at question '12 [12]' (Please specify the topics in working with fiber-reinforced plastics in which you would like to have a support in form of design guidelines. The topics are divided into four areas: material characterization, technology, simulation and design.))

Please choose **all** that apply:

- Material selection regarding the requirements on the product
- Lack of knowledge about the local material properties
- Statements on manufacturability using certain materials
- Feasibility analysis due to lacking / little experience in the area of fiber-reinforced plastics
- Other:

[39] What contents should be available in the design guideline on the topic of "optimal utilization of anisotropic behavior of the fiber-reinforced composite"?

(Only answer this question if the following conditions are met: Answer was 'Planning' at question '2 [2]' (Which department do you work in?) and Answer was 'Strongly relevant' at question '12 [12]' (Please specify the topics in working with fiber-reinforced plastics in which you would like to have a support in form of design guidelines. The topics are divided into four areas: material characterization, technology, simulation and design.))

Please choose **all** that apply:

- Information on the feasibility analysis. Is the use of fiber-reinforced plastics worthwhile?
- Knowledge about the possibilities and limits of the material
- Knowledge about local material properties
- Information on suitable test programs for validation
- Information on suitable manufacturing processes
- Other:

[40] What challenges do you see relating to the topic “optimal utilization of anisotropic behavior of the fiber-reinforced composite”?

(Only answer this question if the following conditions are met: Answer was 'Validation and Verification' at question '2 [2]' (Which department do you work in?) and Answer was 'Strongly relevant' at question '12 [12]' (Please specify the topics in working with fiber-reinforced plastics in which you would like to have a support in form of design guidelines. The topics are divided into four areas: material characterization, technology, simulation and design.))

Please choose **all** that apply:

- Missing / inaccurate material characteristics
- Scattering material properties
- Missing knowledge for calculation / simulation
- Missing or inadequate static material models (elastic-plastic) in the simulation
- Missing or inadequate static material models (damage / fracture) in the simulation
- Missing or inadequate dynamic material models (elastic-plastic) in the simulation
- Missing or inadequate dynamic material models (damage / fracture) in the simulation
- Other:

[41] What contents should be available in the design guideline on the topic of "optimal utilization of anisotropic behavior of the fiber-reinforced composite"?

(Only answer this question if the following conditions are met: Answer was 'Validation and Verification' at question '2 [2]' (Which department do you work in?) and Answer was 'Strongly relevant' at question '12 [12]' (Please specify the topics in working with fiber-reinforced plastics in which you would like to have a support in form of design guidelines. The topics are divided into four areas: material characterization, technology, simulation and design.))

Please choose **all** that apply:

- Provision of material models and material parameters for the calculation / simulation
- Information on suitable methods for carrying out a calculation / simulation
- Influences of the material properties on the crash and impact behavior of the component
- Effects of manufacturing parameters on the component properties
- Other:

[42] What challenges do you see relating to the topic “optimal utilization of anisotropic behavior of the fiber-reinforced composite”?

(Only answer this question if the following conditions are met: Answer was 'Design ' at question '2 [2]' (Which department do you work in?) and Answer was 'Strongly relevant' at question '12 [12]' (Please specify the topics in working with fiber-reinforced plastics in which you would like to have a support in form of design guidelines. The topics are divided into four areas: material characterization, technology, simulation and design.))

Please choose **all** that apply:

- Insufficient knowledge about the production-induced fiber orientations and their influence on the component
- Powerful computer-assisted methods for structural optimization with consideration of manufacturing-relevant restrictions
- Missing knowledge for the simulation of component behavior
- Other:

[43] What contents should be available in the design guideline on the topic of "optimal utilization of anisotropic behavior of the fiber-reinforced composite"?

(Only answer this question if the following conditions are met: Answer was 'Design ' at question '2 [2]' (Which department do you work in?) and Answer was 'Strongly

relevant' at question '12 [12]' (Please specify the topics in working with fiber-reinforced plastics in which you would like to have a support in form of design guidelines. The topics are divided into four areas: material characterization, technology, simulation and design.))

Please choose **all** that apply:

- Knowledge about the possibilities and limits of a material
- Information about the influence of production parameters on the component properties
- Approaches to the consideration of process-dependent fiber orientations directly in the simulation
- Overview of methods to perform calculations (eg warpage, shrinkage)
- Other:

[44] What challenges do you see relating to the topic "optimal utilization of anisotropic behavior of the fiber-reinforced composite"?

(Only answer this question if the following conditions are met: Answer was 'Production' at question '2 [2]' (Which department do you work in?) and Answer was 'Strongly relevant' at question '12 [12]' (Please specify the topics in working with fiber-reinforced plastics in which you would like to have a support in form of design guidelines. The topics are divided into four areas: material characterization, technology, simulation and design.))

Please choose **all** that apply:

- Uneven shrinkage / warping of the component
- Uncertainties about process parameters for optimum component properties
- Uncertainties about process parameters by the post-processing
- Other:

[45] What contents should be available in the design guideline on the topic of "optimal utilization of anisotropic behavior of the fiber-reinforced composite"?

(Only answer this question if the following conditions are met: Answer was 'Production' at question '2 [2]' (Which department do you work in?) and Answer was 'Strongly relevant' at question '12 [12]' (Please specify the topics in working with fiber-reinforced plastics in which you would like to have a support in form of design guidelines. The topics are divided into four areas: material characterization, technology, simulation and design.))

Please choose **all** that apply:

- Information about suitable production processes and process parameters as well as their influence on the component properties
- Information on suitable processes as well as process parameters by the post-processing
- Other:

[46] What challenges do you see relating to the topic "optimal utilization of anisotropic behavior of the fiber-reinforced composite"?

(Only answer this question if the following conditions are met: Answer was 'Research and Development' at question '2 [2]' (Which department do you work in?) and Answer was 'Strongly relevant' at question '12 [12]' (Please specify the topics in working with fiber-reinforced plastics in which you would like to have a support in form of design guidelines. The topics are divided into four areas: material characterization, technology, simulation and design.))

Please choose **all** that apply:

- Missing / inaccurate material characteristics
- Scattering material properties
- Absence of material models

- Powerful computer-assisted methods for structural optimization with consideration of manufacturing-relevant restrictions
- Insufficient knowledge about the production-induced fiber orientations and their influence on the component
- Other:

[47] What contents should be available in the design guideline on the topic of "optimal utilization of anisotropic behavior of the fiber-reinforced composite"?

(Only answer this question if the following conditions are met: Answer was 'Research and Development' at question '2 [2]' (Which department do you work in?) and Answer was 'Strongly relevant' at question '12 [12]' (Please specify the topics in working with fiber-reinforced plastics in which you would like to have a support in form of design guidelines. The topics are divided into four areas: material characterization, technology, simulation and design.))

Please choose **all** that apply:

- Provision of material characteristics
- Provision of material models
- Methods for prediction of component behavior based on scatterings in material behavior
- Information about the influence of production parameters on the component properties
- Approaches to the consideration of process-dependent fiber orientations directly in the simulation
- Other:

[48] Would you advocate a chapter to support the cost estimation of fiber-reinforced components in a design guideline?

Please choose **only one** of the following:

- Yes
- No
- Unsure

[49] What points of the cost estimate should be considered in a design guideline?

(Only answer this question if the following conditions are met: Answer was 'Yes' at question '48 [38]' (Would you advocate a chapter to support the cost estimation of fiber-reinforced components in a design guideline?))

Please choose **all** that apply:

- Production cost (incurring tool costs, process costs, ...)
- Quality costs (component inspection, waste,…)
- Other:

[50] How many employees are employed in your company?

Please choose **only one** of the following:

- Micro enterprises (fewer than 10 persons employed)
- Small enterprises (10 – 49 persons employed)
- Medium-sized enterprises (50 to 249 persons employed)
- Large enterprises (more than 250 persons employed)
- Other:

[51] To which activities of product development can you assign your daily tasks?

Please choose **all** that apply:

- Project planning
- Profile detection
- Idea detection
- Modeling of principle solution and Embodiment
- Validation / Verification
- Prototype sampling
- Production
- Market Launch
- Analysis of utilization
- Analysis of decommission
- Other:

Others

[52] Do you have any additional suggestions, opinions or critique concerning the design guidelines for fiber-reinforced plastics?

Please write your answer here:

Thank you very much for your participation!

Submit your survey.
Thank you for completing this survey.

C. Subjects for content of design guidelines and technical information to support product development with FRPs

Required contents in design guidelines for FRP

Load-compliant design: Approaches to the reinforcement of parts in visible/invisible areas Recommendations on force transmission and design of a force application zone Recommendation for design of post-process zones Recommendations for selecting sufficient safety factor Recommendations for the damping of vibrations Recommendations for the fiber orientation of layers for dimensional stability Recommendations for suitable constructive reinforcements depending on boundary conditions.
Production-compliant design: Recommendations for a suitable design type, taking into account manufacturing restrictions Recommendations against the influence of process boundary conditions on the occurrence of manufacturing effects and their impact on component properties Notes on geometric restrictions depending on manufacturing processes.
Design of joining parts: Recommendations for selecting suitable join partners/fasteners Recommendations for necessary pre-treatments Recommendations for appropriate measures against creep behavior during preload Recommendations against environmental impacts Recommendations for repair options of a joint.
Corrosion-resistant design: Recommendations for selecting a suitable combination of materials Recommendations on long-term protection against unfavorable material pairing Recommendations against effects of temperature and humidity on corrosion Recommendations for the treatment of corrosion-inhibiting/corrosive factors.
Post-processing: Recommendations to avoid delamination for different post-processing Recommendation for suitable post-processing strategies including process parameters
Recyclable product design: Design recommendations on recyclable design.

Other technical information needed for optimal support

Load-compliant design: Information about the advantages and disadvantages of different constructive reinforcements.
Production-compliant design: Information about the advantages and disadvantages of different manufacturing processes Information about suitable process parameters for a given material system and component design Information for manufacturing process control Information on the influence of process boundary conditions on the occurrence of manufacturing effects and their causes Information about suitable test methods for quality assurance.
Design of joining parts: Information about advantages and disadvantages of different joining technologies.
Structure simulation and optimization: Recommendations for choosing the appropriate material model Information about methods to consider process-depending fiber orientation directly during the simulation Information on methods for predicting component behavior based on scatter in material behaviour Recommendations for a damage progression calculation Criteria to evaluate the accuracy of the simulation model.
Process simulation and optimization: Recommendations for determining the demolding strategy after production Recommendations for determining the insertion position under consideration of process boundary conditions Recommendations for determining the drape strategy depending on the geometry of component Information about the calculation of thermal distortion/thermal residual stress.
Post-processing methods: Information on the advantages and disadvantages of different post-processing methods Information on heat dissipation for machining post-processing Information on surface pretreatment for coating.
Material properties and material characterization: Information about the possibilities and limitations of a material Information on material properties Recommendation for determination / estimation of necessary parameters Recommendations for the assessment of failure mechanisms

Information about methods for determining the scatter in the material properties Information about the influence of manufacturing processes on material properties Recommendation of suitable test methods for material characterization.
Material behavior: Information on creep and relaxation processes, maximum temperatures and maximum loads Information on the influence of temperature on electrical conductivity Information on the degradation of mechanical properties over time and under external influences.