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Ecological Lightweight Design for Sustainable Composites: Need for Application of Frugal Engineering Principles

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Abstract

Lightweight design is regarded as a technological approach to engineer products in a more energy and material efficient and therefore resource-saving way. In this sense, high-tech multi-materials, also referred to as composites, have become very popular for many decades due to their adaptability of material characteristics as well as high specific mechanical properties. However, composites in particular have also challenging characteristics, for example in the end-of-life of a product, as they cannot be recirculated in a typical material stream, or can only be recycled to a very limited extent (also known as "downcycling").

Alongside a common product lifecycle, we therefore describe challenges and constraints of ecological lightweight design and underpin the identified issues using semi-structured interviews with experts from the lightweight industry. We further approach the topic through the theoretical lens of frugal engineering, which critically evaluates and reduces the effective features and performances needed for an innovation thus resulting in more affordable and sustainable outcomes. Arguably, frugality might play a decisive role in ecological material transition as technology-driven innovation paradigms in search for the best material are substituted by more use case oriented engineering principles in search for the most suitable material.

Keywords: Lightweight, composites, sustainability, product lifecycle, frugal innovations, frugal engineering

1 Introduction

Lightweight as an interdisciplinary design philosophy pursues the primary goal of reducing the mass of a technical system while maintaining functionality without disregarding other innovation constraints (Klein and Gänsicke, 2019; Wiedemann, 2007). In the light of increasing environmental orientation of companies, lightweight is gaining a growing attention both in academia and practice due to efficiency optimization of products (Herrmann et al., 2018). In this way, the discipline of lightweight design combines economic drivers such as material efficiency and reduction of total cost of ownership (TCO) with an ecological focus, manifested in lower energy consumption and reduced negative environmental impact during the use phase.

As a result of the efficiency optimization, Klein and Gänsicke (2019) highlight that a considerable increase in overall lightweight design costs are accepted across diverse industries, for example automotive (accepted increase of 7 €/kg), aviation (accepted increase of 500 €/kg) or aerospace (accepted increase of 3000 €/kg). Hence, expensive high-tech lightweight composite materials can lead to a significant decrease of energy consumption and improved lifecycle assessments (Helms and Lambrecht, 2006). However, as materials are continuously optimized for lightweight applications, more and more criticism is being expressed regarding the overall sustainable orientation of these innovations (Herrmann et al., 2018) that go far beyond just decarbonization efforts of the use phase.

Especially in the light of circular economy as a vital strategy to encounter (ecological) sustainable development (Kirchherr et al., 2017), composite materials, such as fiber-reinforced polymers (FRP) must be critically scrutinized (Chatziparaskeva et al., 2022). Such multi-material structures typically consist of a polymer matrix into which specific fibers or fillers made of carbon (CFRP), glass (GFRP) or hemp (NFRP)[1] are embedded thus tailoring the material properties individually to the respective application (Schürmann, 2007). Other types of composites are for example metal polymer composites, in which different groups of materials such as aluminum and GFRP are bonded together. A schematic representation of a typical fiber composite material is shown in Figure 1.

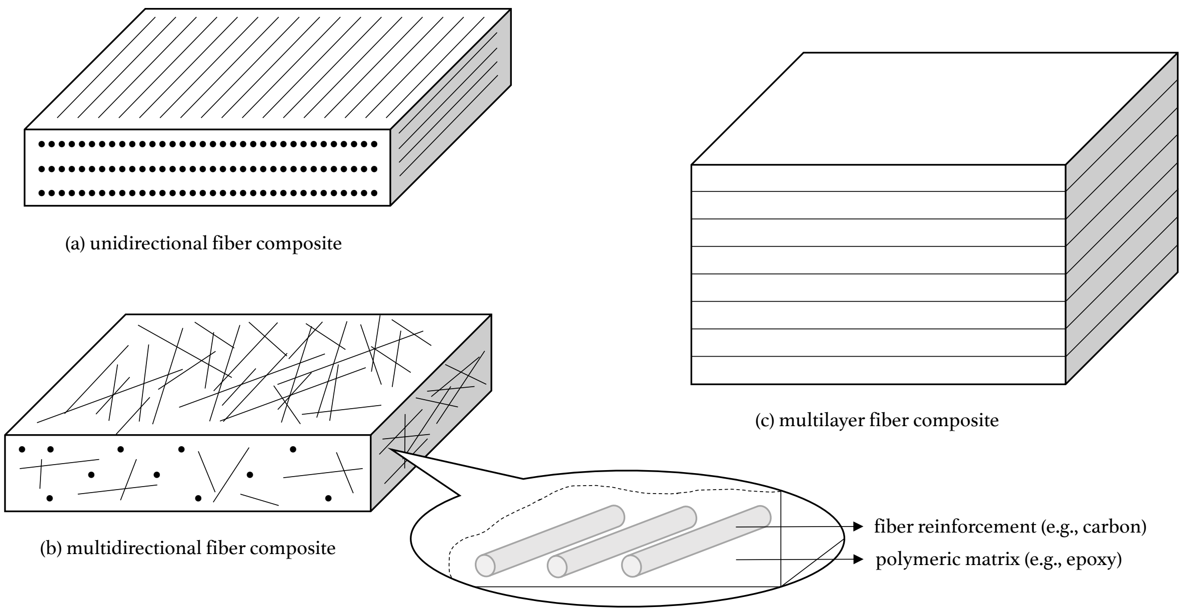

Figure 1: Examples of composite lightweight materials (own illustration based on Schürmann (2007))

[1] CFRP: carbon-fiber-reinforced polymer, GFRP: glass-fiber-reinforced polymer, NFRP: natural-fiber-reinforced polymer). Fiber composites in particular have outstanding technical properties such as high specific strengths (strength values in relation to density) and are therefore particularly well suited for lightweight applications.

Although the diffusion of these materials into different industries such as aerospace, automotive or mechanical engineering varied, a broad and increasing use of composites has been observed since the 1960s (Schürmann, 2007). Nowadays, major sections of an aircraft, such as the fuselage and wings, are made of composites, but they are also used in automotive, especially for trim parts and safety-relevant crash components. In addition to machinery and civil engineering, composites are also increasingly utilized in sports equipment such as bicycles and tennis rackets.

As illustrated in Figure 1 composites do not represent monomaterial compounds, so that consequently they limit the separability of the individual components and therefore conflict with basic circular economy strategies, which call for the circularity of materials in technological or biological cycles (Braungart and McDonough, 2002; Ellen MacArthur Foundation, 2013, 2016; Ghisellini et al., 2016). Chatziparaskeva et al. states that "[e]ven if composite materials offer great engineering opportunities, their integration in the circular economy remains challenging" (2022, p. 388).

These conflicts which are often referred as a discrepancy between *relative* and *absolute* sustainability (Hauschild et al., 2017) or *eco-efficient* and *eco-effective* sustainability (Braungart and McDonough, 2002; Young and Tilley, 2006), can be observed particularly well in the field of sustainable lightweight design (Forel Studie, 2018; Hengstermann, 2016). Adopting an end-to-end and circular-oriented perspective alongside a common product lifecycle, it is crucial to also consider raw material extraction, production processes and end-of-life treatment of these materials.

With this working paper we emphasize these issues by adopting a holistic perspective on sustainable lightweight using the example of composite materials and aim to provide a detailed overview of the most frequently identified challenges based on literature review. In section two, we examine potential challenges in a *relative* sense, meaning we zoom in on a certain stage of a product lifecycle before we discuss the findings in a wider and *absolute* sense. Using expert interviews in section three we aim to get a first hands-on impression of the perception of the challenges within the industry and thus underpin as well as extend the literature findings. In addition, we also examine the topic from the perspective of frugal engineering, which, in contrast to a "*bigger and better ideal*", proposes a new approach in which the necessity of certain innovations features and performances is critically evaluated based on the corresponding use case of the markets (Beise-Zee et al., 2021; Radjou and Prabhu, 2015; Weyrauch and Herstatt, 2016; Winkler et al., 2019).

1.1 A Brief Market and Literature Overview

To underline the increasing importance and market dynamics of lightweight design of the past decades, a study conducted by the German research organization Fraunhofer back in 2014 provides interesting insights about numbers of publication and patents. On the one hand, these figures can be used to draw direct conclusions about general academic interest, on the other hand, patent data reveal the medium-term technological and economic importance within an industry. Both number of publications (100 in the base year 1991 to approximately 1300 in the peak year 2012) and the patent applications (100 in the base year 1991 to 360 in the peak year 2010) demonstrate a high increase and thus illustrate the medium- and long-term importance of lightweight design (Leichtbau BW GmbH, 2014).

Despite ongoing environmental concerns, the latest market forecasts suggest that global demand for carbon fiber in particular will continue to rise in the coming years, after a small slowdown in growth in 2020 due to the Covid-19 pandemic (Sauer and Schüppel, 2022). The researchers estimate a possible demand of 122kt in 2024 compared to a demand of 92kt in 2021 and 33kt in 2010 – which results in a compound annual growth rate (CAGR) of +9.77% between 2010 and 2021.

With regard to the academic literature, Herrmann et al. (2018) provides an extensive review on (sustainable) lightweight design and lifecycle engineering (LCE). In particular, the researchers identified 131 papers and provide interesting findings relevant for this working paper. 71% of all identified papers focus on lightweight materials, followed by the manufacturing and production process with 35%, end-of-life treatment and challenges with 26% as well as the investigation of secondary lightweight effects (indirect lightweight savings) with 15%.[2] With this numbers it can be demonstrated that the overall environmental assessments and the material selection receive by far the greatest attention in the literature. However, the authors also note that "[w]hile many publications aim at achieving a holistic view on environmental impacts of lightweight structures, most quantitative studies are limited to impacts on climate change or the energy demand of the studied system. Less than half of the quantitative studies analyse further impact categories" (Herrmann et al., 2018, p. 657).

Due to its high market penetration and large savings potential, the automotive industry has a significantly higher presence in the literature than, for example, the aerospace industry. Herrmann et al. (2018) find that the automotive industry is covered in 55% of all research papers, whereas the aerospace industry (despite the high importance for lightweight designs) is covered in only 11% of the identified publications, the machine tooling industry in only 5% of the total share.

2 Relative and Absolute Perspectives of Sustainable Lightweight Design

In this section, the relative (section 2.1 to section 2.4) and absolute perspectives (section 2.5) of sustainable lightweight design using the case of composite materials will be discussed.

2.1 Early Innovation Phase and Green Material Selection

The early innovation phase and (green) material selection represents the start of a holistic discussion of environmental sustainability of composite materials. In this phase, the focus is on efficiency aspects and decarbonization, e.g., how much harmful greenhouse gases can be avoided in the entire lifecycle of a product by using lightweight materials. The decisions and assumptions made during the early product development might have a significant influence on the overall environmental performance of parts, components and products (Ashby, 2009). As also intensively discussed within lifecycle engineering, it is necessary to consider environmental aspects and planetary boundaries first and already at this point of the product development process (Hauschild et al., 2017).

Due to the large number of possible materials and their combinations as well as their manufacturing processes and transport routes, it becomes necessary to carry out a differentiated analysis of the environmental compatibility of materials (Frischknecht, 2020). Besides the high complexity of quantitative lifecycle assessments in general, Bovea and Pérez-Belis (2012) illustrate the wide variety of possible approaches, methods and tools ranging from a first broad assessment of the environmental impact to the most detailed quantitative analysis of innovations. The scholars conclude that "[t]hese tools vary widely in their complexity, quality and the time required to apply them, and no clear classification has been drawn up to allow the most suitable technique to be selected for each application" (Bovea and Pérez-Belis, 2012, p. 70). Although traditional lifecycle assessments are nowadays standardized such as in the ISO 14040 and ISO 14044, the stages specified in the standard, such as the definition of system boundaries and impact categories, also leave a large degree of flexibility (Frischknecht, 2020). Latest research of the most commonly used impact categories in lifecycle assessments in the automotive industry demonstrates that "climate change is by far the most relevant impact category followed by resource use, human toxicity and ecotoxicity" (Mikosch et al., 2022, p. 1) despite academia calls for the usage of a wide variety of different impact categories.

More practically, Liu and Müller (2012) found that the emission of greenhouse gases in the production of primary aluminum may vary significantly by a factor of three, depending on the selected production location and the associated transport routes. Further, Herrmann et al. states that "the application of global averages can mask opportunities to significantly reduce environmental impacts by sourcing materials from regions with favourable production conditions" (2018, p. 657). An ongoing action research project of our institute within the material development of a large German automotive OEM shows that the LCA values are often not available in the early innovation phase, are characterized

[2] If the total mass of a moveable system is reduced through the efficient use of materials, other technical subsystems such as brakes or powertrains can be reduced in size as well, thus creating a so-called secondary lightweight effect.

by a high degree of non-transparency and can thus not be used for any further decision-making at this stage. Ashby underlines the wide variety of values using the example of required energy in MJ/kg to produce aluminum over the years 1960 to 2010. The data show an average value of 204 MJ/kg with a standard deviation of 58 MJ/kg. As a result, break-even analyses within environmental management and lifecycle engineering might be biased by this uncertainty so that conclusions regarding an environmentally advantage of certain materials can be just as inaccurate.

2.2 Production Phase

With 35% of all research papers examined by Herrmann et al. (2018) production and the manufacturing process take on an equally important role and are among the most frequently addressed topics. The main focus in these publications is on the reduction of production times, energy, waste elimination and automation. Particularly for materials with very high required processing energy, such as aluminum or CFRP, waste avoidance and recycling within the production stage is a decisive factor for a better environmental performance.

A common example is the comparison between the so-called organosheets[3] predominantly used in the automotive industry and the multiaxial tape layup technology used in the aerospace industry (Kropka et al., 2017). By using tape material with a small width the final component geometry can be replicated more efficiently so that the waste rate can be reduced from approximately 25-30% to 10%. In general, the literature agrees that as a result of the high energy demand during the production processes a significant weight saving potential must be realized in order to compensate for the high manufacturing energy required (Kellens et al., 2017; Kropka et al., 2017).

2.3 Operating Phase – the Case of the Automotive Industry

In addition to the material selection and production phases, the operating phase of a (lightweight) product represents the most important and decisive role in the context of sustainable lightweight design. In this phase, the negative environmental impacts that may have occurred during the production of a material must be fully compensated so that eventually the final product begins to generate a positive environmental impact ("break-even"). Further, any negative consequences of an end-of-life scenario must also be compensated in the operating phase.

However, citing the case of the automotive industry, these break-even calculations are anything but easy. Weymar and Finkbeiner state that "[d]epending of the technology, a specific amount of driven kilometers is necessary to gain an environmental advantage over the lifecycle. As a consequence, the total amount of kilometers driven in a car's life in reality by the customers should be known in order to make robust recommendations based on LCA. The status quo of the assumptions used for the mileage in a car's life in current automotive LCA studies is rather based on assumptions [...]. There is no validated primary data published on the lifetime mileage of cars. As a consequence, there is neither a harmonized approach between different car manufacturers nor on the industrial association level" (2016, p. 216).

With this in mind, we used several sources to develop a normal distribution of driven kilometers of passenger vehicles until end-of-life in the German automotive market. Therefore, the study is based on various statistics on the total number of passenger cars registered in Germany (Statista, 2020), the total mileage of all German passenger cars within a year (Statista, 2019) and the age distribution when the passenger cars are scrapped (Weymar and Finkbeiner, 2016, p. 219).

First, the average annual mileage of a passenger car was calculated, so that the average mileage of a 21-year-old vehicle (reference year 2012) could be determined. The resulting value pairs, consisting of the age of the car and the corresponding mileage, could be combined with the age distribution when the car was scrapped. For this purpose, the distribution published by Weymar and Finkbeiner

[3] Organosheets are plate-shaped semi-finished fiber composite products with a thermoplastic matrix that can be easily reshaped on a large scale for subsequent manufacturing steps.

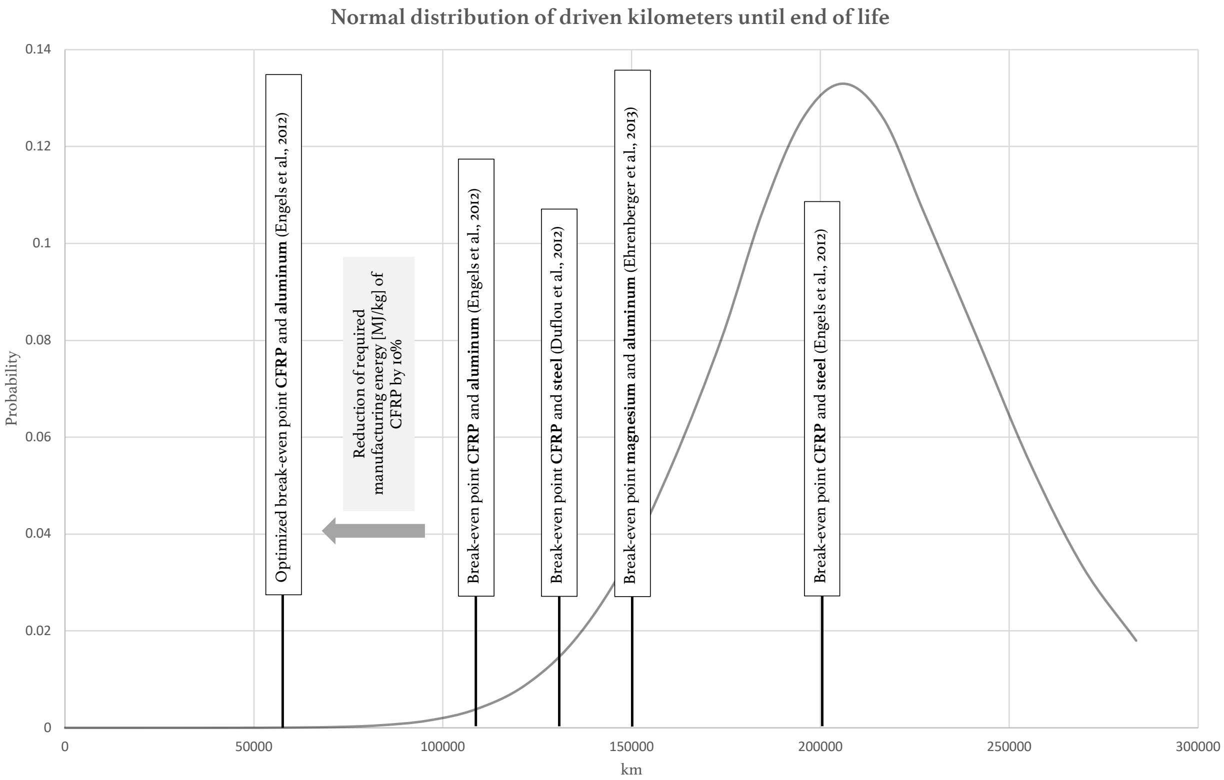

Figure 2: Normal distribution of driven kilometers of a passenger vehicle until end of life in Germany

(2016) was approximated using a normal distribution (main value 16 years and standard deviation 3 years) and the x-values "age in years" were replaced with the new x-values "total kilometers driven as a function of age". The result is shown in Figure 2.

As stated, one of the most important considerations in the context of sustainable lightweight is the calculation of the break-even point, meaning that the higher negative environmental impacts of a composite material during production and end-of-life are amortized by a more environmentally friendly use phase. Again, a high variety of underlying assumptions for LCA calculation could be observed from the literature. For demonstration, we added some break-even points in the distribution curve of Figure 2 that show that the majority of scrapped vehicles were able to achieve a positive environmental footprint during the use phase.[4]

Approaches of Sustainability-Oriented Technology Management

Although most of the break-even points are smaller than the mean value of the normal distribution (approximately 206,000 driven kilometers until end-of-life), there is always a certain proportion of vehicles that cannot compensate the negative environmental footprint of the used materials. In order to improve the lifecycle impact of these vehicles, two main approaches can therefore be applied:

– Shifting the break-even points to the left so that they are met by more vehicles (i.e., the distribution remains the same)

– Shifting the entire distribution to the right (i.e., increase of the mean value while break-even points remain the same)

[4]The points shown in Figure 2 name the material with the more negative environmental footprint first, based on manufacturing processes (Duflou et al., 2012; Ehrenberger et al., 2013; Engels et al., 2012). The second-named material is substituted by the first-named. In that way and from a decarbonization perspective, it is beneficial to substitute steel with CFRP after 200,000 driven kilometers (Engels et al., 2012).

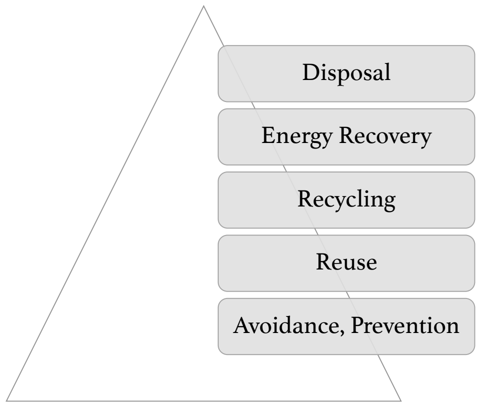

Figure 3: Waste hierarchy pyramid (based on Van Ewijk and Stegemann (2016))

The former approach is also illustrated in more detail in Figure 2. Engels et al. (2012) underlines that a 10% minimization of the required production energy of CFRP leads to a high decrease of the break-even point (as indicated by the arrow). Hence, we argue that on this basis the importance of continuous optimization, especially with regard to manufacturing processes must be emphasized within a sustainability-oriented technology management.

The second issue – the shift of the distribution to the right – has a much higher significance for *strategic* technology management. As explained, the mean value is influenced by the factors "age of the vehicle at end-of-life" and the "annual kilometers by the vehicle". If the mean value is to increase over time, these two influencing factors must also increase.

Increasing the life time of a vehicle can be achieved, for example, by promoting and supporting the market acceptance of a longer usage and by expanding repair options and services. Further, it becomes crucial to avoid planned obsolescence and therefore to design technical components in such a way they can be used for many hundreds of thousands of kilometers without causing damage (Rivera and Lallmahomed, 2015).

An increase of driven kilometers per year and vehicle might be realized through higher technical efficiency and thus an improved cost-effective operation of the cars. Another example might be a higher intensity of the utilization. In private ownership, a car is not used for the majority of its lifetime so that an increasing demand of car-sharing services will also result in improved environmental footprints.

2.4 End-of-Life Phase

So far, the discussion of sustainable lightweight materials has focused primarily on aspects of decarbonization (ecological footprint, LCA analyses, break-even scenarios), however, in the end-of-life context, the focus shifts to aspects of circular economy and circular material streams. In this sense, challenges can arise in sustainability-oriented technology management, since materials that contribute to decarbonization are not necessarily appropriate for circular economy purposes.

The waste hierarchy model (see Figure 3) commonly used in environmental management distinguishes between different scenarios for the end-of-life of a component or material (Van Ewijk and Stegemann, 2016). The model suggests that the waste prevention and avoidance strategy should be pursued first – only then strategies of reuse, recycling, (energy) recovery and disposal (landfill) should be considered in a descending order (Ghisellini et al., 2016; Kirchherr et al., 2017; Velenturf and Purnell, 2021). A major challenge of recycling is the quality decrease of the recycled material (secondary material) compared to the original material (primary or virgin material). The phenomenon of material depreciation as a result of recycling, also known as "downcycling", means that materials are only recycled to a certain extent and can then no longer be used in a meaningful way or being used in lower-quality applications (Henning and Moeller, 2011; Ladhari et al., 2021; Schirmeister and Mülhaupt, 2022).

Due to their heterogeneity, composite materials are subject to severe challenges in the context of downcycling (Chatziparaskeva et al., 2022; Herrmann et al., 2018; Niemeyer and Ziegmann, 2012). By implementing substantially downcycled composites in parts and components, the challenges of limited recyclability is transferred to the product lifecycle of the next product. In addition, various studies have demonstrated that the full recycling potential of these materials is not fully exploited so that "[o]nly 34 tons of CFRP are estimated to be available for recycling from a total amount of 1.2 million tons in 2050" (Herrmann et al., 2018, p. 666).

Since the usage of steel and aluminum as lightweight materials is considerably higher compared to composites, the consolidation and local recycling processes for the former are significantly simpler. Despite the increasing importance of composites, these materials still account for only a small proportion of all materials used, yet they are widely distributed globally. Local recycling strategies have little or no economic viability due to low volumes and the necessity for specialized separation technologies. The transport and consolidation of rather small quantities to centralized recycling facilities is therefore not economically viable (Herrmann et al., 2018; LAGA, 2019). Following this argumentation, design-for-circularity becomes crucial, that "covers how the aim of design should change in a sustainable circular economy by combining design efforts at the levels of material selection and product design, supply chains and overarching industrial systems [...] in an effort to create resource circulating societies [...]" (Velenturf and Purnell, 2021, p. 1449). In that sense, Herrmann et al. (2018) underlines that the existence of a market for secondary materials and applications is equally important for a long-term economic and sustainable recycling strategy. However, studies show that recycling of composites, such as GFRP whose main users are the wind turbine, boat building and automotive industries, is not practiced for economic reasons (Chatziparaskeva et al., 2022; LAGA, 2019).

In summary, it can be shown that for a holistic sustainability evaluation of materials, any challenging end-of-life scenario must be taken into account as early as possible within product development. In this context, technology management must address and reveal these trade-offs between decarbonization and circular economy as well as the use of secondary raw materials with limited recyclability.

2.5 Absolute Perspectives of Sustainable Lightweight Design

So far, the challenges of sustainable lightweight design along a typical product lifecycle have been presented and briefly explained. We now take a more absolute perspective and illustrate the importance of the topic by means of two commonly used frameworks within the discussion on sustainability management and circular economy.

2.5.1 From Relative to Absolute Sustainability

The consideration and ecological improvement of individual life phases – from material selection, production, use phase to the end-of-life – represents the basic frame of any lifecycle engineering approach.

As demonstrated earlier, lifecycle phases might be analyzed and optimized in isolation, yet results must be applied to the entire lifecycle of a product. According to Hauschild et al. this approach fosters the understanding that lifecycle engineering is "defined as sustainability-oriented product development activities within the scope of one to several product lifecycles" (2017, p. 6).

This view, also referred to as bottom-up thinking, can be interpreted as a representative of *eco-efficiency* measures of sustainability management that try to improve the environmental footprint of technologies without scrutinizing the technology itself (Braungart and McDonough, 2002; Dyllick and Hockerts, 2002; Hauschild et al., 2017; Young and Tilley, 2006). However, increasing efficiency does not necessarily have to lead to more sustainable results in an *eco-effective* sense, as the critical environmental aspects of a certain technology may not be completely eliminated. In that sense eco-efficiency is often criticized as it "works within the same system that caused the problem in the first place" (Braungart and McDonough, 2002, p. 62).

Scholars emphasize that the underlying concept of lifecycle engineering must be oriented towards an *absolute* understanding of sustainability that considers the planetary boundaries first, which is also referred to as top-down approach (Alting and Jøgensen, 1993; Hauschild et al., 2017; Herrmann et al.,

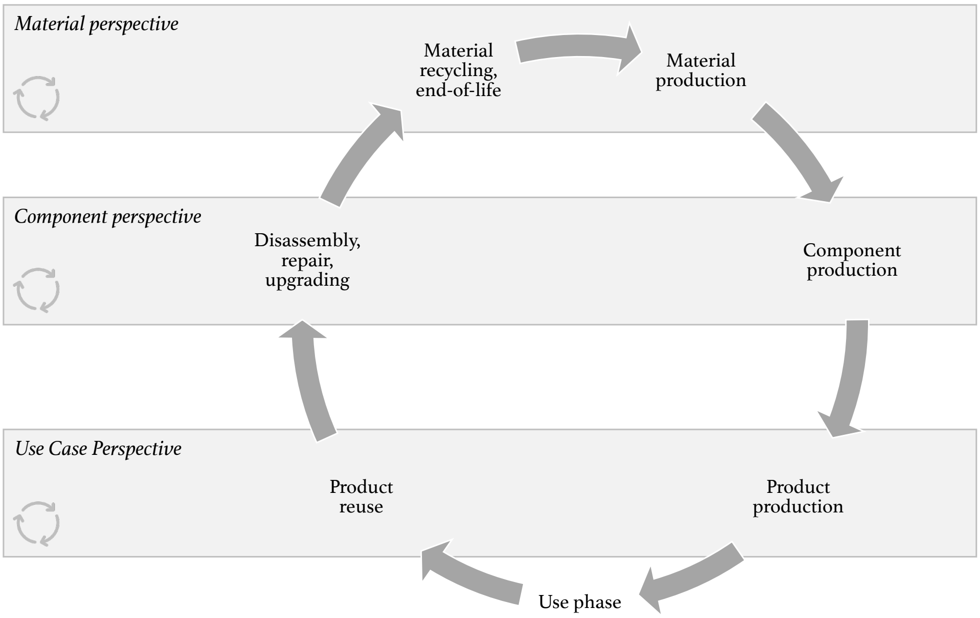

Figure 4: Resource States framework (based on Blomsma and Tennant (2020))

2018). Hence, Herrmann et al. (2018) translates these two perspectives into the context of sustainable lightweight materials asking if the use of any lightweight material just improves the ecological performance (relative perspective) or if the use if any lightweight material is truly environmentally sustainable (absolute perspective). Given the challenges presented, these questions appear to be highly justified.

2.5.2 From Materials to Components and Applications

A simple separation in materials, components and applications allows the aforementioned challenges to be further conceptualized. As a basis serves the "Resource States framework" developed by Blomsma and Tennant, which builds on the criticism of the academic debate of circular economy that does not sufficiently cover the question "whether to approach resource circulation from the perspective of elements, molecules or materials; or whether to adopt the perspective of products or finished goods" (2020, p. 1). In this sense circularity can be designed and understood in various subsystems, i.e. circulating *products* as a result of reutilization and redistribution, circulating *components* as a result of disassembly, maintenance, repair and upgrading or eventually circulating *particles* as a result of material recycling.

As part of a holistic and absolute approach, it is essential to include all three perspectives equally in a technology impact assessment. For example, composite components can be reused in other products or components (Chatziparaskeva et al., 2022). Nevertheless, even in this scenario, it must be ensured that at some point the underlying material can circulate as the challenge of a limited recyclability does not "disappear" by using a circular component approach (Blomsma and Tennant, 2020).

It is therefore critical to consider if materials are chosen that can eventually only be landfilled or thermally utilized – even if parts might temporarily circulate (e.g., through disassembly and reuse of a composite part in a vehicle). One example of this challenge is illustrated by Chatziparaskeva et al. (2022) who cites the case of wind blades made of GFRP that are reused on a playground in Rotterdam as a consequence of poor recyclability.

2.6 Interim Conclusion

In order to compile the multifaceted results, the challenges along the product lifecycle are summarized in Table 1 and thus provide the basis for the industry perspective considered hereafter.

Challenge	Description
High and growing market demand	Strong increase in the substitution of materials, especially in the automotive and aerospace sectors, by lightweight (composite) materials with uncertain disposal scenarios
Ecological evaluation	Limited ability to quantify the ecological impact of a material due to its complexity, lack of traceability, influences of manufacturing processes and unknown transport routes; average values often show a high degree of variance
Production efficiency increase	Reduction of production energy and waste generation within manufacturing phase
Determination of break-even points	Lack of a harmonized approach to determine total mileage in the automotive sector; necessity to include further impact categories in lifecycle assessments
Optimization of break-even points	Influence on break-even points through production optimization, promotion of sharing-economy initiatives and avoidance of (planned) obsolescence
Undefined and multifaceted end-of-life scenarios	Quality loss of the recycled materials compared to the primary material (downcycling), limited use of recycling potential of materials, unprofitability of recycling products due to a lack of market demand for materials
Absolute and relative sustainability	Lightweight design between eco-efficiency and eco-effectiveness; necessary reorientation of the industry towards the implementation of circular approaches
Circular economy in the Resource States framework	Differentiated view of possible measures on various circular subsystems consisting of materials, components or finished products

Table 1: Challenges of ecological lightweight composites

3 Industry Perspectives of Sustainable Lightweight Design

To get a first impression of how the identified challenges are perceived within the industry we conducted semi-structured interviews (n=8) with experts and managers from automotive, aerospace as well as start-ups and municipal agencies. We were particularly interested in initial solution proposals and the role of (strategic) technology management. A graphical representation of the interview results is illustrated in Figure 5.

We used a semi-structured interview guide shown below, which at the same time provided thematically separated categories for the following analysis of the individual interview data (Kuckartz, 2018; Meuser and Nagel, 1991). The content analysis of the interviews was primarily aimed at identifying general, technical and economic key messages. Extended periods of silence or any follow-up questions of the experts do not contain any meaningful contribution with decisive value for answering the research question(s). The related thematic overviews are presented subsequently.

The Connection of Composite Lightweight Design and Sustainability
In what way do you think composite lightweight design and sustainability are connected? Does composite lightweight design necessarily lead to more sustainable, environmentally friendly technologies?

Lightweight design can lead to a direct contribution to more sustainable technologies due to fewer resource and energy demand during the use phase and efficiency improvements. However, six of the eight interviewees already mentioned the challenging end-of-life issue of composites which is seen as destructive in the context of ecological sustainability. One expert explained that "*there is not necessarily a causal relationship between lightweight design and sustainability, although they are interrelated*". Another stated that the use of high-tech lightweight materials is only appropriate for products with a long lifecycle, not for mass products such as cars or fast moving consumer goods. Regarding the example of the automotive industry an interviewee emphasized that "*if the main focus in the develop-*

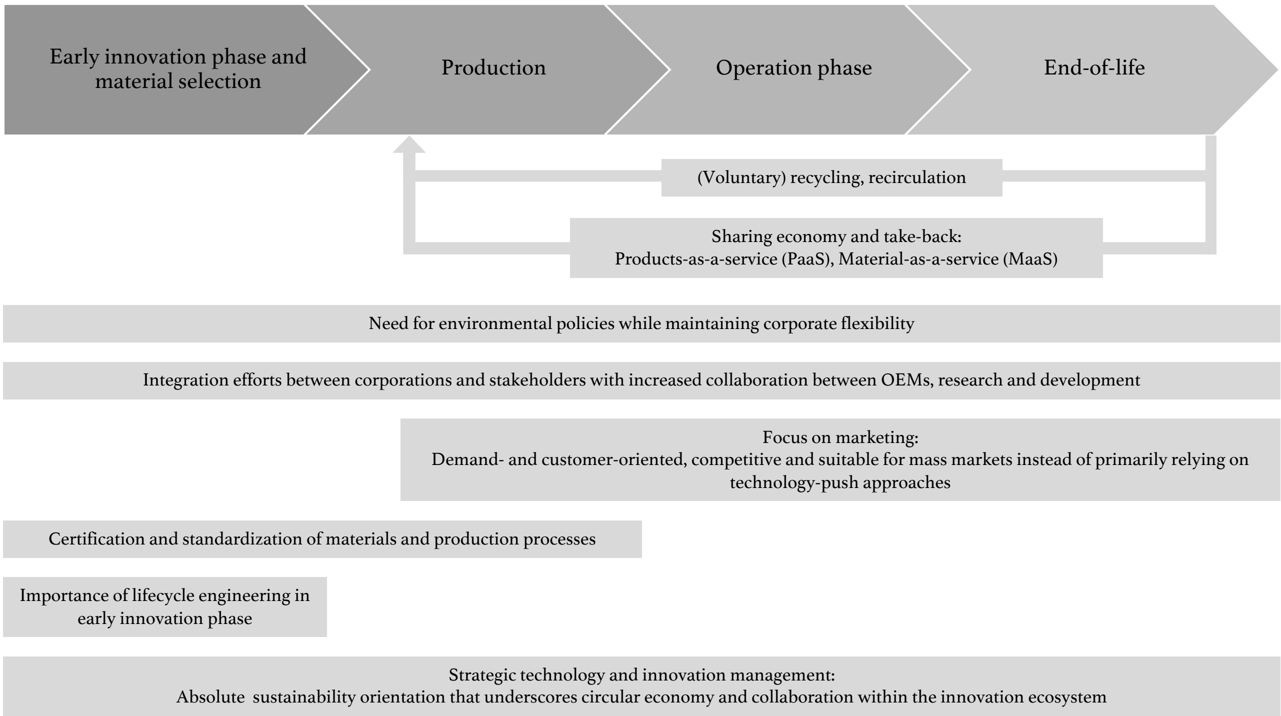

Figure 5: Solution proposals to encounter identified challenges (based on expert interview study)

ment of a car is on environmental compatibility, composites should not be used" thus highlighting the identified challenge in the context of circular economy.

Optimization Potential of Lightweight Design along the Product Lifecycle
Alongside a typical product lifecycle – where do you foresee the most potential for making lightweight composite materials more environmentally friendly?

In general, the answers to this question showed varying results. However, a certain emphasis could be identified with regard to material selection in the early innovation phase, production optimization as well as the improvement of the end-of-life phase. Therefore, the primary challenge is to mitigate the difficult end-of-life issues of composites, e.g., by avoiding waste in production as far as possible. Experts shared that "*a major potential for making materials more environmentally friendly is in the material selection phase. This is the easiest and most effective way to influence which materials are used and how they will behave in the end-of-life phase*". Especially with regard to chapter four of this working paper, one interviewee highlights an interesting view that "*it is important that composites such as CFRP are not used everywhere, but rather with careful attention – for applications where it really makes sense and for products that have long lifecycles*".

Demand for Secondary Materials
What are the causes of a low demand of secondary, recycled composites and materials?

Again, a wide variety of answers has been recorded. Interestingly, challenges within marketing were highlighted. In many industries, secondary materials have a rather poor image, because "downcycled materials" are generally perceived as being inferior, although they still have outstanding properties in some cases. An expert suggested that "*recycled CFRP has not been successful in marketing itself in such a way that it reaches a broad application*". Furthermore, greenwashing and lack of transparency within the industry were also criticized.

Lightweight Design between Sustainability, Cost and Performance Constraints
In your view, do sustainable materials have a realistic market potential, even if they are more expensive than virgin materials and a certain decrease in technological performance has to be accepted?

Four of the seven experts interviewed on this question do not see any market opportunity in sustainable, but more expensive and possibly technically inferior materials. The reason for this is the (purchase) decision of engineers, managers and consumers, who value functionality and affordability above sustainability. Market success would only be feasible with the appropriate legal conditions.

Possible Measures to Encounter the Identified Challenges
What is your perspective on (a) the broader implementation of lifecycle engineering within the development process?, (b) an increased emphasis on environmental policies?, (c) the implementation of measures to foster circularity and sufficiency, such as sharing economy?, (d) an increased collaboration between manufacturers (OEMs), suppliers and research?

The experts support the promotion of lifecycle engineering, even if in some industries, such as aerospace environmentally oriented material strategies only have a low importance. Governmental intervention and regulation might be useful, as long as a certain degree of corporate flexibility is still maintained. One expert suggested that "*one possible solution to improve the overall situation would be to use standardized and certified materials in a product-as-a-service or material-as-a-service system. If these are returned within a sharing economy and customers pay for the services instead of the actual products, this would be an excellent possibility to develop circular materials. Companies would receive materials with the return of the products*". Another interviewee had a similar view and stated that "*the more research, development, suppliers and companies cooperate with each other and the more precise, standardized material and information flows exist, the better. Advantages would arise for all partners involved*".

4 The Role of Frugal Engineering

Finally, we will discuss the contribution of frugality and frugal engineering in the context of the above-mentioned challenges and management strategies. We therefore provide an overview of the academic origin of frugality, state possible definitions of frugal innovations, and explain the connection to sustainable product development. We then aim to develop future research directions that will investigate the approaches of frugal engineering in the context of sustainable lightweight design.

4.1 Frugal Innovation and Constraint-Based Thinking

Frugal innovations stem from the debate on how emerging markets can be penetrated with affordable and good-enough product innovations to promote the prosperity of these nations on the one side, and to enter new growth markets, especially for Western incumbents, on the other (Brem, 2017; Govindarajan and Trimble, 2012; Prahalad, 2005; Radjou and Prabhu, 2015).

For companies and new product development it is particularly important to design innovations that fit the respective application accurately, so that the resulting outcomes are as affordable as possible while at the same time being robust and of good quality (Rao, 2013; Weyrauch and Herstatt, 2016; Winkler et al., 2019). Frugal innovations are therefore also referred to as *affordable green excellence* or *good-enough* innovations (Herstatt and Tiwari, 2020; Tiwari and Herstatt, 2020). They represent product features and performances that are neither too good nor too bad from a user perspective and therefore represent a kind of *golden mean of innovation* (Tiwari et al., 2016; Tiwari and Herstatt, 2013).

Especially in the context of emerging markets, frugal engineering proves to be an effective management method due to numerous innovation constraints, such as financial, resource or institutional limitations (Agarwal et al., 2021; Bhatti et al., 2018). A frugal innovation therefore pursues the primary goal of "doing more with less (for more)" and therefore rejects overfulfillment of required features of products (Radjou and Prabhu, 2015). Weyrauch and Herstatt (2016) provide three major characteristics of a frugal innovation that are widely shared in academia. Based on literature review and expert interviews they define a frugal innovation as a product with concentration on core functionalities and an optimized performance level while being affordable and achieving a significant cost reduction at the same time. Other conceptualizations (not further detailed within this working paper) include research about frugal mindset (Krohn and Herstatt, 2018) and frugal processes (Knizkov and Arlinghaus, 2020; Soni and Krishnan, 2014).

By focusing on the innovation process, frugal engineering does not merely pursue the goal of reducing features and performances alone, but rather evaluates which attributes an innovation outcome needs to offer, where upgrades need to be made, and where reductions can lead to a more suitable product (Beise-Zee et al., 2021).

With regard to the increasing academic and practical interest in sustainable development and corporate sustainability, frugal innovations might represent an essential strategy for companies to holistically improve the sustainability performance of their innovations (Achtelik et al., 2022; Albert, 2019; Dima et al., 2022; Hossain, 2021; Rosca et al., 2017). In that sense Albert states that "relating to resources [...], it is argued that for frugal innovation resources are used economic/frugal/limited/less, are conserved, are saved, are reduced, are lower consumed, are minimized, and that more sustainable and local resources are used. Frugal innovation improves/maximizes energy and material efficiency. Substitution (with local and renewable materials and processes), as well as sufficiency, is described as part of the ecological sustainability of frugal innovation. Furthermore, frugal innovation creates value from waste (waste as a resource), existing components and materials are reused, recycling is performed instead of sourcing and due to modularity and ease of repair, the effective life of frugal innovation is extended" (2019, pp. 5-6).

The combination of reduction, sustainability and affordability gives rise to investigate the previously discussed challenges of ecological lightweight design through the theoretical lens of frugality and to derive possible research directions and questions.

4.2 Frugal Engineering and Sustainable Material Transition: A Research Agenda

In particular, we build our argumentation on two aspects that the interviews revealed. First, one expert stated that high-tech composites should only be used when really necessary for the respective use case. Again, this fact demonstrates that frugal engineering can support managers and engineers to critically assess necessary performances and thus avoid overengineering of products. In doing so, frugal engineering carefully manages the underlying innovation constraints related to sustainability, lightweight design, cost and quality, instead of pursuing technology-driven paradigms that might lead to an overfulfillment of features or performances.

In this sense, we expect that composites might be implemented in some products, although other materials would be more suitable based on a *holistic* evaluation and after careful consideration of various innovation constraints. Following this line of reasoning, composites would certainly be advantageous from a purely lightweight design and technology-driven point of view. In a holistic context that increasingly integrates (absolute) sustainability, development costs and affordability (from the customer's perspective), the circumstances may look different. Furthermore, innovation requirements that have driven the implementation and diffusion of composites in the first place must be critically scrutinized for their necessity. There is no doubt that these materials are well justified in many applications such as aerospace. However, in view of the increasing environmental orientation of companies and the decisive role of materials in achieving a circular economy, it is important to reduce the increasing diffusion of particles which uncertain or even harmful disposal scenarios.

Secondly, due to downcycling, recycled materials experience a negative perception in the industry, so that possible market demands remain low and recycling processes are often unprofitable. However, composite waste (e.g., recycled carbon fiber) in particular still demonstrates outstanding properties that would still be quite suitable for some applications. Arguably, more sustainable and less expensive materials should not be abandoned just because they have the stigma of being supposedly inferior.

A frugal approach critically scrutinizes the feasibility of "inferior" technological solutions and therefore avoids such possible stigma and biased perceptions. If the use of composites is the best holistic solution, a frugal engineering mindset allows greater consideration of secondary materials. Frugal innovation principles do not seek the absolute best technology but evaluate what is most suitable for the respective innovation.

For future research, it would therefore be interesting to investigate to what extent frugal approaches succeed in mitigating overengineering and which improvements can actually be achieved in search for affordable, yet good-enough and ecological sustainable (composite) materials. For a more theoretical discussion, it is just as important to understand where the phenomenon of overengineering and the negative association with recycled materials originates, why technology-driven paradigms are generally favored over a general market, environmental and use case orientation, and what specific methods can be used to introduce frugal engineering approaches in an organization.

5 Conclusion

This working paper has analyzed the challenges of sustainable lightweight design using the example of high-tech composite materials along a typical product lifecycle. One major issue identified is the optimization of the eco-efficiency of products, such as reducing the ecological footprint or the decarbonization within the use phase. At the same time, however, the use of composites is often contrary to the demands of circular material streams resulting in challenging end-of-life phases as well as a lack of advancement of absolute sustainability. Using an expert interview study with participants of diverse industries such as automotive, aviation and aerospace the identified challenges of the literature could be confirmed and extended.

In particular, the negative perception of recycled materials compared to virgin materials as well as the technology-driven utilization of composites give rise to evaluate the challenges using the theoretical lens of frugal innovation and engineering in greater depth for further research.

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