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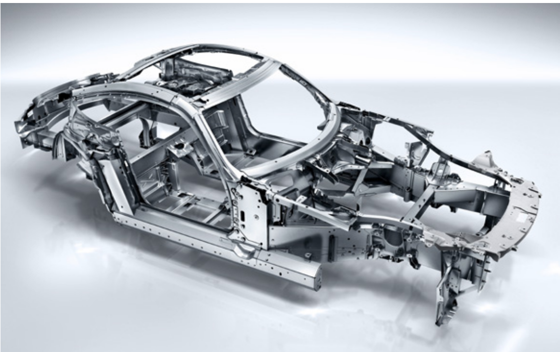
VDI ZRE Publications: Brief analysis No. 17

Resource efficiency in lightweight engineering

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Brief analysis No. 17: Resource efficiency in lightweight engineering

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The brief analyses of VDI ZRE provide an overview of current developments related to resource efficiency in research and industrial practice. They each contain a compilation of relevant research results, new technologies and processes as well as examples of good practice. The brief analyses thus provide a broad audience from business, research and administration with an introduction to selected areas of resource efficiency.

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LIST OF ABBREVIATIONS

3D CP	3D composite print
AFS	Aluminium foam sandwich
AHSS	Advanced high strength steel
AiF	Arbeitsgemeinschaft industrieller Forschungsvereinigungen „Otto von Guericke“ (German Federation of Industrial Research Associations "Otto von Guericke”)
AWI	Alfred Wegener Institute
BMBF	Federal Ministry of Education and Research
BMUB	Federal Ministry for the Environment, Nature Conservation, Construction and Nuclear Safety
BMWi	Federal Ministry for Economic Affairs and Energy
CAD	Computer-aided design
CAE	Computer-aided engineering
CAIRE	Composite adaptable inspection and repair
CAO	Computer-aided optimisation
CFRP	Carbon fibre reinforced plastic
CFS	Carbon fibre sensors
CMC	Ceramic matrix composite
CNT	Carbon nano tubes
CO_2	Carbon dioxide
C/SiC	Carbon fibre reinforced silicon carbide
DMLS	Direct metal laser sintering
DLR	German Aerospace Centre
ELiSE	Evolutionary light structure engineering

EMPA	Swiss Federal Laboratories for Materials Science and Technology
EPP	Expanded polypropylene particle foam
Fe-CrMnNi	Iron chromium manganese nickel
FEM	Finite element method
FIM	Fibre injection moulding
FLM	Fused layer modelling
FML	Fibre metal laminates
FOREL	Forschungs- und Technologiezentrum für ressourceneffiziente Leichtbaustrukturen der Elektromobilität (Research and Technology Centre for Resource-Efficient Lightweight Structures in Electromobility)
FRP	Fibre reinforced plastic
GFRP	Glass fibre reinforced plastic
HSD	High strength and ductility
CED	Cumulative energy demand
SMEs	Small and medium-sized enterprises
CRMD	Cumulative raw material demand
LCA	Life-cycle assessment
LEAP	Leading edge aviation propulsion
LED	Light emitting diode
LSI	Liquid silicon infiltration
NASA	National Aeronautics and Space Administration
PAG	Premium Aerotec
PAN	Polyacrylonitrile
PEEK	Polyether ether ketone
PPS	Polyphenylene sulphide

PSU	Polysulfone
PTFE	Polytetrafluoroethylene
RCCF	Research Centre Carbon Fibres Saxony
rCF	Recycled carbon fibres
rCFRP	Recycled carbon fibre reinforced plastic
ReLei	Production and recycling strategies for electromobility for the recycling of lightweight structures in fibre-reinforced plastic hybrid construction
RTM	Resin transfer moulding
SAS	Steel aluminium foam sandwich
SKO	Soft kill option
SLM	Selective laser melting
SUV	Sports utility vehicle
UD	unidirectional
VDMA	Verband Deutscher Maschinen- und Anlagenbau (Mechanical Engineering Industry Association)
ZLP	Zentrum für Leichtbauproduktionstechnologie (Centre for Lightweight Production Technology)
ZrO_2	Zirconium (IV) oxide

PART 1: BRIEF ANALYSIS

1 INTRODUCTION

Lightweight construction is a prime example of demonstrating the potential of resource efficiency. Resource efficiency potentials in the utilisation phase of mobile products have already been investigated frequently and are widely known. In addition, the various lightweight engineering strategies and materials also offer opportunities for increasing resource efficiency in the production phase and in recycling and disposal. Companies that produce efficiently and thereby save on material costs gain a clear competitive advantage and are less dependent on price fluctuations on the raw materials market. This is especially true when new technologies, innovative design adjustments, new lightweight strategies and improved manufacturing processes are used. Lightweight construction can be achieved by material saving, material substitution, functional extension or constructive measures.

Potential for greater resource efficiency in the manufacturing process for lightweight construction applications can be found in all material classes. The use of traditional and new materials will change in the future. A survey of 240 experts from science and industry on the topic of lightweight construction for electromobility suggests significant changes in the future use of materials (Figure 1). It is expected that the use of specific high-strength steels and reinforced plastics will increase, whereas classic steels will used increasingly less frequently.[1]

1 Cf. Gude, M. (2015), p. 24.

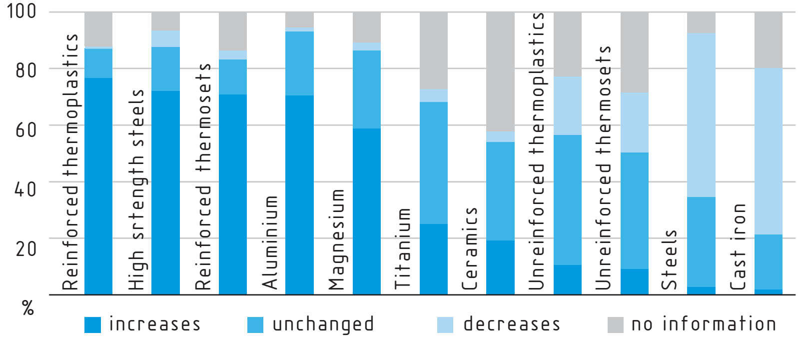

Figure 1: Assessment of the use of materials for structurally relevant lightweight components in the next five years with regard to electromobility[2]

Particularly noteworthy are the new hybrid and composite materials made of combinations of metals, plastics (including fibre-reinforced plastics), ceramics and renewable raw materials. Depending on the manufacturing process and the degree of integration of functions in the components, they not only offer optimised lightweight applications, but also opportunities to implement resource efficiency even more effectively.[3]

In view of these potentials, the large number of technical possibilities and the economic and normative background, it is no longer a question of whether it makes sense to use lightweight construction methods and thereby increase the resource efficiency of products. Lightweight construction has already become successfully established in the industrial production of products. This is illustrated by the numerous product innovations and the optimisation of materials and components. It is still unclear or open in many cases which resource efficiency potential are still hidden in the new or modified production and recycling processes for innovative materials and products in lightweight construction and how they can be leveraged as economically as possible.

2 Cf. Gude, M. (2015), p. 24.
3 Cf. Leichtbau BW (2014), p. 6.

To assess the resource efficiency of a lightweight construction product, the entire life cycle has to be considered.[4] For example, comparatively higher energy consumption can arise in the production of new lightweight construction materials.[5] Innovative composite materials composed of a variety of components create new recycling challenges. Often the development of technologies to break down these composite materials and recycle sorted materials is often still required here. In particular, automation plays an important role in terms of cost reduction.

In the automotive industry, lightweight construction is mostly used to meet the statutory reduction of greenhouse gases and new safety requirements and to increase the range of electric vehicles. German carmakers recognise various trends in the implementation of lightweight design concepts. Among other things, materials and composite materials made of aluminium, high-strength steel, magnesium or fibre-reinforced plastic are increasingly being used.[6]

The motivation to operate lightweight aircraft manufacturing is primarily the fuel savings achievable during operation, but also the increase in cargo capacity and the ability to build ever larger aircraft. Many aircraft manufacturers also see great potential in additive manufacturing. The time required for the development and printing of near-net-shaped components is shorter. In particular, for the small series typical in aviation and for spare parts required less frequently, components that do not require tools to be made or long production chains are attractive.[7]

This brief analysis provides a current overview of innovative technologies in lightweight construction and outlines existing resource efficiency potentials with a focus on the automotive and aviation industries. The focus is on changing processes in product manufacturing, the use of new materials and composites and the integration of functions into materials or components. In addition, potentials and obstacles for recycling and disposal are identified. Possible inefficiencies in recycling in individual cases cannot be covered in the

[4] Cf. Vogt, M; Malanowski, N.; Glitz, R. and Stahl-Rolf, S. (2015), p. 17.

[5] Cf. e-mobil BW GmbH (2012), p. 20.

[6] Cf. Vogt, M; Malanowski, N.; Glitz, R. and Stahl-Rolf, (2015), p. 12 et seqq.

[7] Cf. Oberndorfer, D. (2015).

context of this brief analysis. In the case of the mobile products in focus here, however, such effects are usually more than offset by efficiency gains in the utilisation phase.

The research and development landscape in lightweight construction is developing rapidly, with the result that this brief analysis can only represent a selection of current technologies and research projects.

2 ASSESSMENT OF RESOURCE EFFICIENCY

The subject of this brief analysis is technology that contributes to increasing the resource efficiency of lightweight engineering products. In the following, therefore, criteria are developed that allow a qualitative assessment of the use of resources in production and recycling/disposal.

The life cycle of a product (cradle-to-grave) consumes resources. There is therefore potential for saving resources in every phase.[8] But especially in product manufacturing (gate-to-gate) and in recycling and disposal, that potential is often neglected (Figure 2). In the manufacturing process, companies are concerned with technical feasibility, economic issues and legal framework conditions. The resource efficiency potentials that arise for the utilisation phase of mobile products have already been discussed extensively in the literature,[9,10,11] and will not be addressed further here.

8 Cf. VDI 4800 Part 1:2016-02.
9 Cf. Bansemir, H. et al. (2007).
10 Cf. Leichtbau BW GmbH (2014).
11 Cf. Kaiser, O. S. (2014).

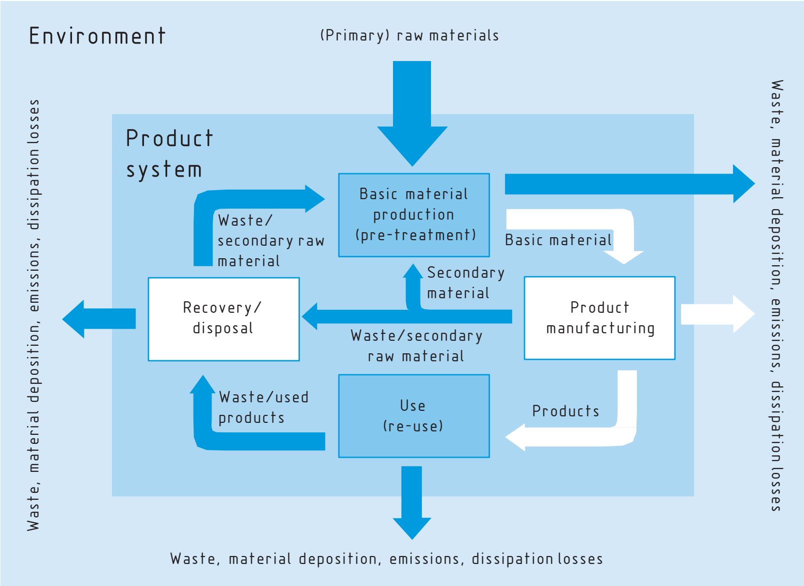

Figure 2: Resource use in the product life cycle using the example of material flows. Focus on product manufacturing, recovery and disposal.[12]

In accordance with the principles for life-cycle assessment according to DIN EN ISO 14040, the guidelines VDI 4800 Part 1[13], Part 2[14] and VDI 4600[15] substantiate the assessment principles for resource efficiency. VDI 4800 Part 1 describes methodological principles and strategies for conserving natural resources. VDI 4800 Part 2 explains the assessment of raw material and water consumption and land use. For an energetic assessment of products and services, the guideline VDI 4600 explains how a primary energy assessment can be performed using the cumulative energy demand (CED) calculation.

By analysing the life cycle of products, a variety of influencing factors can be identified which can be used to increase resource efficiency. However, these factors may also result in conflicting objectives. For example, saving material

[12] Cf. VDI 4800 Part 1: 2016-02, p. 19. Reproduced with permission of the Association of German Engineers

[13] VDI 4800 Part 1:2016-02.

[14] VDI 4800 Part 2:2016-03 (draft).

[15] VDI 4600:2012-01.

usage can result in a reduction in product life. In the following, examples are shown based on VDI 4800 Part 1, which is particularly relevant with regard to resource efficiency in lightweight material construction (chapter 3), in lightweight design (chapter 4) and for recycling and disposal processes (5). Guideline VDI 4800 Part 1 also provides detailed information on product and process resource efficiency potential and measures for implementation.[16]

2.1 Product-related factors influencing resource efficiency in lightweight construction

- **Material selection/material substitution:** Replacement of a material by one or more other materials, e.g. "Smart Materials"[17], composites, renewable raw materials or secondary materials. The effects of material selection on the component must be taken into account. For example, the mass of a component is reduced by the use of materials with lower density at the same volume. At the same time, however, the strength, rigidity or ductility of the component can also change due to the use of the other material.

- **Product design**: A reduction in the use of materials can be achieved by optimising the product shape during product development. An example of this is the integration of functions into a supporting structure. In the process, the resource consumption may be increased by a potentially more complicated manufacturing process.

- **Joining technology**: Greater resource efficiency is possible through the use of an optimised joining process for the product. In lightweight construction this can be e.g. gluing, interlock, forming or pressing. Conflicts of interest can occur due to joining processes during recycling, if a separation of the materials is not possible with justifiable effort.

[16] Cf. VDI 4800 Part 1:2016-02.

[17] According to the definition of Fraunhofer ISC (see Fraunhofer Institute for Silicate Research ISC), smart materials are materials with mechanical properties that can be controlled electrically or magnetically.

- **Product lifetime**: By changing the design of a component, service life and repair intervals can be extended. On the other hand, there may be a better use of resources in production.

- **Repairability**: A material-related change in a component can have an effect on repairability. For example, in the case of components made of carbon-fibre-reinforced plastic (CFRP), repairability is severely restricted compared to those made of steel or aluminium. It can therefore be assumed that relatively more CFRP components must be recycled than those made of steel or aluminium.

2.2 Process-related factors influencing resource efficiency in lightweight construction

- **Energy**: By reducing energy consumption in the manufacturing process, e.g. by using process heat to generate electricity or air conditioning in the building, and efficient energy provision that avoids unnecessary energy transformations, resource efficiency can be increased.

- **Process automation**: Automation of manual or mechanised processes can increase resource efficiency. For example, process data can be precisely recorded and processes optimised as a result. On the other hand, additional machines and sensors, for example, can cause consumption.

- **Production process**: The use of new materials or adapted manufacturing processes can lead to a change in the process chain. In the best case, innovative processes can eliminate manufacturing steps, which can save tools, energy and time. By contrast, additional manufacturing steps such as cleaning can cause increased consumption of auxiliaries. But the use of additional tools which are needed for shaping, for example, can have a negative impact on resource efficiency.

2.3 Recycling and disposal factors influencing resource efficiency in lightweight construction

- **Waste hierarchy:** The German Waste Management Act (§ 6 KrWG) calls for a five-stage waste hierarchy with the sequence of steps (1) waste prevention, (2) reuse, (3) recycling, (4) other recovery of waste, e.g. as energy and (5) waste disposal. Priority is given to the best option from the point of view of environmental protection. In addition to ecological effects, technical, economic and social consequences must be considered. The waste management is thus geared towards waste prevention and recycling, without jeopardising established ecologically sound disposal methods. [18]

- **Recycling-friendly product design:** Even at the product conception stage, the recyclability of the material selection, the component and the product design should be considered. For example, for composites, it should be ensured that the components are easy to separate for recycling.

- **Recyclate quality**: A recycling process must ensure that the recovered secondary materials have a quality comparable to that of primary raw materials. Under certain circumstances, this can only be done with a very high resource consumption.

- **Degree of purity**: Properly sorted materials, especially for components that are made of a variety of different materials and components (composite materials/multi-component materials) is often possible only with great effort. Here, attention should be paid to the requirements of recycling even in the conception phase.

The following sections will look at resource efficiency issues that arise before and after the product's utilisation phase. This involves the use of new materials, and improved and new processes in the manufacturing phase, in recycling and disposal. In addition to good practice examples, potentials arising from current research and development projects are shown. For a quick overview, blue-shaded boxes indicate measures that can increase resource efficiency in lightweight construction, and these are assigned to influencing factors.

[18] Cf. KrWG (2012).

3 RESOURCE EFFICIENCY POTENTIAL IN LIGHTWEIGHT MATERIAL CONSTRUCTION

This section deals with the substitution of higher density materials with lower density materials, ideally while maintaining or improving the mechanical properties. Decisive here are the resource efficiency potentials which can be achieved in the manufacturing phase.

3.1 Metals

In vehicle construction and aerospace engineering, the metals steel, aluminium, magnesium and titanium and their alloys are the elementary materials.

3.1.1 Steel

Steel is still the most important material in vehicle construction, especially in the bodywork sector, but also in many other vehicle components. This is especially true for the lower and mid-range vehicle segments with high volumes, because steel is significantly cheaper than aluminium or CFRP. High-strength steels, which enable components with smaller wall thicknesses and thus contribute to reducing the vehicle mass, are primarily considered for lightweight construction with steel. Even if the mass reduction potentials of high-strength steels are somewhat smaller in direct comparison with aluminium or fibre composites, this can often be compensated for by the lower resource costs in production and the recycling of steel in the overall balance.[19]

This is also a result of the significant increases in resource efficiency in steelmaking that have already been achieved in recent decades. Thus, between 1960 and 2010, the specific primary energy consumption per tonne of crude steel was reduced by 40%, while the iron efficiency indicator, i.e. the ratio of rolled steel produced to iron used, increased from 65% to 90% total output. In addition, the share of steel scrap used in crude steel production increased to a total of 45%, while the use of water was reduced to about 10.4m^3 per tonne of crude steel. Substantial contributions to these efficiency gains are achieved through technological improvements in the processes of steel mills and rolling mills. Further potential for increasing efficiency in this

[19] Cf. e-mobil BW GmbH (2012).

area is estimated to be up to 37% for the period 2010 to 2050. There are also effects that go beyond mere consideration of the respective process routes. Blast furnace slags from steelmaking are already being used as clinker substitutes in cement production, reducing CO_2 emissions that otherwise result from burning the clinker.[20]

Due to the already very high recycled content of almost 50% in crude steel production in Germany, large quantities of primary raw materials are saved. This amounts to about 1.5 t of iron ore and 0.65 t of coal per ton of steel scrap. However, the recycling potential in the EU is already almost exhausted. The collection systems and processing techniques are already optimised and offer little room for improvement. The increasing outflow of recycled material through the export of steel scrap may even lead to a deterioration of the availability of secondary material in the future.[21] The ability to repeatedly recycle steel also affects the specific greenhouse gas emissions of steelmaking. Starting with six lifecycles, the specific global warming potential drops to just under 1,000 kg CO_2 equivalent per tonne of hot rolled strip produced. This value is based on a material-pool-oriented and product-independent approach and includes both the electric furnace and the blast furnace route in the analysis. [22]

[20] Cf. VDMA (2013).
[21] Cf. Stahlinstitut VDEh, Wirtschaftsvereinigung Stahl (2015).
[22] Cf. Neugebauer, S. and Finkbeiner, M. (2012).

Resource efficiency measures for lightweight material construction with steel

Material selection

- Use of high-strength steels in production
- Low-density steels, good formability and reduced machining costs in production (research project)

Product design

- Material savings for solid steel components

Manufacturing process

- Near-net strip casting instead of continuous casting saves heat and rolling processes

Material selection

Depending on the component, 10 to 40% less weight than conventional steel construction can be saved by **using innovative high-strength steel grades**. Assuming that a reduction in vehicle mass by 100 kg leads to a fuel saving of 0.35 litres per 100 km[23], it can also be used to estimate the CO_2 reduction potential for the utilisation phase. For an estimated total mileage of the German car fleet of 600 billion kilometres in 2020, this results in a potential reduction of CO_2 emissions of 11 million tonnes solely through the consistent use of high-strength and higher-strength steels in passenger car production.[24]Dual-phase and multi-phase steels are used in bodywork as innovative high-strength steels (Advanced High Strength Steel, AHSS). Driven by the increasing competition of other lightweight materials, steel manufacturers are continuously working to improve the properties of these types of steel in close cooperation with industrial users. The biggest challenge is the combination of high strength, ductility and formability. ThyssenKrupp solves this, for example, by adding special alloying elements and using targeted heat

[23] Cf. The Boston Consulting Group (2010), p. 23.
[24] Cf. The Boston Consulting Group (2010), p. 23.

treatment.[25] Salzgitter Flachstahl GmbH, with its HSD high manganese steel product family, has brought a lightweight structural steel with high strength and high elongation at break to market maturity.[26] When manufacturing with high-strength steels, it must be remembered that they **require increased machining** effort and that tool life can be reduced.

In addition to the strategy of developing increasingly stronger steels, efforts are continuing in materials research to develop particularly lightweight steel alloys that do not lose strength and **are easy to** form. As a rule, the addition of aluminium as an alloying element leads to the material becoming brittle and no longer easy to form. In order to combine all the desired properties in one material, a constant search is being carried out for new alloy compositions and production processes. For example, scientists at the Institute of Ferrous Technology in Pohang, South Korea, have developed a new **low-density steel alloy** that contains 5% nickel in addition to iron, manganese, aluminium and carbon. The steel bar produced under argon atmosphere is first rolled to a sheet of 1 mm thickness. It is then heated again to about 900 °C and quenched after 15 minutes with water. By this subsequent heating brittle inclusions with so-called B2 structure are evenly distributed in the austenite matrix, thereby increasing **strength and ductility significantly**. Although there is still a long way to go from these laboratory experiments to the industrial application of such innovative, particularly lightweight alloys, the novel microstructure which has been achieved and observed in this way provides a further impulse for the development of new resource-efficient steel alloys for lightweight construction.[27]

Product design

The lightweight construction potential of innovative steel developments for vehicle construction has already been comprehensively explored in various studies by different industrial and research consortia. These include the EU-

[25] Cf. ThyssenKrupp.
[26] Cf. Salzgitter Flachstahl GmbH (2012).
[27] Cf. Kim, S.-H. et al. (2015), pp. 77–79.

funded project SuperLIGHT-Car[28], InCar from ThyssenKrupp and FutureSteelVehicle by the global steel industry association WorldAutoSteel[29]. All of this work, however, focuses mainly on the body or on sheet-based lightweight solutions. Therefore, the Massiver Leichtbau initiative launched in 2013 has set itself the goal of demonstrating the **lightweight construction potential of steel material and solid forming** technology for a mid-range estate car as a reference vehicle. A total of 3,500 components with a total mass of 838 kg, mainly from the powertrain and chassis areas, have been analysed. This corresponds to almost half of the total mass of the reference vehicle. From this, 399 lightweight designs based on solid forming processes were generated and evaluated. These included, for example, approaches to **using the shaping possibilities of forging technology** in order to use them in components such as differential bevel gears or spur gears to make them more efficient, so that they can be smaller and lighter with the same load capacity. Other ideas are based on the introduction of recesses or holes to reduce the component mass. Overall, a potential mass reduction of 42 kg was determined for the components considered. In addition to the lightweight construction potential that can already be exploited, the study also identified further research needs. For example, it has been found that the relationship between the purity of the steel and the resulting dynamic component strength must be better understood in order to develop new steelmaking techniques for steel construction.[30]

Manufacturing process

In order to save further resources in the production of high-strength lightweight steels, Salzgitter Flachstahl GmbH, SMS Siemag AG and Clausthal University of Technology have developed **horizontal strip casting as an efficient production method** for steel products. In contrast to conventional continuous casting, a strip only 15 mm thick is cast directly from the melt. The material is thus already about twenty times thinner than the billets from continuous casting. During further processing into sheet metal components, energy-intensive heating and rolling processes are saved by the near-net strip casting. Overall, the **energy demand for the process steps of casting**

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[28] Cf. WorldAutoSteel (a).

[29] Cf. WorldAutoSteel (b).

[30] Cf. Raedt, H.-W.; Wilke, F. and Ernst, C.-S. (2014), pp. 58–64.

and hot rolling can be reduced to about one third. Rapid cooling on a conveyor belt revolving at casting speed also has a positive effect on the casting quality. The method is therefore particularly suitable for the production of lightweight structural steels with high strength and ductility and a tailor-made property profile. The consortium was nominated for the German Future Prize 2014 for this development.[31]

3.1.2 Aluminium

With its comparatively low density of 2.7 g/cm^3 and very good forming properties, aluminium is a proven lightweight material in automotive, aerospace and other applications. The percentage by weight of aluminium in passenger cars has risen continuously over the past decades. In Europe, the average amount of aluminium used in new cars increased from 50 kg in 1990 to 140 kg in 2012. By 2020, values of 160 kg to 180 kg are expected.[32]

The production of materials from primary aluminium requires around seven times as much energy as when producing the same amount of unalloyed steel material by the blast furnace route.[33]

When recycling aluminium scrap, it should be noted that separation of alloy elements is not possible. For recycling, the alloy components of the scrap must therefore be known and sorted out separately.[34] Otherwise, the alloy components will be mixed in and thus the material properties of the secondary material will deteriorate compared to the primary material.

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31 Cf. TU Clausthal (2014).

32 Cf. European Aluminium Association (2013), p. 10.

33 Cf. Umweltbundesamt (2016).

34 Cf. Martens, H. (2011), p. 94.

Resource efficiency measures for lightweight material construction with aluminium

Material selection

- Application-related material savings through the use of aluminium foams
- Fibre-reinforced aluminium foams (research project)

Energy

- Use of secondary aluminium to reduce the energy demand during material production
- Flexible approach to energy supply in production of aluminium by means of fused-salt electrolysis using a controllable heat exchanger
- Utilisation of residual heat from processes, e.g. rolling in downstream processes
- Melting of aluminium by solar thermal energy (research project)

Manufacturing process

- Use of additive manufacturing processes instead of machining to reduce production waste

Recyclate quality

- Production waste recycling from cleaned aluminium shavings to pressed briquettes

Material selection

In some applications, the use of materials can be reduced by using a **cellular aluminium foam** instead of solid aluminium. Depending on the manufacturing process, foams can be achieved with densities of 0.5 to 0.9 g/cm^3, i.e. the **material used can be reduced to less than one fifth of solid material**, but the strength decreases. Aluminium foams produced by melting or powder metallurgy can be used in many ways in lightweight construction. In addition to low density, these materials have further advantageous properties. Aluminium foams are very stable and are suitable as energy absorbers for crash-related components. This makes aluminium foam interesting both for load-bearing structures in the automotive industry and for applications in rail vehicles, e.g. in front modules for traction vehicles. Often the aluminium foams are integrated into sandwich components between aluminium foam sandwich (AFS) and steel aluminium foam sandwich (SAS) sheets.[35]

Another variant consists in the **addition of fibres to reinforce the aluminium foam.** For example, foams with better mechanical strengths can be produced by the admixture of glass fibres to the metal powder in the powder metallurgical process. The density is only slightly increased compared to unreinforced aluminium foam. The development of such fibre-reinforced aluminium foams is still at an early stage and practical applications are still a few years away.[36]

Energy

While the low density and very good recycling properties of aluminium have a positive effect on the overall balance compared to other lightweight materials, the high **energy demand** for the production of primary aluminium has a negative impact in the life-cycle assessment.[37] Therefore, a central starting point for increasing resource efficiency in lightweight aluminium construction can be found in the **reduction of the use of primary aluminium** through increased **use of secondary aluminium**. If there is an increase in the overall demand for aluminium, it must be remembered that the supply of secondary aluminium may not meet demand under certain circumstances and therefore the demand for primary aluminium may increase despite a high recycling rate.

The standard process for producing primary aluminium by **fused-salt electrolysis** requires a constant supply of large amounts of electrical energy. Although the energy demand for this process cannot be reduced physically-chemically, the company TRIMET in cooperation with scientists from the University of Wuppertal has managed to maintain this process with **a flexible energy supply**. For this purpose, a **controllable heat exchanger** has

35 Cf. Knuth, L. (2015), pp. 20–25.
36 Cf. Albrecht, R. and Lange, G. (2014), pp. 26–30.
37 Cf. e-mobil BW GmbH (2012), p. 24.

been developed which enables flexible furnace control. With this system, the energy balance in the furnace is kept constant even with fluctuating power supply. An aluminium lake integrated in the cell with ten tons of liquid aluminium serves as a buffer, so that the subsequent foundry process is not disrupted. As an additional benefit, electrolysis furnaces equipped in this way can serve as a "virtual battery" and thus as an energy store to compensate for fluctuations in the power grid. Thus, this technology also contributes to the integration of volatile renewable energy sources and security of supply in the context of the energy transition.[38]

In the established processing methods, resource savings are also possible. For example, Aluminium Norf GmbH has developed an innovative kiln concept to increase energy efficiency in the heat treatment of cold-rolled aluminium strip. An intelligent control technology records the thermal state of each individual aluminium strip and uses this data to control the further annealing process. Thus, the bands can be further processed directly by **using the residual heat from the rolling process**. In addition, the hot exhaust gases of the annealing furnace are used to preheat the **protective gas required**. The energy requirement for this processing step could be reduced by 45% in this way.[39]

To produce cast components, aluminium must be heated to about 700 °C to melt it. In order to reduce the associated CO_2 emissions, researchers from the German Aerospace Centre (DLR) are working together with the company aixprocess and partners in South Africa in a project funded by the German Federal Ministry of Education and Research (BMBF) **to melt aluminium using solar thermal energy**. For this purpose, the aluminium to be melted is introduced into a tubular furnace, which rotates slowly. Sunlight is concentrated on the furnace via a multi-mirror system. From 2017, the process is to be tested at the DLR solar power plant in Jülich. Implementation should take

[38] Cf. KlimaExpo.NRW.
[39] Cf. Effizienzagentur NRW (2014).

place from 2018 in South Africa. The practically emissions-free molten aluminium would then be transported in the liquid state to processing plants in the area.[40]

Manufacturing process

A promising approach to the use of energy-intensive materials such as aluminium in a way that saves resources is the current development of **additive manufacturing processes**. While the machining of aluminium components means that a large part of the raw material used is waste and has to be recycled, in the ideal case of additive manufacturing **only as much material is processed as is required for the respective component geometry**. Direct metal laser sintering (DMLS) and selective laser melting (SLM) are of particular interest for additive manufacturing of components made of aluminium alloy and aluminium matrix composites. In many R & D projects, the development of these technologies in recent years has advanced so far that components made from various aluminium alloys (e.g. A6061, AlSi12, AlSi12Mg, AlSi10) are being produced by DMLS or SLM for end applications, particularly in the aviation sector. General Electric Aviation has already produced parts for the next generation of leading edge aviation propulsion (LEAP) engines made with SLM.[41] Together with its subsidiary Premium Aerotec (PAG), Airbus plans to begin series production of aluminium components for military and passenger aircraft by additive manufacturing as of 2017. Airbus expects to achieve material savings of up to 90% over conventional production.[42]

Current research also focuses on making more complex high-strength aluminium alloys useable for additive manufacturing. For example, a project funded by the Federal Ministry for Economic Affairs and Energy (BMWi) at the Technical University of Dortmund is working on the development of an additive manufacturing process for the alloy EN AW-7075. The project is investigating how process-related defects affect the fatigue strength of the

[40] Cf. Ingenieur.de (2015).
[41] Cf. Manfredi, D. (2014).
[42] Cf. Airliners.de (2015).

components in order to use these findings to optimise the manufacturing process.[43]

The question of whether additive processes are generally more ecological than conventional manufacturing processes cannot yet be answered and has to be examined for every application. An important factor for resource efficiency is the usage profile of the production machine. In this context, Industry 4.0 opens up new possibilities for implementing additive manufacturing in a way that saves resources. Industry 4.0 stands for the fourth industrial revolution, which is characterised by a new kind of organisation and control in the value chain. Prerequisites for the successful implementation of Industry 4.0 processes are the real-time availability of all relevant data by networking all the components involved in value creation, as well as the ability to derive the optimal value-added flow from the data at all times.[44] With these prerequisites, intelligent networking of the additive manufacturing machines with one another, integration into the logistics concept and optimisation of the usage profiles are possible.[45]

Recyclate quality

A more efficient use of resources is also possible if **production waste can be returned directly** to the material stream on site. Thus, for example, HMT Höfer Metall Technik GmbH & Co. KG has found a way to recycle aluminium shavings produced during the production and further processing of aluminium profiles in-house. To allow the shavings to be melted again, they are first compressed in a press to **form briquettes**, a process which also recycles any cooling lubricants adhering to the shavings. The **compressed and cleaned waste material** can be melted easily and formed into pins that are used again as a starting material for extrusion. This saves the company from having to store and transport aluminium shavings to a central recycling plant. In addition, the material can be fed back into the production process without any loss of quality because it does not differ from the purchased raw material

[43] Cf. TU Dortmund (2015).
[44] Cf. VDI/VDE-Gesellschaft Mess- und Automatisierungstechnik (2014), p. 2.
[45] Cf. Richter, S.; Wischmann, S. (2016), p. 23.

in terms of composition and properties thanks to the in-house material cycle.[46]

3.1.3 Magnesium

Due to their low density and high specific strength, magnesium alloys are an alternative to aluminium alloys and steels. In the aviation sector, the market for magnesium applications is currently small, but by the year 2020 an absolute growth of 30% is forecast.[47] The material has been used in the automotive industry since the Model T Ford, and engine blocks and gearboxes of the VW beetle have already been made from Mg-Si alloys.[48] Magnesium is 35% lighter than aluminium and has similar mechanical properties. The price of raw materials per unit of mass is about 30% higher than that of aluminium, but is comparable in terms of volume price or standardised raw material costs in the component.

Magnesium can be obtained by energy-intensive thermal reduction or electrolysis processes. The production of magnesium material requires around seven times as much energy as the production of unalloyed steel material in the blast furnace route.[49] In the future, magnesium could also be obtained as a by-product from increasing seawater desalination.[50] This can lead to a decline in the price of raw materials.

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[46] Cf. Sedlmayr, A. (2015), pp. 46–47.
[47] Cf. Leichtbau BW GmbH (2014), p. 32 et seq.
[48] Cf. Tschätsch, H.-U. (2012).
[49] Cf. Umweltbundesamt (2016).
[50] Cf. Kawalla, R. (2015).

Resource efficiency measures for lightweight material construction with magnesium

Material selection

- Substitution of rare earth elements in magnesium sheet materials (research project)

Product design

- Improved simulation of the behaviour and lifetime of magnesium sheet metal allows reliable lightweight construction using computer aided engineering

Manufacturing process

- Use of additive manufacturing processes instead of machining to reduce production waste through special process chambers and optimised inert gas management
- Improvement of the material properties of magnesium alloys through the casting process (research project)
- Reduction of rolling processes in the production of magnesium sheets (research project)

Recyclate quality

- Properly sorted magnesium scrap allows up to 30 times less energy demand during recycling compared to contaminated magnesium scrap
- Properly sorted production waste recycling of sprues from die casting production

Material selection

The **substitution of rare earth elements in magnesium sheet materials will be** explored in the period up to 2017 as part of the BMBF-funded project SubSEEMag. Magnesium alloys have special requirements in terms of mechanical properties and fire safety and should be replaced by those without rare earth elements that have comparable properties. In addition to material selection, a suitable microstructure design could be helpful in designing the material properties.[51]

Product design

For industrial use of magnesium sheets in vehicle construction, a knowledge of their deformation and strength behaviour is required, as they differ greatly from those of the magnesium casting alloys. At the University of Applied Sciences Landshut in the BMBF-funded research project "Fatigue strength analysis for lightweight wrought magnesium alloys" (MagFest), it was determined that there are significant differences between simulations using conventional calculation methods for cast magnesium alloys and the experiments carried out. **New calculation models** have therefore been developed, which better describe the **behaviour and service life** of the thin sheets. This makes the **construction of reliable lightweight structures possible using computer aided engineering (CAE)**.[52]

Manufacturing process

3D printing of magnesium is now also possible. Selective laser melting has so far been used for stainless steel, aluminium and titanium alloys, but not for magnesium alloys. Scientists at the Fraunhofer Institute for Laser Technology ILT in Aachen have developed a process technology that compensates for **strong smoke generation by means of a special process chamber with optimised inert gas management**. Preferred applications in a spin-off start-up include medical implants, but the demonstrator has already produced a 1/4 scale motorcycle triple clamp.[53]

The Institute for Metal Forming at the Technical University Bergakademie Freiberg is investigating the **casting and rolling of flat magnesium products with reproducible properties**. Thus, the material properties of several alloys are being improved significantly in terms of elongation at break and tensile strength by means of casting rollers. The alloys are suitable for non-

[51] Cf. Kawalla, R. (2015).
[52] Cf. Hochschule Landshut (2015).
[53] Cf. Nolis, P. (2016).

load-bearing areal components whose surfaces are not exposed to strong corrosive or abrasive influences.[54]

The Helmholtz Centre Geesthacht is focusing on handling of magnesium sheets. At the Institute of Materials Research, a new hall has been built with a magnesium casting rolling mill, with the help of which magnesium sheets and their applications are to be thoroughly researched. The Magnesium Innovation Centre (MagIC) located there is also working on processes that **form magnesium sheets in only three rolling stage instead of up to 40 steps**, thereby making production more efficient and cheaper.[55]

Recyclate quality

Comprehensive end-of-life recycling concepts do not yet exist because, in particular, processes for removing **impurities** such as iron, copper and nickel are not available on an industrial scale. About **30 times more energy is required** to produce one kilogram of primary magnesium than for the production of **clean magnesium scrap**. Downcycling or dilution of magnesium scrap with pure primary magnesium is usual only until the degree of contamination falls below the specified limits.[56]

Recycling of magnesium currently takes place mainly in **single-grade alloys**, as found in the foundries as **clean production** waste. **Up to 50% of a die-cast component** is processed as scrap.[57]

3.1.4 Titanium

As a lightweight material, titanium does not achieve the low density of aluminium and magnesium, but it saves about 40% of mass compared to steel materials. Pure titanium, titanium alloys and titanium aluminides are used. Their specific density-related strength is higher than that of steels and aluminium alloys, even at higher temperatures. Titanium aluminide alloys in particular have a high specific strength even at 800 °C and more, which

[54] Cf. Kawalla, R. (2015).
[55] Cf. Tschätsch, H.-U. (2012).
[56] Cf. Duwe, S. (2015).
[57] Cf. Friedrich, H. E. (2013), p. 331.

predestines them for use in motor and engine construction. Pure titanium, on the other hand, is highly resistant to corrosion and easily deformed. Long established in aviation, around the year 2000 titanium was used for the first time in vehicle construction, exhaust systems and springs, and in oscillating and mechanically loaded engine components such as connecting rods, valves and exhaust gas turbocharger wheels.[58]

The production of titanium material requires around twenty times more energy than production of unalloyed steel material via the blast furnace route.[59]

Resource efficiency measures for lightweight material construction with titanium

Product design

- Optimisation of product design and process parameters through simulation processes during production by centrifugal casting

Manufacturing process

- Reduction of re-melting steps in titanium production by adaptation of the titanium alloy to the application
- Use of additive manufacturing processes instead of machining to reduce production waste

Recyclate quality

- Research on the recycling of titanium shavings by adapting machine and equipment concepts

Product design

Aerospace components of about one metre in size, such as door frame components or engine casings with low wall thicknesses of only around five millimetres, can be produced in **centrifugal casting**. As part of the EU project

[58] Cf. Friedrich, H. E. (2013), pp. 336–347.
[59] Cf. Umweltbundesamt (2016).

"Casting of Large Ti Structures" (COLTS), simulation processes **were developed** for this purpose and validated in experiments, with which both the **design and the process parameters for the casting process can be** optimised. In this way, problems can be identified at an early development phase and the use of materials minimised.[60]

Manufacturing process

For vehicle construction, new, cheaper **titanium alloys** are currently being developed that **are no longer based on the safety requirements of the aerospace industry** and thus can be melted in a **reduced number of remelting steps in a vacuum arc furnace** using less energy.[61]

Additive manufacturing has also extended to titanium – in 2014, Airbus installed 3D-printed cabin holders for the crew rest room on board the A350 XWB for the first time (Figure 3). The assembly was **previously machined from aluminium and is now being "printed" from titanium powder**, which makes it 30% lighter.[62] Bionic methods are also contributing to the optimisation of topology.[63]

[60] Cf. Koeser, O. et al. (2015), pp. 12–18.
[61] Cf. Friedrich, H. E. (2013), p. 347.
[62] Cf. VDI-Z (2016).
[63] Cf. Biokon (2015).

Figure 3: Holder for aircraft cabin components made by 3D printing[64]

Recyclate quality

Machining of semi-finished titanium products into structural components for the aerospace industry requires a very large amount of accumulated titanium shavings, which can be up to 95% depending on the component. Due to the impurities introduced into the chips, further processing of the scrap is not possible, so that titanium materials must be made exclusively of primary material. In the BMWi-funded research project "Process chain **recycling of titanium shavings**" (RETURN), up to 70% of the shavings are therefore to be recycled in order to be able to produce titanium alloys of aerospace quality. Approaches include **new cooling lubrication strategies and adapted machine tool concepts**, **alternative cutting materials and an inline analytical examination of the recycling suitability** of titanium shavings.[65]

3.2 Fibre-reinforced plastics

Due to the unique combination of excellent mechanical properties and low mass, fibre-reinforced plastics (FRP) are becoming increasingly important for

[64] Photo: Ansgar Pudenz, German Future Prize 2015

[65] Cf. University of Hanover (2015).

lightweight construction. There is a variety of possible combinations of glass or carbon fibres of different lengths (short fibres, long fibres or continuous fibres) with different matrix plastics (thermosets and thermoplastics). In particular, high-strength carbon fibre reinforced plastics (CFRP) are being used more and more frequently as lightweight construction materials and are therefore in direct competition with steel and aluminium construction methods.

The aviation industry and increasingly the automotive industry are among the main demand drivers for this development. In the aerospace industry, the Airbus A350 and the Boeing 787 are already large-capacity passenger aircraft in mass production with more than 50% high-strength composites in their structure. In the automotive sector, the BMW electric vehicle i3 is the first car to be produced with a complete CFRP body in medium-sized series. Even if such a construction method for large-scale models is not expected before 2020, it is anticipated that the use of high-strength CFRP components in the automotive industry will steadily increase. For continuous-fibre-reinforced CFRP, demand growth of 17% per annum is forecast by 2020, with the demand for the automobile industry growing at 33% a year. By contrast, annual growth of only 5% is expected for continuous fibre reinforced plastic. However, even by 2020, the estimated absolute mass of continuous fibre reinforced plastic produced will still exceed the mass of CFRP by more than tenfold.[66]

A major obstacle to the use of such lightweight materials, especially in the automotive industry, is still the high costs. These, in turn, are largely due to the production processes for FRP that have little automation and are not suitable for large-scale production. According to a study by Roland Berger and the German Mechanical Engineering Industry Association (VDMA), the greatest cost-cutting and resource-efficiency potentials can be found in the area of manufacturing processes and the supply of carbon fibres (Figure 4). In the production of glass fibre and the manufacture of matrix materials, however, there is only small savings potential.[67]

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[66] Cf. Lässig, R. et al. (2012), p. 32 et seqq.
[67] Cf. Lässig, R. et al. (2012), p. 15 et seqq.

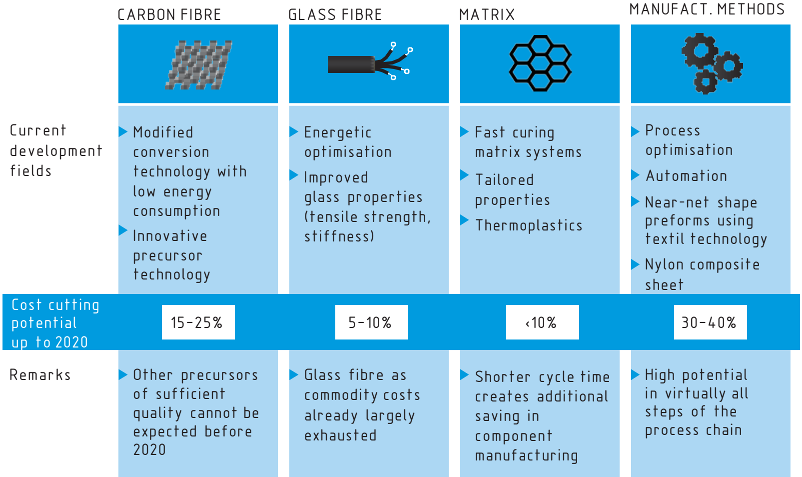

Figure 4: Innovation and cost reduction potentials in the FRP value chain[68]

When looking at the life cycle, there are further challenges, especially for continuous CFRP. The use of CFRP achieves the lowest component mass compared to steel or aluminium. Especially when the carbon fibres are introduced unidirectionally in the load direction in the composite material, mass savings of 79% are possible compared to a reference component made of conventional steel. However, the high energy demand for the production of carbon fibres and the manufacture of CFRP components, and the absence of an appropriate recycling option for CFRP in the overall balance have a negative impact.[69] In addition, damage to the composite material has had to be repaired by replacing the entire component thus far, which is neither resource efficient nor economical. Some key approaches to increasing resource efficiency in carbon fibre delivery, carbon fibre component manufacturing processes and material recycling have been described in the brief analysis No. 3 "Carbon fibre reinforced plastics in automotive engineering - Resource efficiency and technologies".[70]

An LCA of the most important process chains for the efficient production of CFRP components was carried out within the framework of the BMBF-funded

[68] Cf. Lässig, R. et al. (2012), p. 16.
[69] Cf. e-mobil BW GmbH (2012).
[70] Cf. Eickenbusch, H.; Krauss, O. (2013).

project MAI Enviro under the leadership of the Fraunhofer Institute for Chemical Technology (ICT) by the Institute for Functionally Integrated Lightweight Construction (FIL). In this case, for various processes and process steps, such as preforming of flat semi-finished products, direct roving fibre placement, automated fibre placement or resin transfer moulding (RTM), the primary energy demand and the material flows are recorded and compared. Significant potential savings were identified in primary energy, in particular from non-renewable resources. For the thermoset and thermoplastic-based CFRP production process chains, possibilities for reducing the primary energy demand from non-renewable sources by 3 - 38% compared to the baseline through suitable resource efficiency measures were identified. The greatest potential is seen in the reduction of waste (25 – 30%), in the use of regenerative energy sources for the production of polyacrylonitrile (PAN) carbon fibres and in further processing into high-performance composite components (around 38%). In the follow-up project MAI Enviro 2.0, the plan is to increase the availability of robust process balance data, to extend the existing life-cycle assessment models and to include output-related impacts on the environment such as greenhouse gas emissions in the assessment.[71]

Due to the more dynamic market development and the expected resource efficiency potentials, the main focus below will be on carbon fibre reinforced plastics.

Resource efficiency measures for lightweight material construction with fibre reinforced plastics

Material selection

- Production of carbon fibres from mesophase pitches or renewable raw materials, such as lignin
- Use of hemp fibres to reinforce polypropylene

Product design

- Optimization of the material usage by component simulation using the finite element method

[71] Cf. Hohmann, A. et al. (2015).

Repairability

- Different repair methods for material removal and material application (research project)
- Mobile milling robots for milling out damaged areas (research project)
- Networking automotive workshops and manufacturers of repair patches (research project)

Energy

- Reduction of the processing temperature of hemp-reinforced polypropylene in the injection moulding process

Process automation

- Transformation of manual processes into fully robot-based processes (research project)

Manufacturing process

- Reduction of waste and material use by producing complex CFRP component geometries from smaller sub-preforms with load-optimised fibre alignment
- Cement-free preforms and load-adapted fibre density through fibre injection moulding (FIM)
- Preforms eliminate waste through 3D fibre spraying
- Saving of manufacturing steps and energy through in-situ polymerisation, i.e. simultaneous polymerization and shaping
- 3D printing of CFRP components by integrating the continuous fibre into a plastic strand in fused layer modelling (FLM) (research project)
- Efficient production of small quantities by 3D printing of fibre-reinforced plastics (research project)

- Production of large lightweight structures by mobile robots (research project)

Simulation of process chains for the optimisation of CFRP production (research project)

Material selection

The standard process for the production of carbon fibres is based on the crude oil product polyacrylonitrile (PAN) as a precursor, which is processed by energy-intensive oxidation and carbonisation and further downstream process steps to make carbon fibres. In particular, the carbonisation step at temperatures of about 1400 °C is very energy intensive. In addition, only about 50% of the mass of carbon present in the precursor is converted into the resulting carbon fibre. Basically, approaches to saving resources result from the use of alternative precursor materials, but this leads to fibres with sometimes significantly different mechanical properties. Thus it is technically possible to **produce carbon fibres from mesophase pitches instead of polyacrylonitrile**. The carbon yield here is 80% of the mass of carbon present in the precursor. Pitch-based carbon fibres show a higher modulus of elasticity, but also a lower strength compared to PAN-based fibres, so they are only relevant for some niche applications. There are also approaches to **producing carbon fibres from lignin or cellulose**. The carbon yields of around 25% of the mass present in the precursor are even lower than in the PAN process route. For this, the fossil raw materials are replaced with renewable raw materials. However, since the quality and the mechanical properties are significantly worse than with conventional PAN-based fibres, these processes currently play hardly any role in the market. It can be assumed that oil-based PAN will maintain its dominant role as a precursor for the production of carbon fibres even in the medium term.[72]

The research in the field of carbon fibre production is being supported at the newly founded Research Centre Carbon Fibres Saxony (RCCF) at the Technical University of Dresden. From June 2016, a carbon fibre plant will be in

[72] Cf. Jäger, H. and Haider, P. (2014), pp. 24–28.

operation there, with which the **production of tailor-made fibres from fossil and from renewable raw materials** is to be researched. The plant offers the possibility of producing fibres with different mechanical properties in order to determine parameters on a laboratory scale that can be used in future in industrial production.[73]

The automotive supplier Hib Trim Part Solutions GmbH from Bruchsal developed a **raw-material-efficient mixture of loose hemp fibres, polypropylene and wax**, which is processed into pellets. The wax is used in the extruder of an injection moulding plant as a melting aid for the plastic. The hemp should have already reached a first rotting stage after the harvest, so that its ingredients do not outgas during processing. After injection moulding, the material has an **impact resistance** that cannot be achieved with the usual mixtures of short natural fibres, plastic and adhesive. With these, sharp edges are created in cracks, making them impossible to use interiors, for example to underfill panels made of wood, plastic and aluminium. Moulded parts made of hemp-polypropylene injection moulding are 20% lighter than those made of conventional plastics. Half of the mineral-oil-based plastic can be replaced by the renewable raw material hemp - in the other processes with natural fibres, this share is only about one third.[74]

Product design

The **developments in simulation methods** offer further potential for increasing the resource efficiency of fibre composite materials. One focus is on a more precise component calculation with numerical tools such as the **finite element method**. With a more calculable prediction of the component behaviour, the **component design can be optimised** and in this way **material can be saved**. In addition, improved process simulation can be used for integrated optimisation of the entire process chain, which generally also has a positive effect on resource efficiency.[75]

73 Cf. TU Dresden (2016).
74 Cf. Langen, R. (2015), p. 15.
75 Cf. Lässig, R. et al. (2012), p. 19.

Repairability

Research is being carried out into the repair of composite fibre components from various fields of application in the European project "ReCarbofit". Damage to a component can be caused in different ways and to a different extent. For this reason, there are also a variety of repair techniques. In individual cases, it must be decided which type of repair is suitable. For this, the **suitability of the various methods for material removal and material build-up** was examined after assessment of the damage.[76] The repair techniques were summarised in a morphological box to select the appropriate procedures (Figure 5). The results from the test specimens examined generally show good stiffness values of up to 115% compared to the reference specimens. The removal of material by laser proved to be particularly precise, so that no post-processing is required. In comparison with the replacement of a complete CFRP component, the repair represents the more economic option with 20-30% of the production costs.[77] In addition, a repaired component does not need to be recycled.

[76] Cf. Ellert, F. (2015).
[77] Cf. Ellert, F. (2015).

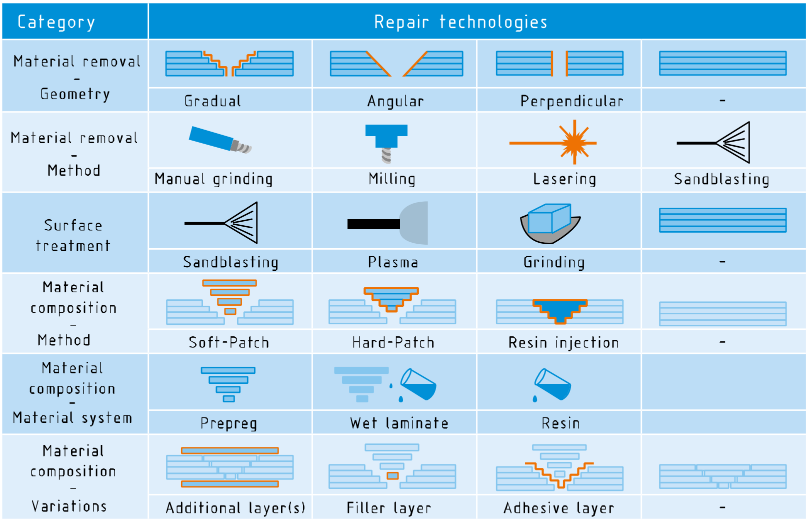

Figure 5: Repair techniques for fibre composite components[78]

In aircraft, sheets of composite material or metal are riveted in place to repair CFRP components[79], which both destroys the fibre structure at the riveted point and is counterproductive in terms of lightweight properties. Lufthansa Technik AG is currently developing a **mobile milling robot** in the Composite Adaptable Inspection and Repair (CAIRE) research project, based on the predecessor project "Rapid Repair", which uses suction cups to hold onto the outer skin of aircraft and repair damage there. The robot **scans the point to be repaired and independently calculates the size of the surface to be repaired**. After the damaged piece has been milled out, a repair patch is applied and glued under vacuum at high temperatures.[80]The mobile robot can also be used to repair extensive damage to hard-to-reach places such as on and under the wings. After improving the bond strength and durability test results, it is predicted that this procedure will be introduced in Lufthansa in 2016.[81]

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[78] Cf. Ellert, F. (2015).
[79] Cf. Lufthansa Technik: Im Fokus.
[80] Cf. FLUG REVUE 2015.
[81] Cf. Lufthansa Technik: Projekte.

In the automotive industry, too, the complete replacement of defective CFRP components should be avoided. For this purpose, RWTH Aachen University has launched a project to support classic workshops in detecting damage by collecting specific data on CFRP components. This data is analysed automatically and sent to a manufacturer of **industrially produced repair patches**. The finished patches are sent to the workshop and inserted there. The project will develop methods for standardised data collection and quality assurance.[82] **Networking of the workshops with the manufacturers of the patches** enables a resource-efficient repair of CFRP damage and reduces the logistical repair effort.

Energy

The **processing of a hemp-plastic mixture described in the material selection section saves energy** because the processing temperature in the extruder can be reduced from around 260 °C for pure plastics to around 160 °C for hemp injection moulding.[83]

Process automation

DLR's Centre for Lightweight Construction (ZLP) is developing new processes for automated production of CFRP components for aerospace applications at its Augsburg and Stade sites. The aim of the research is to **convert manual processes into fully robot-based processes** and thus improve resource efficiency through increased product quality. Focal points include low-contact and non-destructive handling, the reduction of joints, production-integrated, non-destructive quality control in CFRP production and the development of new deposition technologies.[84]

Manufacturing process

For the production of CFRP components in high volumes and short cycle times aimed at the automotive industry, especially the RTM, a liquid impreg-

[82] Cf. Lightweightdesign (2015), p. 6.
[83] Cf. Langen, R. (2015), p. 15.
[84] Cf. German Aerospace Centre (2015).

nation process, is regarded as a particularly promising production technology. [85, 86]A central process step is so-called "preforming", in which a near-net shape fibre preform is produced from several layers of a semi-finished textile fibre by suitable draping techniques. However, components with a complex geometry can only be achieved to a limited extent with a continuous preform. In addition, the conventional preforming processes results in fibre waste of up to 30%. For **complex three-dimensional component geometries, the preforms are therefore composed of several smaller sections**, the so-called "**subpreforms**".

Researchers at the Karlsruhe Institute of Technology are working on an integrated approach to optimisation, with which preforming with subpreforms can be made significantly more resource-efficient. The stresses experienced by the component in the subsequent application, restrictions imposed by the draping methods used, and the resulting waste when cutting the semi-finished product layers are all taken into account. For example, the division of the preform into the subpreforms is selected so that **areas with different load directions are separated from each other in the later application**. As a result, the anisotropic load capacity of the fibre material can be exploited and thus material can be saved. The number of semi-finished fibre layers is determined individually for each subpreform on the basis of the expected load. This also contributes to an efficient use of materials. Finally, the blanks of the various preforms are arranged on the semi-finished fibre webs in such a way that there is as little waste as possible. All optimisation steps are repeated iteratively to achieve an overall optimum of resource efficiency.[87]

Fibre blowing, known as fibre injection moulding (FIM), can be used for material-efficient production of preforms in the RTM process chain. In this process developed by the company Fiber Engineering GmbH, short or long fibres are blown together with thermoplastic binder fibres by means of a blow moulding machine into a tool mould. Subsequently, the fibre mixture is pressed into the component contour in the near-net shape mould. Hot air

[85] Cf. Wagner, H. et al. (2013).
[86] Cf. Eickenbusch, H. and Krauss, O. (2013), p. 25 et seqq.
[87] Cf. Fleischer, J. et al. (2016), pp. 82–84.

is introduced to activate the binding fibres, which fix the component in the desired shape. Up to now, this process has been used to produce insulating and damping components primarily for the automotive industry. Here the compressed fibre components already represent the finished component, that is, there is no further step to consolidate with a matrix plastic to make a fibre composite component.

Scientists at the wbk Institute for Production Technology at the Karlsruhe Institute of Technology have further developed the fibre-blowing process into a particularly material-efficient preforming process, which can be used to produce load-bearing fibre composite structural components by means of a subsequent RTM process. On the one hand, material-efficiency contributes to the waste-free production of the final contour of the preforms. On the other hand, by special adaptation of the injection tool, the **fibre density in the component can be varied and thus adapted to the local load distribution in the later application**. In order to make this method usable for the production of components for higher loads, continuous fibres can also be applied to the cover layer of the pressed preforms made of short or long fibres, which specifically increase the load capacity and rigidity of the component. The next step is the development of an automated tooling system combined with a placement system for the targeted introduction of continuous filaments. [88]

Another option for resource-efficient **preforming** in CFRP production in the RTM process is offered by the **3D fibre spraying process** developed at the Institute of Plastics Processing (IKV) at RWTH Aachen as part of an AiF project. With this technology, preforms made of cut fibres can be produced without any waste and suitable for large-scale production. For this purpose, the fibres coming from a roving are cut to a length of 50 mm and then transported through a Venturi nozzle in a stream of air onto a storage tool. They pass a fibre guiding unit, in which they are aligned, so that they are introduced into the component with a uniform orientation. The fibres are held on the perforated tray by vacuum before an added binder provides permanent fixation of the fibres in the preform. Cycle times of five minutes can be achieved with this preforming process. Further processing of the composite component then takes place in the RTM process. The further development

[88] Cf. Fleischer, J. et al. (2015), pp. 14–19.

work focuses on increasing the degree of orientation of the fibres and creating more complex components by integrating apertures, stiffening structures and force transmission elements into the preforms. [89]

There is also potential for increasing resource efficiency when merging the fibre preform and plastic matrix into the finished composite component. A promising approach is, for example, in-situ polymerisation of the matrix material directly in the mould. Researchers at the Institute of Plastics Processing (IKV) at RWTH Aachen have developed this technology for **in-situ polymerisation** of caprolactam to make polyamide 6. Instead of the polymeric matrix material, the monomer is injected into the tool in which the preform is located. Above all, the viscosity of the monomer, which is several orders of magnitude lower than that of the polyamide melt, has a positive effect on the infiltration of the fibres. As a result, higher injection speeds can be achieved and at the same time the pressure on the fibres is lower, so that their arrangement is maintained. For the polymerization reaction, temperatures of up to 170 °C are needed. Through this **concurrent polymerisation and shaping, the process is particularly energy-efficient** because the energy and time required for upstream hydrolytic polymerisation by the supplier is completely eliminated.

In 2012, a first prototype machine for in-situ polymerisation of caprolactam was created. However, there is still a need for further research and development up to series production of CFRP components, for example for the automotive industry. [90]

The innovation trend of additive manufacturing processes also offers potential for CFRP components with regard to more resource-efficient component production. However, the challenges of using such manufacturing processes are significantly greater when compared to homogeneous composite materials. **3D printing with fibre reinforced plastics** is therefore still in a very early stage of development. Researchers at the Fraunhofer Institute for Production Technology and Automation are working on a so-called 3D fibre printer, which can be used to print components made from a carbon-fibre-reinforced plastic. The approach is based on the **integration of continuous**

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[89] Cf. Hopmann, C. and Fecher, M. L. (2014), pp. 52–57.
[90] Cf. Egger, P. (2014), pp. 58–62.

fibres into the plastic strand using fused layer modelling (FLM), an established process for 3D printing with plastics. The composite of matrix plastic and reinforcing fibre is applied in layers. The fusion and bonding of fibre and thermoplastic polymer matrix take place in the melting head of the system.

Restrictions exist for the maximum construction volume and the surface quality, which is conditioned by the layers deposited on each other. By means of a downstream smoothing process, it is possible to achieve surface qualities which approximately correspond to those of injection-moulded components. It is also possible to integrate other materials, semi-finished products or components into the resulting component in the ongoing process. The maximum fibre content that can be achieved with this method is 10%. For industrial use of this technology, there is still a considerable need for research and development.[91]

With the aim of developing solutions for additive manufacturing of fibre reinforced plastics, the network 3D Composite Print (3D-CP) has been created under the direction of the Fraunhofer Project Group Regenerative Production with representatives from research and industry, covering all stages of FRP production. It focuses mainly on **efficient production of components in small quantities** and on repairs. For example, extremely lightweight mirrors can be made for sports cars from fibre reinforced plastics **using 3D printing**.[92]

Under a cooperation agreement between TU-Braunschweig and the German Aerospace Centre, research is being carried out into the combination of lightweight construction and Industry 4.0. The research project **aims to produce large lightweight structures using two battery-powered mobile industrial** robots. The robots carry out handling and driving tasks, automated by sensors and algorithms for localisation, path planning and load-bearing

[91] Cf. Fischer, A. and Finus, F. (2014).
[92] Cf. Fraunhofer IPA (2016).

tasks. The research project aims to gain insights into new production techniques for fibre-reinforced plastics, which can be used in the manufacture of aircraft or vehicles.[93]

In a subproject of the Active Research Environment for the Next Generation of Automobiles (ARENA2036 with participation of the DLR Stuttgart), the **complex processing of CFRP is simulated in a closed, digital process chain**. These calculations are intended to clarify how CFRP can be simulated throughout the life cycle. The resulting models then allow the selection of suitable material configurations.[94]

3.3 Other lightweight materials

In addition to metallic materials and fibre-reinforced plastics, pure plastics and technical ceramics play an important role, the resource-efficient processing of which is presented in this section.

3.3.1 Plastics

Fibre-reinforced plastics are widely used for lightweight construction. Pure plastic products are used much less frequently in lightweight construction. Nevertheless, there are also aspects of resource-saving manufacturing and lightweight applications relating to polymers. The study "Lightweight construction – trends and future markets and their significance for Baden-Württemberg" locates medium-weight lightweight construction potential with moderate market significance in the plastics industry. 17% of companies in the plastics processing industry use lightweight construction processes.[95]

[93] Cf. DLR-Institut für Faserverbundleichtbau und Adaptronik (2015).
[94] Cf. Lightweightdesign (2013).
[95] Cf. Leichtbau BW GmbH (2014), p. 7.

Resource efficiency measures for lightweight material construction with plastics

Manufacturing process

- Dynamically tempered injection moulds allow the use of plastic foams on optically appropriate surfaces
- Research into plastic composite with expanded polypropylene particle foam

Manufacturing process

The foaming of plastic offers the possibility of reducing the density of the material and reducing use of raw materials. A disadvantage lies in the poor surface quality of the foamed plastics, as surfaces often have streaks and thus can only be used for car interiors, for example, with a facing. In 2015, Covestro AG (until 2015 Bayer MaterialScience AG) presented an integrated, production-ready material and process approach based on polycarbonate under the project name "Surface Technologies", which delivers high-gloss, textured decorative components. It is based on a **dynamically tempered injection mould with an integrated, physical foaming process**. Microcellular foams are generated by supercritical nitrogen, which is injected into the injection cylinder and thus directly into the melt. With dynamic mould temperature control, the glass transition temperature of the thermoplastic polycarbonate rapidly cools down to the demoulding temperature during injection. This integrated process not only allows for better quality features, but also reduces the moulding wall thickness.[96]

For automotive interiors, BMW is developing a **plastic composite of expanded polypropylene particle foam (EPP)** on an injection-moulded polypropylene carrier and with a polyolefin-based decorative film. In application as an instrument panel, for example, the lower mass of this system in the utilisation phase is an advantage, while the components are manufactured in production in a more ecologically sustainable way than the state of the art,

[96] Cf. Gutbrod, M. (2015).

according to the company. The cost-effectiveness of the manufacturing process has also already been established, but improvements in manufacturing technology are still required for mass production.[97]

3.3.2 Technical ceramics

Technical ceramics are inorganic non-metallic materials. Technical ceramics obtain their typical properties, such as low density, high dimensional stability, but also a low fracture resistance, by a raw form being subjected to a sintering process at high temperatures between 1050 °C and 2200 °C.[98]

3.3.2.1 Solid ceramics

Solid ceramics have a high heat resistance and are resistant to wear and chemical influences, which is why they are used, for example, in spark plugs, lambda sensors, piezo injectors and particulate filters. Due to their low density, they contribute to lightweight material construction for vehicles as a whole, but above all as moving masses. Silicon nitride valves and compressor wheels in turbocharged internal combustion engines and silicon carbide ceramic water pumps are examples of this.[99]

Resource efficiency measures for lightweight material construction with technical ceramics

Manufacturing process

- 3D printing process enables the production of ceramic components with low raw material costs and flexible design
- Production of ceramic laminate by means of layering on film (research project)

Manufacturing process

In contrast to metals and polymers, **additive manufacturing for technical ceramics** represents a new type of process. The first 3D printer was

[97] Cf. Geltinger, A. (2014).
[98] Cf. IZTK – Informationszentrum Technische Keramik (2001).
[99] Cf. Friedrich, HE (2013), p. 348 et seq.

launched in 2012 by the Viennese company Lithoz GmbH[100], which has to date sold a low two-digit number of its machines. Slip, a high-viscosity photopolymer consisting of binder and ceramic particles made of high-purity alumina, is used for production. The process works with **small amounts of raw material, because unconsumed slip from one layer can be reused directly for further layers.** The layer thickness is 25 to 100 microns, while application of up to 100 layers per hour is possible, corresponding to 2.5 to 10 mm per hour. Through a mask exposure process, this speed is independent of component moulding. Finally, the product is sintered in the oven.[101] The material density in the final product is at least 3.96 g/cm^3, which is 99.4% of the theoretically possible density. The strength values are similar to those of classically manufactured ceramics.[102] As with all additive processes, the **shape can be designed as required** and it is suitable for prototype construction and small batch production in special machine construction and in medical technology. In aviation technology, casting cores for turbine blades with complex cooling channel geometries are one application option.[103]

Aluminium brake discs with a ceramic layer applied to them could eliminate the need for heavy cast iron and reduce unsprung masses in the chassis. The ceramic layer protects the relatively soft aluminium brake disc and takes care of the friction work. The Swiss Federal Laboratories for Materials Science and Technology (EMPA), the Politecnico di Torino, the Spanish brake manufacturer Fagor Ederlan and the Fiat Research Centre have set themselves the task of making a lightweight brake suitable for cost-effective mass production in order to penetrate the small car segment. Suitable base materials are low-cost aluminium oxide and silicon carbide for good heat conduction. They are applied as a two millimetre thick **ceramic laminate** made of **15 individual layers**. Each layer is **mixed with water as a slip, then applied to a plastic film**. Finally, the layers are pressed together, the interme-

[100] Cf. Lithoz GmbH (2012), p. 63.
[101] Cf. Asche, S. (2016), p. 23.
[102] Cf. Lithoz GmbH (2012), p. 63.
[103] Cf. Asche, S. (2016), p. 23.

diate plastic is burned away and the various layers are connected and compacted at several hundred degrees. The results of the demonstrator will show whether this production technology can supplement the mass produced but expensive Ceramic Matrix Composite (CMC) brake discs for luxury-class cars.[104]

3.3.2.2 Ceramic matrix composites

Ceramic matrix composites consist of fibres embedded in a matrix material. The fibre content of 40 – 50% ensures an increase in toughness. Ceramic materials or carbon are used as fibre material. The fibres used have a diameter of around 10 µm.[105]

Resource efficiency measures for lightweight fabric construction with ceramic matrix composites

Manufacturing process

- Embedding steel in ceramic structures (research project)

Recyclable product design

- CMC components, e.g. brake discs, make resource-efficient recycling of production waste more difficult

Manufacturing process

In future, **ceramic structures based on ZrO2 could also be combined with Fe-CrMnNi-based** steel. For this purpose, a ceramic structure is introduced into a liquid steel bath. The application is particularly focused on the energy absorption potential of the bodywork during an accident, since both ceramic and steel undergo phase transformations during deformation, the combination of which would allow resource efficient use of the materials.[106]

[104] Cf. Klose, R. (2014).
[105] Cf. Bertau, M.; Müller, A.; Fröhlich, P. and Katzberg, M. (2013).
[106] Cf. Technische Universität Bergakademie Freiberg (no date).

Recyclable product design

Over the past 15 years, composite ceramic brake discs have been launched for sports and luxury vehicles. They are made of carbon fibre reinforced silicon carbide (C/SiC), i.e. they are a ceramic matrix composite, often abbreviated as CMC.[107] CMCs are also available as friction linings in the propeller brake of the Airbus A400M[108] or in high-speed lifts[109]. Of the many manufacturing methods for CMCs, the LSI (liquid silicon infiltration) process is used. Because the mass of a brake disc made of CMC is only one third of a grey cast iron disc, each car would save about 30 kg. Added to this would be an overall lighter chassis design because the unsprung masses are reduced. The service life of **CMC disc brakes**, which corresponds to the service life of a car of 300,000 km, also contributes to resource efficiency.[110] However, the end product is expensive due to complex process steps [111], high cycle times, and the cost of errors, among other things, because **melting of faulty disks** as with cast iron brake disks **is not possible**.[112] There is still potential for a resource-efficient manufacturing process and corresponding cost reduction.[113]

[107] Cf. Friedrich, HE (2013), pp. 357 et seq.
[108] Cf. Kindervater, C. (2014).
[109] Cf. Heidenreich, B. and Goering, J. (2008).
[110] Cf. Friedrich, HE (2013), p. 354 et seqq.
[111] Cf. Technische Universität Hamburg Harburg (2015).
[112] Cf. Reichert, F.; Langhof, N. and Krenkel, W. (2015).
[113] Cf. Nestler, D. (2012), p. 203 et seqq.

4 RESOURCE EFFICIENCY POTENTIAL IN CONSTRUCTIVE LIGHTWEIGHT ENGINEERING

Constructive lightweight engineering not only uses modified materials, but also modified structural measures to achieve lightweight construction goals. Thus, thin-walled components are optimized by mechanical analysis in structural optimisation and hybrid construction. Functional integration, joining methods and biomimetic approaches play an important role. Resource efficiency potentials before the utilisation phase are also considered in this section.

4.1 Hybrid design

A hybrid component is created by combining two or more different materials within a component.[114] These materials complement each other equally and have different tasks with an overall increased load capacity compared to the materials used individually. For example, in hybrid construction with metal and plastic, the metal is responsible for the high rigidity, while the plastic ensures the overall strength of the component by means of a rib structure and can also have injection-moulded mounts for other components.[115] Different materials in combination thus provide better properties or additional functions in the component. The number of manufacturing steps can also be reduced. Not considered here is the so-called multi-material design, which refers to assemblies and bodies in mixed construction, in which various materials and classes of materials are installed side by side, such as aluminium castings, sheets, profiles and hot and cold-formed steel. [116]

A big challenge in hybrid construction methods are joining processes suitable for mass production which connect the different materials with different coefficients of linear expansion reliably and permanently.[117] If successful, hybrid designs are suitable for mass production. For 20 years, the front end

[114] Cf. Fraunhofer-Institut für Werkzeugmaschinen und Umformtechnik IWU.

[115] Cf. Ehrenstein, G. W.; Amesöder, S.; Fernández Díaz, L.; Niemann und H., Deventer, R. (2003), pp. 152 et seq.

[116] Cf. Bayern Innovativ (2015).

[117] Cf. Friedrich, H. E. (2013), p. 624.

of the Audi A6 has been made from a hybrid combination of sheet steel – later aluminium – and an injection-moulded, modified polyamide.[118]

As joining methods, punctual riveting or clinching can be used, as can surface bonding methods or corresponding hybrid joining methods. Thermal-mechanical processes such as resistance element welding and friction element welding also play a role, as do innovative variants of arc welding.[119] In the following sections on metal-metal and metal-plastic composites, aspects of resource efficiency in manufacturing are of particular interest.[120]

4.1.1 Metal-metal composites

Metal-metal composites usually consist of steel and aluminium in lightweight construction. Such thin steel-aluminium sheets cannot be connected by fusion welding in a way that meets requirements. Welding leads to the formation of brittle intermetallic compounds. The shrinkage stresses that also come about due to different coefficients of linear expansion usually lead to breakage of the connection. Corrosion due to the difference in electrochemical potential is another difficulty.[121] A common alternative is to melt the aluminium in a welding or laser soldering process without a brittle intermetallic phase and to use it as solder for the steel.[122]

Resource efficiency measures for constructive lightweight engineering using metal-metal composites

Manufacturing process

- Forming of composite components made of steel and aluminium, thereby saving on process steps (research project)

Joining technology

- Laser soldering allows joining of material-saving tailored hybrid tubes made of steel and aluminium.

[118] Cf. LANXESS Deutschland GmbH (2006).
[119] Cf. Friedrich, H. E. (2013), pp. 652–662.
[120] Further information on the topic “resource efficiency of joining techniques” can be found in the VDI ZRE Brief Analysis no. 16 (see Drechsler, K.; Kirmes, S. (2016))
[121] Cf. Friedrich, H. E. (2013), p. 625.
[122] Cf. Rasche, M.; Lange, E. (2016), pp. 54–59.

Manufacturing process

The DFG-funded Collaborative Research Centre 1153 "Tailored Forming", based at the Institute for Forming Technology and Forming Machines (IFUM) at the University of Hanover was launched in 2015 with the aim of **forming different semi-finished products made of high-strength steel and aluminium**. Here, too, parts customised for the application are made. In the process, the different materials must be materially bonded to form the hybrid semi-finished product and then reformed together and post-machined. This would make it possible to join complex geometries of metal composites for the first time. [123]

Joining technology

The Institute for Integrated Production Hanover (IPH) and the Laser Centre Hanover (LZH) are currently working on a combination of tailored tubes and **material composites made of steel and aluminium, the Tailored Hybrid Tubes**. The aim is a mass saving of 10 - 20% for such customised tubes, which are used as axle beams, cockpit crossbeams, seat crossbeams, components in rear seat backrests or as impact protection in doors. In a first step, several tube sections made of **steel and aluminium** are joined together to form a long **hybrid tube by means of laser brazing. With so-called hydroforming, tubes can be reshaped, to adapt their geometry and thickness to the load at the specific point.**[124] **Compared to welded halves of deep-drawn sheet metal elements, Tailored Hybrid Tubes have high stiffness with reduced material usage due to the closed cross-section. This project is funded by the BMWi and the AiF.**[125]

4.1.2 Metal-plastic composites

The hybrid materials with plastic are usually metal-plastic composites; the plastic also includes fibre-reinforced plastics.

[123] Cf. Bougueche, A. (2015).
[124] Cf. IPH – Institut für Integrierte Produktion Hannover (2014).
[125] Cf. Förster, J. (2014).

Resource efficiency measures for constructive lightweight engineering of metal-plastic composites

Product life

- Use of CFRP components with corrosion-free titanium for fatigue-free components (research project)

Manufacturing process

- Laser structuring of titanium material allows titanium CFRP hybrid construction with fewer work steps
- Continuous manufacturing process for fibre-metal laminates improves production efficiency

Product design

- Simulation of connections between aluminium and CFRP

Product life

In aviation, increased resource efficiency is often achieved not only by lower mass, but also by increasing the lifespan of heavily loaded components. The BMBF project "Transhybrid" focuses on the reduction of moving masses in the tail rotor area of a helicopter **using CFRP components together with corrosion-free titanium**. The **fatigue resistance** of the drive shaft of the tail rotor with its high speeds and the required temperature resistance to hot gases is being investigated.

Manufacturing process

The work in the BMBF project "Transhybrid", which was described in the previous section "Product life", is also having an impact on the manufacturing process. **The conventional titanium-CFRP hybrid design requires six process steps, while the innovative design developed in "Transhybrid" takes only four steps**. The key element in achieving a defined bond is the **laser structuring of the titanium component**. Furthermore, an innovative test procedure is being developed to create a model for a possible failure of the adhesive bond. This knowledge increases the fatigue strength and the drive shaft requires less frequent replacement. [126]

Fibre-metal laminates (FML), comprising an alternating arrangement of thin metal sheets with fibre-reinforced plastic layers, are ideal for components with a large surface area that are subjected to tension or bending. They are durable and resistant to damage. They are used in aircraft construction, such as the Airbus A 380, where they are made of aluminium and duroplastic CFRP. Disadvantages are the sequential production method involving long process times and the lack of formability after production.

In the DFG-supported Federal Cluster of Excellence "MERGE", **a continuous manufacturing process** has been developed that substantially improves production efficiency **and enables forming of the semi-finished products**. The basis is still an aluminium alloy, but the new feature is the use of thermoplastic, fibre-reinforced composites, made of layers of fibre film tapes made of polyamide 6 or polypropylene with unidirectional continuous fibres, which can be made of glass, basalt or carbon fibres. The strips as precursors are manufactured and wound in a continuous process.

At Chemnitz University of Technology, a special primer layer has been developed as a suitable pretreatment, which is produced during thermal compression and can be mass produced by inline production. The experiments at the TU Chemnitz have so far been run with batch production. In the future, all components are to be processed as semi-finished products from the roll in one process step. Patterns of three metal and two plastic layers of carbon fibre reinforced PA 6 with about 4 mm thickness have comparable flexural strengths and stiffness to duraplastic FML. They are deformable by deep drawing and are being tested in the automotive industry as roof cross members and wishbones. [127]

[126] Cf. Hombergsmeier, E. (2014), p. 11 et seq.
[127] Cf. Nestler, D. et al. (2015), pp. 20–25.

Product design

An alternative to a sophisticated measurement technology in production is the simulation of the adhesive bonds in the development phase. This approach was pursued by the automotive supplier Brose in Coburg within the framework of the BMBF project "REAL4HYBRID – **Simulation of joining techniques between aluminium and carbon fibre reinforced plastics**". The Brose lightweight door is made of CFRP and aluminium. Self-piercing rivet joints help bonding because they provide instant bond strength. The computing time and the workload for simulation models of adhesive joints have been too long so far. The new software from Weimar Dynardo GmbH, which uses simple laboratory tests for model building, enables development times that are weeks or months shorter and lower costs, while almost completely doing away with the need for physical prototypes.[128]

4.2 Structural optimisation/lightweight structural engineering

The structural optimisation of components in lightweight engineering is used in particular to save material with optimal load design and stress reduction. Principles for structural optimisation can be found, for example, in Lothar Harzheim.[129] For the present brief analysis, two categories are distinguished in structural optimisation: Topology optimisation and component structuring.

Innovative lightweight construction solutions with great savings potential are offered by the use of biomimetic processes. Biological constructions are created with as few different materials as possible in a hierarchical structure with minimal resource and energy consumption. Nevertheless, they are usually very stable, flexible and often multifunctional.[130] Biological models for technical lightweight solutions include, for example, growth of trees or mammalian bones, the structure of plant stalks, the shell structures of marine organisms and optimal self-organising structures such as the honeycomb structure of honey bees. The implementation of biological inspirations in

[128] Cf. Dlugosch, G. (2016).
[129] Cf. Harzheim, L. (2007).
[130] Cf. Seitz, H. (2013), p. 30 et seqq.

technical solutions requires the use of different construction methods, depending on the application. Examples of biomimetic lightweight construction and its resource efficiency potential can be found in the following sections.

4.2.1 Topology optimisation

Methods with which a favourable basic shape of a component with regard to its mechanical load is determined are conventionally used in aerospace and in vehicle and aircraft construction. Here you will find a wide range of methods such as the finite element method (FEM) and biomimetic methods such as computer-aided optimisation (CAO) and soft kill option (SKO). CAO is used for shape optimisation with the aim of improving fatigue strength and SKO for topology optimisation for lightweight components. These computer-based simulation techniques can be supported by other methods such as the use of evolutionary algorithms for component optimisation. The aim of the component optimization is primarily to save material with optimum design of the components with regard to the required load cases. With the CAO and SKO methods already established on the market and used in vehicle construction, high mass and thus material savings can be achieved compared to conventional components. Here, mass reductions are possible, in particular for castings such as wishbones (12%), engine mounts (28%) or lorry wheel hubs (35%).[131]

Resource efficiency measures for constructive lightweight engineering of metal-plastic composites

Product design

- Improved simulation algorithms – especially for castings – optimise shape and topology for material minimisation
- New biomimetic approaches for complex and innovative lightweight solutions using various optimisation methods, e.g. Evolutionary Light Structure Engineering (ELiSE)

[131] Cf. 3. Ressourceneffizienz- und Kreislaufwirtschaftskongress (2014), p. 51 et seqq.

Product design

The commercial CAO and SKO software for producing the lightest possible castings for the engine compartment and the body does not have the ideal design for Volkswagen AG vehicles and has therefore been adapted to the company's own specifications with the aid of additional algorithms. So additional **algorithms to improve the stiffness, tension and operating load and to minimize wall thicknesses** have been developed. In addition, a check is carried out after each simulation step to ensure that the component can be produced by casting.[132] Through this improved simulation method for **cast components, the optimal shape and topology can be determined with minimal material use during production**.

Another method that can be used to systematically develop both individual and various lightweight construction solutions for a variety of applications is **Evolutionary Light Structure Engineering (ELiSE)**, developed by the Alfred Wegener Institute (AWI) and already protected by patent.[133] The design methodology used here goes through five stages - from component analysis to the finished product (Figure 6). The actual biomimetic abstraction process takes place in the screening phase.

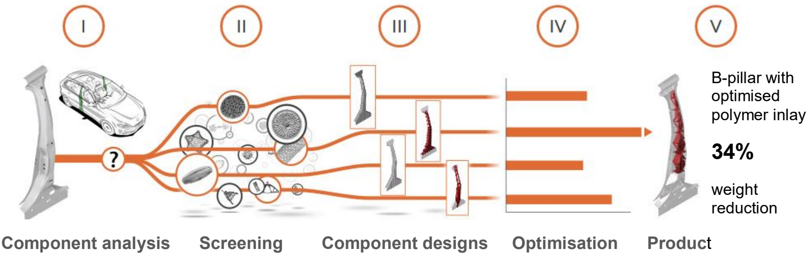

Figure 6: A construction methodology for biomimetic light structure engineering (ELiSE)[134]

The biological models are the extremely stable but very light shells of plankton organisms (diatoms and radiolarians). Based on thousands of organisms

[132] Cf. Manz, H. (2015).
[133] Cf. Hamm, C. (2005).
[134] Alfred-Wegener Institute (2016).

stored in scientific collections and a database of the AWI, different component designs are created, which are **then optimised using methods such as FEM, CAO, SKO and evolutionary algorithms** through to a computer-aided design (CAD) **model of the product required**.[135] This technique can result in lightweight solutions for components that cannot be found using traditional creative methods or traditional design approaches. They have the potential for a mass saving of more than 50% compared to a conventional component.[136] In particular, additive processes such as 3D printing offer great potential for saving material and energy here, as well as for functional integration into the production process. This has been demonstrated impressively using the prototype of a frame for a folding bike (Bionic Bike). The biomimetically optimised and laser-sintered aluminium frame weighs 2.1 kg compared to around 5 kg of a conventional frame. By integrating LED lighting and cable entries, this model achieves a 60% mass saving.[137]

The possibility of using several design principles of nature during the screening phase enables the design of multiple component concepts with a wide range of manufacturing processes and material concepts. By evaluating the resource efficiency of the various solutions, not only the performance of a concept but also initial estimates of the required resources can be considered mathematically and optimised as a target criterion in the 4th phase. A comparison of the concepts with each other then enables targeted selection of the most efficient construction method.

In order to improve this innovative and resource-efficient process further and to make it available to a large number of industrial partners, the AWI and the Institute for Vehicle Concepts at the DLR are planning further development of the process. The aim is to consider the entire value chain in an integrated product development approach. Resource conservation, economic production and consideration of recyclability should already be incorporated into the product development.

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[135] Cf. Maier, M. et al. (2015), pp. 34–39.
[136] Cf. Strauß, O. (2015).
[137] Cf. Strauß, O. (2015).

4.2.2 Component texturing

Improvement of the stiffness of lightweight components is increasingly achieved by texturing the materials or semi-finished products. Due to the higher rigidity, significantly thinner material thicknesses can be used with constant or even improved rigidity, thus saving a not inconsiderable amount of material. Areas of application are primarily sheets of different metals and alloys. However, texturing can also be effective for plastics or paper and cardboard. Textured sheets have a three-dimensional geometry that has better stiffness, thermal conductivity and reduced structure-borne noise. Despite the many advantages of textured sheet metal, there are still challenges in processing, as the material behaves differently in forming processes to non-textured materials.

4.2.2.1 Bead optimisation

One method of producing material-efficient, stiff and thin sheets adapted to different load cases, usually resulting in lighter sheets, is beading. The provision of sheets with beads of different geometries represents a well-known and regularly used, mostly software-based method for producing lightweight engineering products. The requirements for the functions of beads are very varied. Examples include mass reduction, increasing the moment of area or changing the centre of gravity, changing the reaction forces and moments or reducing the springback behaviour, achieving a defined deformation behaviour in crash elements and surface enlargement or flow guidance.[138]

Resource efficiency measures for constructive lightweight engineering through bead optimisation

Product design

- Optimisation of beads e.g. in terms of weld stresses or material efficiency by using evolutionary algorithms

[138] Cf. Reitter, GK (2013).

Product design

Components often have several and often conflicting requirements (e.g. low sheet thickness, high rigidity, unevenly distributed load cases). Not all requirements can be calculated optimally in commercial **software solutions for beads**. One solution from Volkswagen AG in Braunschweig is to significantly improve the results achieved with commercial software with respect to **weld stresses using evolutionary algorithms**. The bodywork manufacturing process has been improved to reduce weld stress by 37%.[139] With the use of evolutionary algorithms, it is also possible to optimise beading with regard to further parameters for maximum material efficiency or production restrictions in the manufacturing process.[140]

4.2.2.2 Vaulting

Vaulting differs from texturing methods such as hydroforming, embossing or beading in that a four or six-cornered structure is formed by an energy-efficient self-organisation process.

Resource efficiency measures for constructive lightweight engineering through vaulting

Energy

- Production of vaulting saves energy through the self-structuring process at room temperature

Manufacturing process

- Vault structuring process for continuous stripes saves material and improves mechanical properties

Energy

The process of vaulting is particularly energy and resource-efficient. A high external pressure is responsible for the formation of the **vault structure**,

[139] Cf. Manz, H. (2015).
[140] Cf. VDI 6224 Part 1:2012-06.

which is applied to the material within a cylinder. The self-organising structures spontaneously arise when an external pressure limit is exceeded and represent the irreversible state of equilibrium. If the system is given as much freedom as possible for deformation, honeycomb-shaped hexagons automatically form as the most stable structure.[141] This process for the production of thin, bending-resistant semi-finished products and precursors was developed by Dr. Mirtsch Wölbstrukturierung GmbH and is especially **energy-efficient in that the structuring process takes place at room temperature and requires no further energy apart from the application of the initial pressure**. The wall thicknesses can be reduced so much that up to 30% material can be saved with constant or better stability.[142]

Manufacturing process

The process of **vaulting** has now been extended so that **continuous strips can be structured**. In the automotive sector, for example, this method is used in the body floor of the concept car C90 from Opel and the rear wall of the Mercedes SLK made of aluminium 6016. This mass-produced component is particularly space-saving with low mass and high rigidity. In addition, the vaulting ensures good noise-damping properties.[143]

Another example from the vehicle industry is a lightweight catalytic converter housing made of stainless steel. This cover is produced for the company Emitec and installed in the motorcycle model R1200GS from BMW. Significant material **savings of up to 40%** can be achieved by the cover, which is only 0.5 mm thick. The original enclosure has a wall thickness of up to 2 mm. In addition, it has **up to 65% improved stiffness** and better durability under thermal stresses.[144] In addition to the significant material savings resulting from the longer service life, there are advantages in terms of recycling.

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[141] Cf. Sterzing, A. (2005), pp. 28–31.
[142] Cf. Seitz, H. (2013), p. 30 et seqq.
[143] Cf. Mirtsch, F. (2016).
[144] Cf. Continental Emitec GmbH (2016).

4.2.2.3 Folding techniques

Other methods that have long been known and used in architecture for producing lightweight engineering products adapted to specific load cases are the various folding techniques. An overview can be found in Arch+.[145]

Resource efficiency measures for constructive lightweight engineering through folding techniques

Product design

- Use of the origami folding technique in industrial applications, e.g. sandwich construction with core of folding honeycomb, folding into the smallest possible space or folding whole lightweight robot units

Manufacturing process

- Folding techniques can reduce or replace process steps such as gluing, welding or riveting
- Use of industrial robots enables automated folding of metal sheets without additional moulds

Product design

The ancient Japanese **folding technique of origami** is increasingly being adapted for **industrial applications** and in part is already in use. For example, the car maker Lexus wanted to show that a lightweight car made of folded cardboard can be produced and driven by means of a 1:1 model.[146] Foldcore GmbH, for example, was also able to show that it is possible to fold paper so that a load of 10 tons can be carried with 10 g of paper pulp.[147] However, there are also industrial applications in shipbuilding and aeronautics with which lightweight materials made of metal, plastics or paper and cardboard in the form of folded cores can be produced by isometric folding. These **folded cores** are characterised by the fact that variable shapes can be generated, which correspond to the target shape and can be produced

[145] Cf. ARCH+ (1996).
[146] Cf. Auto-Service.de (2015).
[147] Cf. Foldcore GmbH (2016a).

in a continuous process.[148] For example, a fuselage prototype was designed for Airbus to save 40% of the cost and 30% of the mass. The resulting **sandwich structure has a lightweight core made of folded** honeycomb and is multifunctional and drainable.[149]

The National Aeronautics and Space Administration (NASA) has used origami technology and in 2014 developed a lightweight solar panel that can be **folded into an extremely small space**.[150] When folded, the panel has a diameter of 2.70 meters, while unfolded it covers 25 metres. Weight and space requirements are crucial criteria due to the high transportation costs into space, and so there are already **foldable robots** that can be sent into space. They consist only of paper, two motors with batteries and a control unit.[151] The challenge was to find the **most suitable fold pattern**. This lightweight and initially flat robot also saves weight and space. It can put itself together within four minutes and start its planned work. Also conceivable is production of a foldable, self-building robot by means of additive processes using more durable materials.[152]

Manufacturing process

There are a variety of benefits and resource efficiency potentials that can be exploited through folding techniques. Thus, for example, **complex components can be manufactured from one piece of material**. **Process steps such as gluing, welding or riveting can be dispensed with**. Since folded, flat materials such as sheets are particularly stable as a result of folding, this also results in lower material consumption, efficient production processes and shorter production times. Even folded products, which are deployed to their full size at their place of use can be transported in a space-saving and logistically efficient way.

[148] Cf. Foldcore GmbH (2016a).
[149] Cf. Foldcore GmbH (2016b).
[150] Cf. Gosch, W. (2014a).
[151] Cf. Gosch, W. (2014b).
[152] Cf. Gosch, W. (2014b).

The process of folding metals usually requires a great deal of effort. The folding of complex origami-inspired structures requires an automated process. London-based RoboFold has developed a process that allows **sheet metal structures to be folded out of one piece**. Based on CAD data, two **industrial robots** bring the metal into the desired shape **without the need for additional forming tools**.[153] The robots can fold geometries and shapes that could not previously be produced industrially. This process is currently of particular interest for single pieces and small batches made of metal sheets, since no further tools or process chains need to be created for this purpose.

4.3 Functional integration

Functional integration is the combination of various functions (e.g. actuators, sensors, lighting, cables, antennas) into one component. The production of the component, but also the component itself, thereby becomes more complex. However, fewer components are required to manufacture the product and production steps are saved. In addition to a considerable mass reduction, effort, cost and space can be reduced.

In most cases, functional integration is referred to in connection with components made of fibre-reinforced plastics. Individual components such as actuators or sensors can be easily integrated into the layers of fibre composites during the manufacturing process. In addition, carbon fibres themselves have electrical conductivity, which means they can be used as sensors. A good overview of research into the use of carbon fibre sensors (CFS) in lightweight components in the automotive and aircraft industries can be found in Alexander Horoshenkoff.[154] Additional functions that can be integrated into fibre composites include, for example, pressure and temperature sensors, integration of electrical and thermal properties, e.g. using carbon nanotubes (CNT), or the use of the electrical properties of carbon fibres themselves as a sensor system. These can be used, for example, as detectors for monitoring the quality of the components with regard to delamination or microcracks.[155]

[153] Cf. RoboFold (2016).
[154] Cf. Horoschenkoff, A. (2014), pp. 28–33.
[155] Cf. Horoschenkoff, A. (2014), pp. 28–33.

Functional integration is not limited to fibre composites. For example, additional functions can also be integrated into the manufacture of components using additive methods such as 3D printing in different materials.

A small but rapidly developing area for lightweight materials is technical textiles. The textile market is rated by Landesagentur Leichtbau BW GmbH as an attractive market of the future with a high potential in the field of lightweight engineering and functional integration.[156] An overview of technical textiles and their use in lightweight engineering can be found in Chokri Cherif.[157] Here are examples of functional integration into technical textiles, such as feeding and incorporation of electrically conductive fibres into the fabric, yarns with integrated glass filaments for reinforcement or with components for self-repair, and inclusion of special fibres for vibration damping.[158]

The use and application of technical textiles is extensively researched and developed in Germany's largest textile research centre, the Institute of Textile and Process Engineering Denkendorf (ITV Denkendorf). One section deals with the functional integration and functionalisation of textiles (smart textiles), which can also be used for functional lightweight construction.[159] The functions can be incorporated directly into the textile and not into the component. If these textiles are used for lightweight applications, functionalisation offers another advantage in terms of component complexity. Examples of applications in textiles include various sensors, vibration damping, shape adaptation, noise reduction, lighting (self-luminous or fluorescent yarns), communication (microphones, loudspeakers), heating (filamentous heating elements), energy storage (heat, photovoltaic, piezo fibres).[160] The integration of sensor technology into safety components can help to monitor such components in all load cases in future, and thus make them safer.

[156] Cf. Leichtbau BW GmbH (2014), p. 12 et seqq.
[157] Cf. Cherif, C. (2011).
[158] Cf. Cherif, C. (2011).
[159] Cf. Institut für Textil- und Verfahrenstechnik (ITV) der Deutschen Institute für Textil- und Faserforschung Denkendorf (2016).
[160] Cf. Planck, H. (2013).

Resource efficiency measures for functional integration in lightweight engineering

Product design

- Components made of shape-variable fibre composite with integrated actuators and sensors can be adapted to load cases
- Material savings through integration of luminous elements in load-bearing CFRP structures
- Material savings through integration of components of the engine in load-bearing CFRP wheel structures
- Material savings through integration of battery systems into load-bearing aluminium frame structures
- Fibre composite materials with integrated functions such as sound and thermal insulation, thermal, sensory or electrical functions and liquid and energy storage for a car floor assembly (research project)
- Inert PTFE in polymers reduces friction in bearings
- Integration of cooling function into polymer housing by embedding copper plates

Manufacturing process

- Optimised extrusion tool with modified melt guide improves the required orientation of additives in injection moulded parts

Product design

Intelligent components made of CFRP with additional functions for aerospace and transport are being researched and developed by the DLR Institute for Composite Structures and Adaptronics. Selected research focal points include a **shape-variable fibre composite with integrated actuators and sensors** and integrated lighting.[161] Creating a flexible wing leading edge of an aircraft with improved flight characteristics is a goal of one project. By embedding an intelligent structure into the wing leading edge, the edge of

[161] Cf. Wiedemann, M. (2011).

the wing can be selectively deformed. Embedded **sensors measure the deformation** and pass it on to control units. Integrated **actuators can then adjust the alignment of the structure**. Piezoelectric composites can be used as sensors and actuators for robust applications. One challenge, however, is that the composites used must be designed for conflicting requirements such as maximum actuation, load bearing capacity and rigidity. In various components, strip conductors can also be integrated e.g. for a power supply, information transmission, or sensors for component monitoring.

In another project, the lighting will be examined and developed as a functional unit with the aim of reducing the number of components and thereby saving space. **Structurally integrated lighting** can be achieved either **by an electroluminescent film or integrated LED**. An A4-sized, 2 mm thick electroluminescent film can be completely embedded in CFRP as a load-bearing structure. A fibreglass fabric protects the film without it being visible. In the case of the LED (120 diodes), wall thicknesses of 4 mm are required. Again, the integrated lighting serves as a load-bearing structure and is also protected by an invisible fibreglass fabric.[162]

An example of functional integration in lightweight wheels for use in electric vehicles is the **fibre composite wheel with integrated electric motor** developed by the Fraunhofer Institute for Structural Durability and System Reliability LBF.[163] In 2012, this development won the prize for one of the best future ideas in the competition "365 Places in the Land of Ideas" in the category “Environment”. What is remarkable about this **lightweight wheel made of CFRP** is that the **motor bell** has been connected to the inner area of the wheel axle. Through the use of CFRP and foam cores in the spokes, it was possible to reduce the mass and increase the rigidity, so that the wheel with CFRP bell weighs only 4.9 kg. Compared to a steel wheel, this corresponds to a mass reduction of 60%. In addition to an electric motor that is connected to the wheel, several sensors were integrated into the wheel in

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[162] **Cf. Wiedemann, M. (2011).**

[163] **Cf. Fraunhofer-Institut für Betriebsfestigkeit und Systemzuverlässigkeit LBF (2016).**

order to achieve further savings in terms of installation space, costs and installation effort.[164]

In order to demonstrate the lightweight construction potential of aluminium for the automotive industry, Hydro Aluminium and fka Forschungsgesellschaft Kraftfahrwesen mbH Aachen have developed a car body concept based on new aluminium alloys, which should enable mass reduction in particular for future electric vehicles. **The integration of the battery system into the load paths of the aluminium body** leads to further mass savings, so that body and battery system are a total of 115 kg lighter than in the reference vehicle, which corresponds to a reduction in the mass of these units by more than 35%.[165]

Multifunctional lightweight materials from the various material groups have great potential to contribute to improved resource efficiency. This explains why the project "ARENA2036" (Active Research Environment for the Next Generation of Automobiles) was able to prevail in the "Research Campus" competition of the BMBF and will now be funded over the next 15 years.[166] Five million euros are available for the next five years. The industry partners will contribute 20 million euros to the project over the same period. Partners of the Baden-Württemberg research campus are made up of large mechanical engineers, various research institutes, the University of Stuttgart and Daimler as an automobile manufacturer. ITV-Denkendorf is also one of the partners. The new research building, into which the "factory of the future" will also be integrated, is being built on the grounds of the University of Stuttgart and financed by the state and the university to the tune of 27 million euros.

The aim of the research campus and research factory is to demonstrate lightweight engineering through functional integration into future automotive applications. This is demonstrated using the prototype of a passenger car floor module, for example. It is based on composite fibre materials, into which **functions such as sound and thermal insulation, thermal, electrical and**

[164] Cf. Haubert, K. (2012).
[165] Cf. Hören, B. et al. (2015), pp. 44–49.
[166] Cf. Lightweightdesign (2013).

sensory functions and fluid and energy storage are integrated (Figure 7).[167]

The Open Hybrid Lab Factory (OHLF) in Braunschweig focuses on production technologies that allow hybrid lightweight structures in the automotive industry to be mass produced and manufactured economically. The entire value chain for hybrid components is being researched – from conception through the automated manufacturing process to recycling. The use of combined material properties reveals potential for weight reduction and functional integration. Due to the adapted use of materials, cost advantages can be achieved over pure CFRP components. The Open Hybrid LabFactory eV, which is organised as a public-private partnership, cooperates with the Technical University of Braunschweig, with the Lower Saxony Vehicle Technology Research Centre, with institutes of the University of Hannover and the Technical University of Clausthal, and with the Fraunhofer-Gesellschaft. Independently of the project, industrial partners participate in setting up and operating the Open Hybrid LabFactory. [168]

[167] Cf. ARENA2036 (2016).
[168] Cf. Lippky, K. et al. (2016), pp. 59–63.

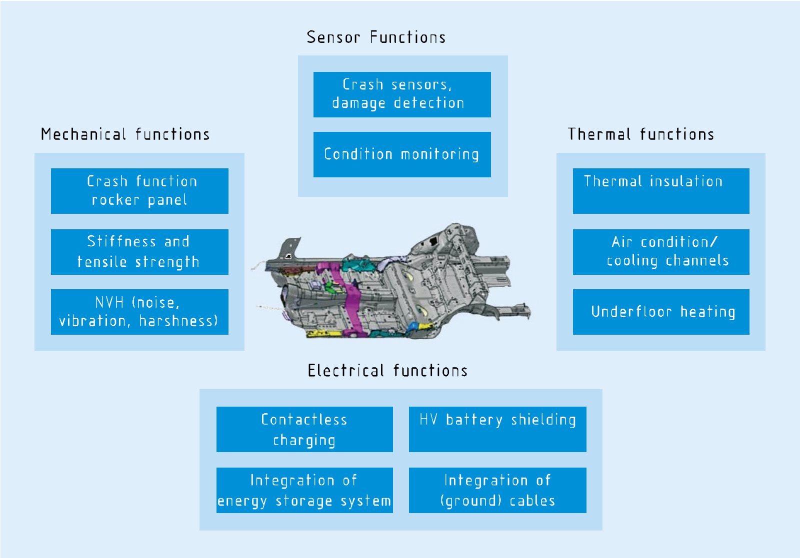

Figure 7: CFRP lightweight engineering with functional integration[169]

With plastics instead of metals, wear-resistant coatings and self-lubricating gearboxes, plain bearings and gears can be made by adding polytetrafluoroethylene (PTFE). The polymer known as Teflon is thermally, chemically and mechanically extremely stable and has a **very low coefficient of friction**, but does not mix evenly and tends to separate. Dr. Dieter Lehmann has made **chemical coupling of the inert PTFE possible** by activating it in a high-energy process. It shares its molecular chains, which form reactive carboxylic acid groups at the ends. These couple, for example, with the carrier polymers polyetheretherketone (PEEK), polyphenylene sulphide (PPS) or polysulfone (PSU). Following this efficient production process, the self-lubricating high-performance plastic, like commercially available plastic granules, is suitable for further processing by injection moulding or extrusion. Market entry is being prepared by the Dresden-based company perfluorence GmbH, a spin-off of the Leibniz Institute for Polymer Research Dresden e.V.[170]

By adding small copper plates to standard polymers they remain electrically insulating, but become more thermally conductive. **Thirty volume percent**

[169] Cf. ARENA2036 (2016).
[170] Cf. Trechow, P. (2014), p. 17.

copper in polyamide 6 can increase the thermal conductivity tenfold compared to pure polyamide 6. This allows heat loss dissipating housings for mechatronic and electronic components, in which active cooling by fans can be dispensed with, thereby reducing the mass. Anisometric additives are used for the modification, such as small plates or fibres, as they tend to touch each other and form thermally conductive networks. The added amount must not be too large because, on the one hand, the processing capacity in injection moulding or extrusion is worse, on the other hand, the price of metals is higher than that of plastics.[171]

Manufacturing process

The example mentioned in the section "Product design", which increases the thermal conductivity of polyamide 6 by adding small copper plates, places greater demands on the manufacturing process. The anisometric form of the additives also conditions the anisotropic property of thermal conductivity: it is usually lowest in the thickness direction that is ideal for heat dissipation, that of the smallest expansion of the component. Small plates and fibres as additives are aligned in plate or box-shaped components mainly in the flow and width directions. The Institute for Plastics Technology at the University of Stuttgart has developed an **innovative extrusion tool for the extrusion of sheets to remedy this problem, with which the additives are increasingly orientated in the thickness direction by changing the melt flow control**. In the thickness direction, the thermal conductivity increases by a factor of 2 to 3, depending on the additive content, compared to production with a conventional tool. Thus, a thirty percent volume addition of copper is sufficient to increase the thermal conductivity in the thickness direction to six times the thermal conductivity of pure polyamide 6. Performance thus increases despite the lower metal usage, and with acceptable processability.[172]

[171] Cf. Bonten, C. and Skrabala, O. (2015), pp. 16–19.
[172] Cf. Bonten, C. and Skrabala, O. (2015), pp. 16–19.

5 RECYCLING AND DISPOSAL OF LIGHTWEIGHT ENGINEERING PRODUCTS

New technical and technological developments for the handling of lightweight components and products after the utilisation phase are considered here only if they have not been included in the previous sections and are related to new lightweight materials or products. Utilisation and disposal include applications for further use or re-use of components after the product utilisation phase and for ecologically meaningful and economical recycling. A need for action exists, in particular, if the only option is energy recovery followed by depositing in landfill due to lack of separation or recycling processes. The aim should also be to preserve the secondary raw materials obtained through recycling in such high quality that they can be used in the same way as primary raw materials, in order to counteract downcycling as effectively as possible. This is rarely the case, especially for CFRP.

In the automotive industry, resource-efficient production and recycling of components is also necessary in view of the requirements of the End-of-Life Vehicles Ordinance. Since 1 January 2015, this regulation requires 85% of the mass of a vehicle to be reused or recycled. Furthermore, increased use of recycled material is a requirement. There is also an obligation to provide information about the recycling and recycling-compatible design of vehicles and their components. [173]

This regulation applies to all newly manufactured vehicles and is of particular importance for light vehicles in electromobility, as they are partly made of materials that are difficult to recycle, such as CFRP. For this reason, since December 2014 the BMBF has been funding a comprehensive joint project for the recycling of lightweight structures of future electric vehicles in the project "Production and Recycling Strategies for Electric Mobility for the Recycling of Lightweight Structures in Fibre-reinforced Composite Technology (ReLei)". Support is provided by the Research and Technology Centre for Resource-Efficient Lightweight Structures for Electric Mobility (FOREL).[174] The association involves universities, suppliers, manufacturers and a disposal

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[173] Cf. AltfahrzeugV (2012).
[174] Cf. ReLei (2016).

company. In the coming years, basic knowledge will be transferred to the industrial development and process chains and an economic and ecological technology assessment (life cycle analysis) will be carried out. Project contents include the development of joining processes suitable for disassembly, adaptation of processing technologies for the production of recycled material for injection moulding and production of complex hybrid sandwich structures with recycled CFRP.

The joint project ReLei was recognised in May 2015 by the Federal Government as one of seven lighthouse projects, which is a special seal of approval for outstanding innovations and technological progress.[175] The expectations of the results for resource efficiency with regard to recycling-compatible production, reuse and recycling of lightweight engineering products are already high at the beginning of the project.

A problematic area with the use of CFRP is still poor recyclability. Pyrolysis and solvolysis processes are currently suitable for the recovery of fibres embedded in the matrix. Energy consumption is very high in both cases, so the cost of recycled fibre is also often not economical. Above all, solvolysis is not yet suitable for large-scale industrial use. In car manufacturing, 20-30% of production waste is produced by cutting carbon fibre before it is embedded in a thermoplastic matrix. The combination of materials and the firm connection of the carbon fibres to the polymer matrix represent a major technical hurdle for the recycling of CFRP components. However, due to the high energy demand in fibre and component manufacturing, the recovery of carbon fibres after the utilisation phase offers great potential for improving the ecological life cycle balance. However, processes for recycling of CFRP are only beginning to be developed. At present, pyrolysis and chemical recycling by solvolysis are the most advanced processes. When using these methods, however, it is more likely that the recycled carbon fibres are downcycled (see Chapter 4).[176, 177]

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[175] Cf. Rischer, L. (2015).
[176] Cf. Eickenbusch, H. und Krauss, O. (2013), p. 38 et seqq.
[177] Cf. Meiners, D. and Eversmann, B. (2014), pp. 371–378.

Recyclate quality

The aim of the Thuringian Institute for Textile and Plastics Research is to recycle textile waste effectively and to produce high-quality products from it.[178,179] In a purely mechanical process, waste from fibre material that has not been treated with resin can be unlocked and processed into short-fibre recycled carbon fibres (rCF). The rCF cost only 25% of the price of new fibres. Their mechanical properties achieve up to 90% of the properties of primary fibres. On this basis, two production routes have been described along which recycled lightweight components can be manufactured. One results in granules for use in injection moulding, the other makes nylon composite sheets.[180]

Manufacturing process

For the production of nylon composite sheets, the process steps must be adapted to work with staple fibres, but can then run with a few simple modifications on conventional plant technology. The tests with different nonwovens made of rCF (wet nonwovens, carded webs, aerodynamically laid webs) have shown that carded webs are most suitable due to their pronounced fibre orientation. After being embedded in a suitable matrix, recycled carbon fibre reinforced plastic sheets (rCFRP sheets) show – in addition to lightweight properties and good stiffness – good hot forming behaviour, so that even complex components for the automotive industry can be produced.[181]

In one example from the automotive sector, a lightweight seat back in hybrid construction has been manufactured with fleeces made of recycled CFRP, variously arranged unidirectional (UD) tapes and with CFRP-reinforced injection moulding.[182] The installation space for the seat back was topologically optimised to the load cases. The outer shell was then made of recycled CFRP nonwovens reinforced with GRP injection moulded ribs at selected locations.

[178] Cf. Reussmann, T. et al. (2014), pp. 18–24.
[179] Cf. Reussmann, T. et al. (2015), pp. 26–31.
[180] Cf. Reussmann, T. et al. (2015), pp. 26–31.
[181] Cf. Reussmann, T. et al. (2014), pp. 18–24.
[182] Cf. Schulte, T. et al. (2015), pp. 38–43.

Further reinforcement is provided by UD tapes with various orientations. In addition, a metal insert made of sheet steel for attaching and adjusting the seat back fitted by injection moulding to create a positive fit.[183] This method enables resource-efficient and cost-optimised production of components through a load-optimised lightweight design that saves material. For example, the backrest described is 50% lighter than the comparable model. [184]

For the production of granules from rCF for use in injection moulding, adjustments to the process engineering must be made. rCF have no defined length and are voluminous, which is why they have to be pelleted or compacted before dosing in the compounding process. Series dosing of this sort has been developed by the Thuringian Institute for Textile and Plastics Research together with industrial partners. Among other things, the electrical systems had to be protected against carbon fibres and adapted cutting blades were used for wear-free application of the granulators. Further processing of the granules of rCF can then be carried out on conventional injection moulding machines. It is noteworthy that the components produced in this way have comparable properties to those produced in the same way from primary fibre products.[185]

In addition to further development and improvement of the processes themselves, a central task currently is to identify suitable applications for recycled carbon fibres with appropriate properties and to adapt the corresponding processes to the use of recycled fibres. One example of this is the development of CFRP recycling semi-finished products for applications in the aircraft industry, which Airbus is promoting together with CTC GmbH and other partners in Stade. The fibres recovered by pyrolysis are processed as short fibres for components in aircraft interiors. The requirements of the fibres are significantly lower than for the high-performance composite materials used in the fuselage structure. As part of a joint project, a process chain for the production of a flat semi-finished product has been developed to create cabin

[183] Cf. Schuck, M. (2015), pp. 14–19.
[184] Cf. Schuck, M. (2015), pp. 14–19.
[185] Cf. Reussmann, T. et al. (2015).

components made of recycled fibre (rCF). The key step involved characterisation and optimisation of an rCF fleece that can be further processed as a prepreg. By early 2017, a first application of such rCF components for aircraft interiors is to be delivered. [186]

[186] **Cf. Herrmann, A. und Witte, T. (2014), pp. 16–19.**

6 CONCLUSION

The results of the literature review presented in this brief analysis make it clear that the resource efficiency potential that lies before the utilisation phase and in recovery and disposal in vehicle construction and the aviation industry can be considerable in some areas.

A trend in lightweight construction is the reduction in the number of parts used to manufacture a product, which saves connections by welding, riveting or gluing. In the best case, the number of process steps, the material and energy consumption and the amount of waste decrease. In addition, products that are made from a few components are usually easier to recycle, since relatively fewer components must be separated. This applies if corresponding recycling processes exist for the resulting composite materials. Due to the large impact of product development on recovery and disposal, the dialogue between producers and recyclers should be strengthened.

Another trend that is emerging in lightweight construction relates to the integration of functional assemblies such as energy storage, lighting or motors in the supporting structures of products to save material. Disadvantages arise from the fact that the individual components mostly consist of various materials and can usually only be separated from one another using processes that consume large amounts of energy and materials (e.g. solvents), if at all. There is still a great need for research and development here.

In hybrid construction, there is a high potential for resource efficiency in the development of manufacturing processes suitable for mass production. For example, the combination of forming and joining processes enables complex geometries to be created in metal composites and reduces the number of process steps. However, there is also a need for research here for sorted recycling.

The additive process of 3D printing offers a high resource efficiency potential in lightweight construction. A variety of materials that are used in lightweight construction, can be processed in this way, such as steel, aluminium, magnesium, titanium, engineering ceramics and CFRP. Components manufactured using 3D printing usually consist of one material and have a free shape. In comparison to subtractive methods (e.g, machining), the number of machining steps and tools required is reduced. 3D-printed components are limited, on the one hand, by the size of the printer and thus the component size, and on the other hand by the production speed and therefore suitability for mass production. 3D printing of lightweight components is currently a complement to conventional plant engineering production. It remains to be seen how this technology will evolve and whether the current obstacles can be counteracted to the point that even large printed components and large series can establish themselves on the market.

The question of resource-efficient recycling and disposal has not been finally clarified for all lightweight construction materials. Compared to the lightweight materials steel and aluminium, which are recovered using established techniques, magnesium, titanium, fibre-reinforced plastics and ceramic matrix composites cannot yet be used for large-scale production in a resource-efficient way.

This disadvantage in recycling can be offset in individual cases in the overall balance due to the mass savings in the utilisation phase. The same applies to higher consumption of resources during production and processing. In general, the intensity of use is crucial.

A final assessment of the resource efficiency of a lightweight engineering product can only be made by considering the entire life cycle individually. Improving resource efficiency before and after the use phase is therefore still crucial in terms of overall optimisation.

PART 2: EXPERT DISCUSSION

1 PROGRAMME OF THE EXPERT DISCUSSION "RESOURCE EFFICIENCY IN LIGHTWEIGHT ENGINEERING"

Frankfurt/M., 15 March 2016

Moderation: Dr. Martin Vogt (Managing Director VDI Zentrum Ressourceneffizienz GmbH)

TOP 1: Welcome and introductory session

TOP 2: Lecture: Potentials for resource efficiency in lightweight engineering - results of a brief analysis by the VDI ZRE, Dr. Oliver Krauß (VDI Technologiezentrum GmbH)

TOP 3: Lecture: Resource efficiency and life-cycle assessment in mobility and manufacturing, Robert Ilg (Fraunhofer Institute for Building Physics IBP, Stuttgart)

TOP 4: Moderated discussion of the lectures

TOP 5: Lecture: Automotive construction: Resource-efficient lightweight engineering in the Open Hybrid Lab Factory, Prof. Christoph Herrmann (Technical University of Braunschweig)

TOP 6: Moderated discussion of the lectures

TOP 7: Lightweight engineering and resource efficiency through 3D printing in aviation, Peter-Leopold Pirklbauer (AIRBUS Group, Hamburg)

TOP 8: Moderated discussion of the lectures

TOP 9: Final discussion

TOP 10: Summary and outlook

2 DOCUMENTATION OF THE EXPERT DISCUSSION

On 15 March 2016, an expert discussion on "Resource efficiency in lightweight engineering" took place in Frankfurt am Main with 23 participants from research, industry, politics and professional networks. The VDI Zentrum Ressourceneffizienz GmbH had organised the event. The discussion blocks addressed the potential for resource efficiency in the production, recycling and disposal of lightweight engineering products. Resource efficiency potential resulting from the use of lightweight engineering products in the utilisation phase were to be excluded as far as possible in order to focus on the less considered potential before and after the utilisation phase. In addition to questions about resource-efficient production processes and economically and ecologically effective recycling, consideration of life-cycle assessment was one of the focal points of the discussion.

Due to the large volumes of materials required, the construction and engineering sectors, followed by the transport industry, are the major application markets for lightweight construction. The focus of the expert discussion was the transport industry. The areas of automotive engineering and aviation were considered, which clearly differ in particular due to the different legal provisions and requirements for the utilisation phase.

2.1 Life-cycle assessment (LCA)

The assumption that lightweight engineering products are in principle more resource-efficient than conventionally manufactured products has been the subject of much controversy. Finally, it was noted that performing a life-cycle assessment can help to evaluate the resource efficiency of a light-weight product over a product with a conventional design. A life-cycle assessment can be carried out in relation to environmental factors (LCA), economic factors (LCC, life-cycle costing) and/or socio-economic factors (sLCA - social life-cycle assessment).

The basis for a life-cycle assessment is provided by DIN EN ISO 14040[187] and DIN EN ISO 14044[188]. The life-cycle assessment considers mass and energy balances of products and processes in defined system boundaries. The crucial aspect here is scaling to a functional unit.

The participants agreed that, in order to carry out a meaningful life-cycle assessment, the consideration of a multitude of different parameters such as the manufacturing processes used, the types of materials and products and information concerning the place of use and the general conditions of use of the product is required. It has been pointed out that some of these parameters are not yet fully integrated into the LCA. Even in the manufacturing process, essential information may be missing. But also data on the region in which the product is manufactured, where it is used and for which application, and information on the probability of failure are not always adequately incorporated into the LCA. Consideration of repairability and recycling in the life-cycle assessment is still very difficult in the absence of knowledge about the composition of products and about appropriate assessment procedures. In addition, how and where the product is used and disposed of must be taken into consideration.

For the evaluation of a product in terms of resource efficiency, participants believe that it is necessary to complete life-cycle assessments for comparable products, i.e. those with the same functional units, in relation to the materials, processes and process chains used (benchmark). For the ecological assessment of moving masses it is interesting to note the point in time at which the resource savings in the utilisation phase compensate for possible additional resource expenditures in the remaining phases of life.

Factors that positively influence a life-cycle assessment were identified, e.g. the use of renewable energy or credits for recycling. A life-cycle assessment for an energy-intensive component made of steel or aluminium, for instance, is more favourable if it can be produced using energy from hydropower or wind instead of fossil fuels. The inclusion of credits for recycling requires appropriate recycling technologies to be used in industrial practice. When

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[187] DIN EN ISO 14040:2009-11.
[188] DIN EN ISO 14044:2006-10.

assessing multi-material components in particular, it is important to evaluate various end-of-life scenarios.

There are various commercially available software tools that can be adapted to corresponding processes and process chains to carry out an LCA. During the discussion, it became clear that the evaluation of mass and energy balances can now take place in a much shorter time, since companies usually have suitable models for this. For development engineers, such software-based tools offer a great deal of support, providing information about the environmental point at which the resource savings of their processes and products are greater than the resource consumption.

2.2 Manufacturing processes

Following keynote speeches on lightweight engineering in the automotive and aerospace industries with a view to increasing existing resource efficiency and exploiting other resource efficiency potential, it was emphasised that the interest in promoting lightweight engineering in both sectors focuses heavily on the utilisation phase. But there is no question that there is still significant resource efficiency potential before and after the utilisation phase.

In the case of aircraft, the considerable potential for savings through lightweight engineering in the long utilisation phase is particularly evident. It was highlighted that even a slight weight reduction in the components results in an extremely high fuel saving. Lightweight engineering is therefore a central strategy. It was noted that unconditional lightweight engineering is used in some areas. This applies both to aviation and to parts of the automotive industry. For example, car manufacturers are investing heavily in new manufacturing facilities to increase the proportion of aluminium in their vehicles. With regard to resource efficiency, there is still high potential along these process chains. According to the participants, up to 70% of the material in the production phase of die-cast aluminium production, such as sprues, is waste and is melted down again. Another example given was the production of large sheet metal parts, in which production waste is also returned to the production process. There is still considerable efficiency potential here.

Lightweight engineering still has significant potential in the production of low-end passenger vehicles with conventional engines and of some electric vehicles. Particularly in the case of vehicles in the high volume segment, it must be questioned how this potential – multi-material construction methods, for example – can be implemented in an economical and resource-efficient way. A wide range of research is still required here.

As explained in one of the lectures, around 35,000 new aircraft will be built in the aviation industry worldwide by the year 2032 to meet the demand for replacement and projected growth of the entire fleet. The global resource consumption of aviation including the utilisation phase is very high compared to other modes of transport. Against the background of the large quantities of raw materials needed that require processing, an increase in resource efficiency in production and in the life cycle is imperative. To achieve this, a number of adjustments in product manufacturing are necessary. Even at the stage of component design, consideration of the life cycle must be integrated systematically. This includes optimised processes, the use of ecologically beneficial materials and alternative energy sources.

Everyone agreed in the plenary session that enormous growth is currently forecast for additive manufacturing. Especially for small volumes, additive processes appear to be resource-efficient and economical in reducing components within a product, producing complex geometries – e.g. with undercuts – and carrying out on-site repairs. Restrictions – especially in aircraft construction – still relate to the fact that achievable component sizes are limited by the size of current 3D printers. The amount of energy required for the production of metal powders (e.g. titanium alloys) also plays a role in the exploitation of resource efficiency potentials. An increase in resource efficiency can usually be achieved by reducing process steps, shortening the logistics chain, reducing the use of tools and reducing the waste of materials that is produced during conventional production of components. It was pointed out that in each individual case it must also be considered whether a component manufactured using additive manufacturing has a positive eco-balance.

The experts also discussed the prospects resulting from the establishment of innovations: new technologies such as 3D printing can pave the way for new business models that support innovation transfer of research results into practice and enable transfer to other industries. In this way, a wider use of new resource-efficient technologies across various sectors can be promoted and accelerated.

The bioeconomy also offers opportunities for more resource efficiency, according to some of the participants. An increase in resource efficiency can be achieved, for example, if more renewable raw materials are considered as lightweight materials. Wood (e.g. planks of balsa wood) may be suitable for use in lightweight automotive construction. The lignin waste from papermaking could be suitable to replace petroleum-based precursors for the production of carbon fibres for fibre composites. Bamboo, too, is a light, elastic and strong natural material which, due to its fast growth rates, is able to bind large quantities of CO_2 and thus has a positive impact on the LCA.

Despite the generally positive assessment, it was noted that there are currently difficulties, especially in ensuring reproducible results in the use of natural materials, to compensate for fluctuating quality related to growth and cultivation. In the field of renewable raw materials, there is still a great need for research and development when it comes to suitable manufacturing technologies and the extraction and origin of raw materials. In the automotive industry, a recycling rate of 95% is required, of which 85% must be material recycling. The use of renewable raw materials is often eliminated for this reason.

2.3 Recycling

When it comes to recycling and eliminating waste after the utilisation phase, stakeholders often have different understandings of the term "recycling". In order to create a common basis, this term was defined in VDI Guideline 4800 Part 1, based on the Recycling Management Act, as a "recovery method that processes waste and residues into products and materials either for the original purpose or for other purposes; this includes the processing of organic materials, but not the recovery of energy or treatment of materials intended for use as fuel or for backfilling"[189]. Lower quality use is referred to as downcycling.

Reuse of aluminium scrap has long been established. Nevertheless, there is potential for optimisation here, since the alloys of the scrap which is returned to the aluminium plant are usually unknown and the scrap is not sorted. The alloys are crucial for the material properties. A declaration on the origin and composition of the waste would significantly reduce the effort of the analysis by the manufacturer and thus simplify recycling. In the discussion it was pointed out that this fact not only applies to lightweight engineering products, but is a fundamental problem in recovery and disposal.

The participants then dealt with the question of recycling fibre composite materials. For CFRP recycling, pyrolysis and solvolysis are used to separate the embedded fibres from the resin so that the carbon fibres can be reused. CarboNXT in Stade and ELG in Great Britain were cited as examples of companies which use their plants for pyrolysis for the recovery of carbon fibres on an industrial scale. However, this process is very energy-intensive and neither economical nor resource-efficient. The recovered fibres are shorter and can only be used for the production of components with lower requirements in terms of strength and rigidity, for example in the form of fleeces (downcycling). Efforts are underway to recycle 85% of waste CFRP by 2020. To the experts, it is currently not clear how this can be done within this period. They estimate that about another ten to fifteen years of development are needed to provide suitable technologies. This applies in particular to solvolysis, which is currently only operated on a research scale. In particular, CFRP from the aircraft industry represents a problem. This applies both to large scale production waste and to waste that is sent for recycling and disposal. Carbon fibre wastes generated during production can be used without complex pre-treatment for products that use short fibres (e.g. fleeces). By contrast, the effort required to dislodge fibres from the matrix material is much higher. Overall, it was questioned how recovery or even recycling of fibre composite plastics can be carried out functionally, ecologically and economically.

[189] VDI 4800 Part 1: 2016-02.

Hybrid components whose materials are glued or otherwise firmly joined together pose a challenge for recycling. The extent to which resource-efficient recycling is possible is not yet assessable by the experts. It was agreed: the more different materials are used to make a component and the more varied the joining techniques, the more difficult it is to recycle. In particular, the energy required to dissolve chemical compounds is very high. With regard to resource-efficient and economical recycling of multi-material systems, there is a need for further research and development. Participants believe that it is increasingly important for all sectors to consider resource-efficient recyclability in product design and involve waste management companies in the development process. At the same time, waste management companies must step up their efforts to develop new recycling processes.

It was discussed how important Germany is in innovative recycling technologies for composites. With regard to patents, some participants do not see Germany as being in a leading role. Japan and the US are considered to be the pioneers, just ahead of China. It was discussed how and under which conditions subsequent implementation in industrial processes takes place in the respective countries. Especially when it comes to implementation, Germany is well positioned in the view of some of the participants in the discussion. Nevertheless, in most industries manufacturers in Germany are currently lacking incentive to promote recycling of their products. One incentive for manufacturers may be the direct benefit that they derive from disposal, as one participant suggested. This would be the case if manufacturers got access to the recyclates from their own products or if they saved the disposal costs. Another way to create incentives that was discussed among the participants concerns the introduction of tradable certificates. Manufacturers could be required buy certificates for recycled materials in accordance with the materials that come onto the market through their products. This can both provide incentives to use materials with good recyclability, and lead to recycled material being used in new products.

2.4 Framework conditions

With regard to the development of resource efficiency potential overall, the participants agreed that Germany occupies a leading position in the world. In the future, it will be important to maintain this position and exploit further potential. One obstacle is obviously the lack of interconnectedness of all the stakeholders involved in the life cycle and the value chain. It was emphasised how important it is for manufacturers to be networked with developers, suppliers, recovery, disposal and recycling companies and to be involved in technological development.

Initial approaches are being implemented in various platform projects, such as the Open Hybrid Lab Factory (OHLF), the ARENA 2036 research campus and the MERGE cluster, where product development and implementation are considered and carried out throughout the entire life cycle.

In-house research and development also identifies solutions for various technical and technological issues, but these are not published for reasons of competitiveness. Despite an understanding of this position, it was regretted that manufacturers – with the exception of those in the automotive industry – often do not provide data about the type and quantity of materials used in the product to protect themselves against competitors. In terms of product responsibility, product liability and recycling, however, it makes sense and is necessary to make this data available.

In addition to the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) and the Federal Ministry of Education and Research (BMBF), the Federal Ministry for Economic Affairs and Energy (BMWi) also supports the increase in resource efficiency in Germany in many ways. For example, networking and knowledge transfer between the stakeholders is carried out in the form of round tables. In addition, work is currently underway on a lightweight engineering expertise atlas, which will be published on the internet at the end of 2016 and is intended for use by waste disposal and recycling companies, among others. A BMWi study on Industry 4.0, which will be completed at the end of 2016, also provides information on how to improve resource efficiency. The funding announcement "Lightweight engineering concepts for road and rail vehicles" is supporting the creation of environmentally friendly concepts in mobility with 40 million euros. Through further initiatives such as joint research into practical applications and the ZIM SME support programme, lightweight projects are also being funded.

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On behalf of:

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for the Environment, Nature Conservation
and Nuclear Safety

of the Federal Republic of Germany

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