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Incorporating Lightweight Design and Design for Sustainability in Product Development – A Meta-Synthesis Based on a Systematic Literature Review

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Abstract: In today's product development, a growing emphasis on sustainability is emerging, highlighting the increasing significance of lightweight design for resource conservation. However, its synergies with design for sustainability remain ambiguous, offering an energy-efficient and emissions-reduced use phase but requiring complex processes throughout other stages of the product life cycle. Thus, systematic approaches for harmonizing lightweight design with design for sustainability are needed. Addressing this, the present work presents three approaches for incorporating both paradigms based on a meta-synthesis from a systematic literature review.

Keywords: Lightweight Design, Design for Sustainability, Product Development, Design for X (DfX)

1 Introduction

In times of progressive global warming, product development is more than ever challenged to contribute to counteracting climate change by innovating efficient products and systems as sustainable as possible. This requires cooperation and collaboration, preferably simultaneously activating all existing levers to enable genuine transformation. This gets evident by the increasing research emphasis within the paradigms of design for environment (eco-design) and sustainability (Brenner and Pflitsch, 2017) as well as regarding the circular economy (with design for circularity) (Kirchherr et al., 2017). Core concepts of the sustainable design paradigm encompass the reduction of environmental impacts (Hauschild, 2015), the closing, slowing, and narrowing of product and material loops (ISO/DIS 59004, 2023), as well as the extension of the useful life of products or components (Bocken et al., 2016).

Furthermore, lightweight design has also become one priority for product development, as it is historically recognized offering benefits in terms of environmental sustainability (Herrmann et al., 2018). Thanks to the targeted and reduced consumption of materials (Choudry et al., 2018) and energy (Monteiro et al., 2022) in products and systems along the entire value chain and the product life cycle, lightweight design may contribute to the conservation of resources and, in consequence, to the minimization of environmental impacts. Meanwhile, not all lightweight products are sustainable, criticisms are emerging, as sophisticated lightweight solutions tend to have difficult end-of-life conditions to maintaining their value retention due to their complex and laborious material and manufacturing design (Das, 2021). Therefore, identifying the synergies and conflicts between lightweight design and other design for sustainability strategies like implementing the circular economy represents a major upcoming challenge, which can only be tackled using a holistic and systematic approach (König et al., 2024).

The present work investigates the relationship between lightweight design and design for sustainability using a meta-synthesis drawing upon a systematic literature review (SLR) and synthesizes three methodological approaches to incorporate both paradigms within product development. Therefore, in Section 2, the histories, definitions, and fundamental principles of lightweight design and design for sustainability are outlined. Motivated by the emerging challenges facing us in today's world, a SLR is carried out in the intersecting field of these two paradigms, whereby the research method is presented in Section 3. Due to the complexity of the SLR, the results cannot be detailed in this publication. Instead, their evaluation is based on a meta-synthesis with presenting the definition of three approaches to incorporate both, lightweight design and design for sustainability, along product development regarding the entire product life cycle as a discussion in Section 4. Based on them, implications for engineering are presented in Section 5. A brief summary as well as an outlook on future work is provided in Section 6.

2 Background and Fundamental Principles

2.1 Lightweight Design

2.1.1 The History and Motivation of Lightweight Design

The definition of the term 'lightweight design' can look back on a long history since the middle of the 20th century shaped by various perspectives and goals. The starting point dates to the 1950s and 60s, with early definitions like that of

Schapitz (1963). At that time, the motivation for lightweight design was driven by the needs of the aviation industry (Shanley, 1952), particularly the necessity for a weight reduction in aircrafts to enable their functionalities as well as to enhance their performance. The fundamental idea was to design materials and structures to fulfill the product's function.

Over time, lightweight design expanded beyond a mere weight reduction of a technical system to enable its functionality. Wiedemann (1986) emphasized the significance of stress-appropriate construction and mechanical optimization in lightweight design. Thus, lightweight design was not only driven by enabling the functionality of a product or system but also by enhancing its technical value. Especially regarding the field of motorsport (Mantovani et al., 2018), this motivation remains evident even today.

Concurrently, cost reduction through lightweight design played a pivotal role as it is crucial for business success and longevity. Klein (1989) underscored that lightweight design should not only lead to improved properties and performance but also be economically viable. This is notably evident until today within both the automotive industry (Kelly and Dai, 2021) and aerospace (Zhu et al., 2018). In this context, cost-related conflicts emerge, concerning acceptable additional expenses for developing lighter products in contrast to the cost savings in energy consumption during the use phase due to the reduced weight of the resulting solution (Caffrey et al., 2015).

While the environmental benefits of lightweight design were initially less prominent, this changed over time. Only more recently, such as in the works of Schmidt et al. (2004), did the spotlight shine on how lightweight design could also have positive environmental implications, reducing energy consumption during usage as well as minimizing emissions. The most comprehensive cross-industry analysis of lightweighting concepts with regard to environmental sustainability is attributed to Herrmann et al. (2018). They formed a framework from the 'life cycle assessment' (LCA) (ISO 14040, 2006) for the analysis of lightweight solutions emphasizing a life cycle engineering. The identification of relevant sustainability criteria as methodologically discussed by Hallstedt (2017) may also be a key topic for sustainability-oriented lightweight design. In this regard, König and Vielhaber (2024) already performed a preliminary analysis regarding environmental and technical sustainability criteria.

2.1.2 A Generic Definition for Lightweight Design

Through these diverse perspectives and emphases, a multitude of definitions of lightweight design have emerged over the years. Some definitions, like those of Kaspar and Vielhaber (2016), are more complex and in great detail, encompassing various aspects, viewpoints and boundary conditions. Further definitions from other scientists, like those of Wiedemann (2007) or Albers and Burkhardt (2011), may be less complex and in less detail but place a stronger focus on specific aspects of lightweight design that hold particular relevance in a given context. Drawing upon the historical progression and diversity of definitions regarding different aspects, goals and boundary conditions of lightweight design, the authors propose the following generic definition:

> *"Lightweight design is an engineering paradigm employing the weight reduction of technical systems as the means to realize one or more overarching development objectives while meeting various boundary conditions."*

Fundamentally, lightweight design mainly does not constitute as an end in itself but rather can serve the realization of other development objectives. Thereby, such goals may be of a technical nature, where the implementation of lightweight design becomes necessary for rendering a product's functionality or the enhancement of its value. Furthermore, objectives may encompass economic considerations, leveraging lightweight design to reduce life cycle costs, or environmental imperatives, harnessing it to minimize environmental impacts. If there are several distinct aspects aiming at the implementation of a weight reduction through lightweight design, on the one hand, these can flow together into the overarching development objectives (e.g., lightweight design to enhance the functionality *and* to reduce the environmental impacts). The development goals must then be compared with each other, may resulting in either synergies or conflicts. On the other hand, the multiple aspects can restrict each other if they are divided into overarching development goals and boundary conditions (e.g., lightweight design to reduce the environmental effects *while* maintaining a specific cost limit for production). In this case, the boundary conditions serve as restrictions of the solution space for the implementation of lightweight design aiming at realizing the development goals. Thus, within the presented definition, these aspects can be integrated and specified in a given context.

The primary means of lightweight design, the weight reduction of technical systems, can be achieved In various ways. These include the lightweight design strategies (form, material, manufacturing, and system lightweight design (Ellenrieder et al., 2013; Kopp et al., 2011)) or various methodologies (e.g., the 'SyProLei' framework of Kaspar et al. (2022)) applicable along the product development process.

2.2 Design for Sustainability

2.2.1 A Brief Insight into the History of Design for Sustainability

The history of design for sustainability is rooted in the growing recognition of the environmental and social impacts of climate change in the 1980s and 1990s. Pioneering approaches for integrating sustainability considerations in product development emerged from McDonough and Braungart (2002), advocating 'cradle-to-cradle design'. More recently, the topic gained further attention by the publication of the '17 sustainable development goals' (UN, 2015), setting a comprehensive framework for sustainable practices in Europe. Thereby, notable individual methods gained prominence, such as the LCA (ISO 14040, 2006) and the 'product environmental footprint' (Manfredi et al., 2012), offering systematic and comprehensive approaches to assess and, consequently, improve the environmental impacts of products. As a consequence of the introduction of the 'Corporate Sustainability Reporting Directive' (CSRD) (European Parliament, Council of the European Union, 2024), these methods will increasingly gain importance for companies (Stridsland et al., 2023). Looking ahead, the forthcoming standard ISO 59004, focusing on the implementation of the circular economy in product development (ISO/DIS 59004, 2023), signifies an ongoing commitment to advancing sustainability principles in product development. Thereby, not only the reduction of impacts is a key concept, but rather the closing, slowing and narrowing of product and material loops. Additional pivotal principles listed within the standard encompass life cycle engineering, promoting resource efficiency, and innovating novel business models (e.g., product as a service).

2.2.2 Fundamental Principles of Design for Sustainability

Design for sustainability fundamentally represents a paradigm shift in design thinking, emphasizing holistic approaches that integrate environmental, social, and economic considerations, also known as the triple bottom line concept (Elkington and Rowlands, 1999). The integration of sustainability aspects into products involves three overarching strategies (Kaspar and Vielhaber, 2017; König et al., 2023a):

- **(Eco-)Efficiency** focuses on optimizing resource use and minimizing waste throughout the product's life cycle (same functionality with less or optimized resource use).
- **Consistency** or **(eco-)effectiveness** emphasizes the harmonization of a product with larger socio-ecological systems, ensuring that it is not only less bad but may be beneficial to the environment.
- **Sufficiency** centers on meeting essential needs while avoiding overconsumption.

Regarding the assessment of environmental sustainability, the ISO 14040 standard (ISO 14040, 2006) highlights four key aspects to be considered:

- The **system perspective** involves considering the entire product system, acknowledging interconnections and dependencies within a broader context (e.g., supply chains).
- The **life cycle perspective** entails scrutinizing the product's entire life cycle, from raw material extraction to the end-of-life treatment.
- Regarding the **impact assessment**, the objective is to understand and assess the magnitude and importance of potential environmental impacts for a product system across its entire life cycle.
- By comparing **functional units**, the underlying product performance is used as the reference when evaluating several technical systems allowing for comparing on purpose-specific quantities.

In essence, these strategies and principles collectively facilitate a comprehensive approach to incorporate sustainability in product development endeavors. Additionally, Hallstedt et al. (2013) identified key elements for the successful integration of a strategic sustainability perspective in companies. These encompass organizational structuring, internal procedural mechanisms, role allocations, and the utilization of appropriate tools, each of them probably also relevant for lightweighting efforts.

2.3 Goal and Scope of this Research

Based on the histories, the definitions and the fundamental principles of lightweight design and design for sustainability, the present work aims to describe the possible incorporation of both paradigms along the product development process. Therefore, the following research question is pursued:

"How can the two design paradigms, lightweight design and design for sustainability, be incorporated along the product development process?"

It is important to note that product development processes are generally individual and vary from organization to organization. Likewise, lightweighting solutions may represent individual technological innovations (e.g., novel materials, production or joining technologies). Thus, in order to answer this research question, a SLR was carried out, which reflects a broad range of scientific works and industrial practices. Considering this context, the present work focuses not on the evaluation of individual material or product solutions, but instead, on the identification of generic and methodological approaches representing the majority of product developments activities across various industries and emphasizing lightweighting and sustainability. Thereby, only the building sector is defined as out-of-scope since it adopts different approaches and ways of thinking. Regarding the concepts of design for sustainability, the focus is only on the environmental aspects.

3 Research Method: A Systematic Literature Review

The SLR represents a way of identifying key scholarly contributions and synthesizing scientific evidence while reducing uncertainties, ensuring objectivity and reproducibility in the results (Lame, 2019). As the aim of this publication is to delineate current research practices, providing insights into both academic and industrial realms, the SLR was chosen as research method to build the basis for answering the research question. The SLR in the present work is based on the PRISMA-statement (PRISMA-P Group et al., 2015). In the next subsection, the procedure of conducting the review in the intersecting field of lightweight design and design for sustainability is presented, followed by the outlining its results.

3.1 The Methodology of the Systematic Literature Review

The SLR has been carried out between April and September 2023. The keywords employed in the search strings are illustrated in Figure 1. Each search string was constructed using a word or combination of words from the lightweight design paradigm (left, blue) appearing in conjunction with a word or combination of words from the design for sustainability paradigm (right, green). Utilizing these search strings, the searches were conducted across three indexed, electronic databases: ‘Web of Science’, ‘IEEE Xplore’ and ‘Science Direct’. Thereby, the search strings were only sought within the title of an entry. The occurrence of the strings in the abstract, the keyword list, or even the full text of an entry was excluded because of an extensively increasing effort in the analysis. Depending on the combination of keywords, this resulted in up to ten times the number of results. In contrast, no restrictions were placed on the search over the time period of a publication.

Figure 1. Keywords for the SLR within the intersecting field of lightweight design and design for sustainability

The keywords identification is mainly based on existing, individual reviews from both discussed design paradigms. In the field of lightweight design, Laufer et al. (2019) have laid the groundwork by identifying synonyms for the term ‘lightweight design’. Regarding design for sustainability, significant terms have been extracted from the publications of Brenner and Pflitsch (2017), Glavič and Lukman (2007), as well as Schäfer and Löwer (2020). They have been complemented by essential aspects of the circular economy due to their increasing relevance for design for sustainability, such as the resource value retention options, which are based on the work of Reike et al. (2018). In addition to terms derived from such existing reviews, an unstructured initial literature review has been conducted over the past years, resulting in the creation of a comprehensive research article database for the fields of lightweight design and design for sustainability. Based on the titles of these articles, additional terms were defined and logically supplemented, culminating in a comprehensive keyword list covering various aspects of both paradigms.

Based on the search strings resulting from the keyword combinations, all resulting entries were first saved (8,798 records; first step: identification) and then further screened (second step: screening) according to the procedure shown in Figure 2. In this second process step, various filters were applied to the resulting entries. First, all duplicates generated by merging the results of the three databases were excluded (1,281 duplicates removed). Subsequently, the screening of the entries' titles was used to exclude all entries that could not be assigned to product development (7,069 records excluded). This particularly included records from the fields of biology, chemistry, and medicine. By means of reviewing the abstracts, all articles that could be assigned to the building sector (per out-of-scope definition) or that did not have both a lightweight design and a design for sustainability emphasis were eliminated (332 records excluded). The screening process was conducted independently by two individuals. Discrepancies between the two were scrutinized and subsequently discussed to ensure minimal loss of entries while maintaining a comprehensive and as objective analysis as possible, according to standardized criteria.

The resulting full texts of all remaining titles were finally examined by both persons (third step: eligibility). This resulted in a further 107 exclusions, for which either the full text was not accessible, should have been already excluded from the analysis based on the criteria described above, or did not contain any specific motivation for the application of both, lightweight design, and design for sustainability. This yielded 189 records, for which a rough overview is provided in the next subsection.

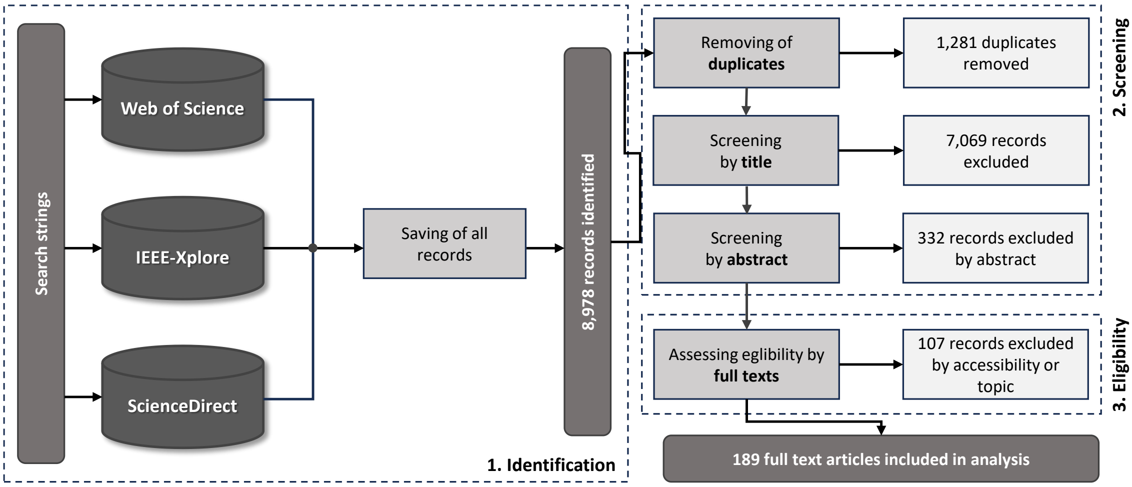

Figure 2. Procedure of full text acquisition for the SLR based on the PRISMA-statement (PRISMA-P Group et al., 2015)

3.2 A Short Overview of the Results

As a total of 189 publications were included in the research, not all articles can be discussed and presented individually and in detail. Nevertheless, Figure 3 shows a classification of the articles in terms of the categories of lightweight design, design for sustainability and the respective industry they address. In this context, individual articles may have addressed multiple aspects within the three categories. As we cannot present each entry as result of the SLR individually, the diagrams should be understood in terms of how the intersecting field of lightweight design and sustainability has generally been addressed so far.

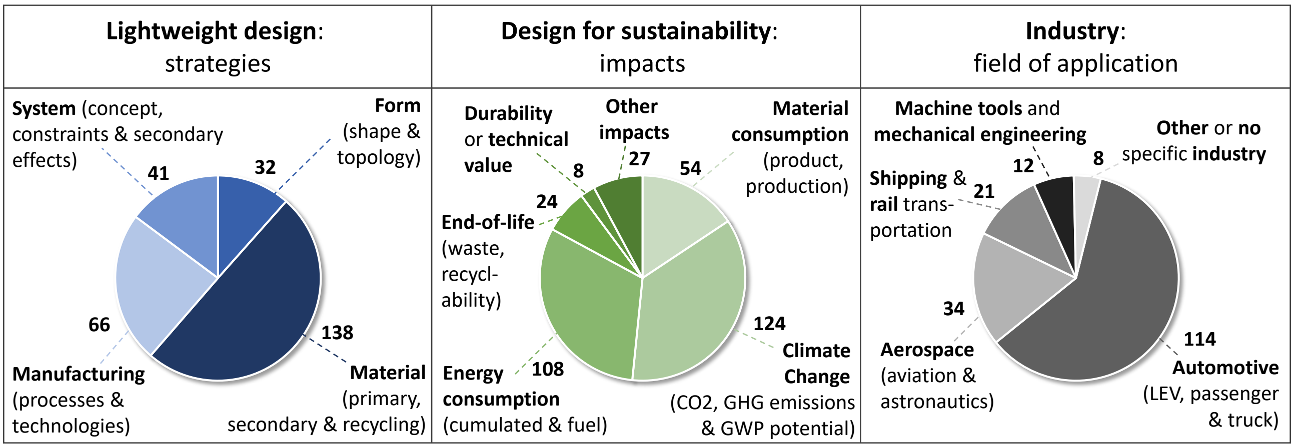

Figure 3. Results of the SLR and their classification within both paradigms, lightweight design (strategies), and design for sustainability (impacts), and within their field of application (industries); values indicating the number of full texts from the 189 records addressing the respective aspect

Having a look at the categorization of the results, it is obvious that the majority of the publications have a material perspective, deal with climate change as environmental indicator, and originate from the automotive industry. The category 'other impacts' in the field of design for sustainability covers aggregated impacts (e.g., the eco-indicator) or individual impact endpoint considerations (e.g., acidification potential), which only appeared in isolated cases. Other industries include the medical industry or energy generating plants. Thereby, also methodological frameworks not addressing a specific industry are categorized into this field of application.

4 Meta-Synthesis: Methodological Approaches for the Incorporation of Lightweight Design and Design for Sustainability in Product Development

Based on the SLR, a meta-synthesis, as described by Chrastina (2018), is performed to synthesize the findings. Thus, the careful processing and comprehensive screening of the full texts emerging from the presented SLR and their careful analysis with regard to the process of product development essentially allows three approaches for incorporating both design paradigms along product development to be defined. They are shown schematically in Figure 4 and will be discussed in the following subsections while illustrating some examples from the SLR for each approach. In this regard, two approaches covering a sequential application of both paradigms are initially presented (Section 4.1 and 4.2), followed by an explanation of the third approach involving the simultaneous application of both paradigms (Section 4.3).

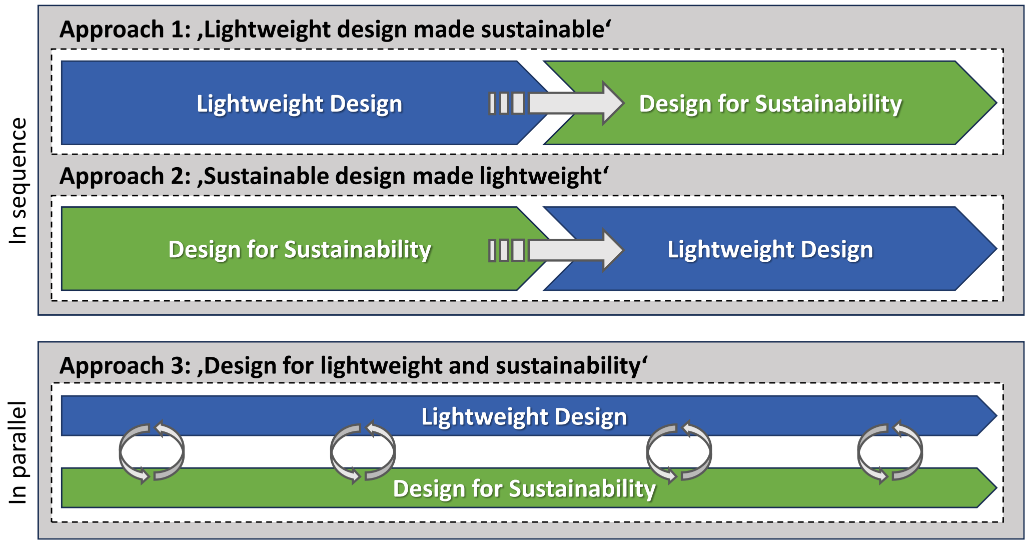

Figure 4. Three approaches to incorporate lightweight design and design for sustainability along the product development process

4.1 Lightweight Design made Sustainable

The first approach covers the sequential implementation of firstly lightweight design and secondly design for sustainability. This must not be seen solely as an approach for the development procedure of a single product generation, but also in an evolutionary way across generations and over time. Thereby, an existing lightweighting solution is newly scrutinized, aiming to assessing its potential for a more sustainable product or, more broadly, evaluating its environmental impacts within, for example, a LCA or a circularity assessment. The underlying concept acknowledges that historically, lightweight design served purposes other than sustainability (e.g., costs or functionality). Alternatively, it is also viable that a solution, initially developed to meet specific environmental sustainability goals (e.g., energy reduction in a product's use phase as for example in the automotive industry), is now being reconsidered more comprehensively - along the entire value chain as well as the product life cycle, now also encompassing aspects like end-of-life value recovery.

This secondary shift in increasing emphasis on design for sustainability may be prompted by an increased societal awareness of sustainability impacts (e.g., global warming), evolving legal regulations, or a revised corporate philosophy. Tangible instances of this approach include the LCA analysis of lightweight materials such as presented by Wegmann et al. (2022). In general, this approach is about evaluating lightweighting solutions with regard to sustainability issues, for example, covering lightweight manufacturing processes (He et al., 2017) or conceptual aspects (Kacar et al., 2018). In the automotive sector, the focus of this strategy is to quantify the reduction of energy consumption and CO2 emissions through weight reduction, as reviewed, for example, by González Palencia et al. (2012). This evolving methodological approach reflects a paradigmatic transformation in lightweight design, aligning with contemporary sustainability imperatives and fostering a holistic perspective on environmental considerations throughout a lightweight product's life cycle.

4.2 Sustainable Design made Lightweight

The second sequential approach foresees firstly the implementation of design for sustainability in a product, and then, secondly, the identification of lightweighting potentials within the sustainable interim solution. Thus, the product development paradigm is reversed in contrast to the first presented approach: a sustainable product or technical solutions, previously made sustainable through other strategies (e.g., use of secondary materials or closed product/component loops), now undergoes an additional weight reduction. This involves products or materials in closed loops, mainly optimized for environmental sustainability by integrating lightweight design to reduce resource consumption. This philosophy's unequivocal aim is sustainability, with lightweight design considered only subordinately, applied in later phases where substantial changes for weight reduction are no longer feasible.

Illustratively, methods like topology optimization are employed. An example of such an application can be found in the works of Lee et al. (2023) or Pfaff et al. (2020). Furthermore, it is also conceivable to assess the suitability of lightweighting principles for achieving sustainability goals and subsequently apply them, as demonstrated, for instance, in manufacturing processes by Liu et al. (2021). This sequential approach includes, in particular, conceptual or system lightweight design after implementing design for sustainability as the first measure, such as at the example of lightweight aircraft seats (Kokorikou et al., 2016), which not only demonstrate sustainability benefits through suitable material selection but also create environmental benefits through lightweighting due to their low weight and, as a consequence, a reduced energy consumption during operation. This approach exemplifies a nuanced integration of design for sustainability and lightweight design, showcasing the adaptability of these paradigms in diverse product development scenarios.

4.3 Design for Lightweight and Sustainability

The parallel implementation of both lightweight design and design for sustainability throughout the product development, centers the third emerging approach derived from the meta-synthesis of the SLR. This approach involves considering fundamental sustainability principles (e.g., life cycle engineering) while strategically deploying lightweight design or other sustainability strategies (e.g., design for circularity) at optimal points along the product development process. A key characteristic of this strategy is less the evaluation of individual lightweighting solutions in terms of sustainability, but rather generalized methodological approaches to product development.

For instance, a defining characteristic is the criterion- and impact-based analysis of lightweight solutions throughout the product development process, leading to the synthesis of novel lightweight and sustainable solutions. This necessitates approaches that encompass both paradigms in all phases of development. Few to no publications fall under this paradigm, notably to be found in the approaches of Kaluza et al. (2017) or, more recently, of König et al. (2023a). They foresee a development process with methodologies for the analysis and synthesis of lightweight and sustainable products. Thereby, for example, the FLCEA ('functional life cycle energy analysis') methodology (König et al., 2024) for analysis of an existing system regarding the synergies and conflicts of lightweight design with other design for sustainability strategies at functional design is outlined. Furthermore, a creativity process, so called LWCM ('lightweight creativity methods') (König et al., 2023b) for synthesis and the generation of novel lightweight and sustainable solutions is part of the design procedure. In general, the key concept of this development approach covers the interplay of methodologies from both paradigms contributing to a comprehensive and innovative integration of lightweight design and design for sustainability throughout the entire product development process, which can be based, for example, on LCA as shown by Herrmann et al. (2018).

5 Implications for Engineering

Based on the SLR and the meta-synthesis some key implications regarding the intersecting field of lightweight design and design for sustainability can be derived for further research in the scientific community and industrial practitioners:

- There is a need for more diversified assessment methods for lightweighting and sustainability, in particular, from an environmental perspective focusing on the inherent features of lightweight design and evaluating and selecting retention options early in product development for promoting synergies of lightweight design with a circular economy.
- A deeper understanding of the timing of actions in the development process is necessary to ensure efficiency and comprehensiveness, with the selection of appropriate methods ensuring detailed results of lightweight products regarding environmental impacts as well as considering varying datasets and knowledge bases of lightweight design and design for sustainability at each phase of product development.
- An absolute perspective on sustainability is lacking in lightweighting assessments, with only relative evaluations of reduction and potential contributions to sustainability. This is a common challenge in design for sustainability despite the lightweighting aspect of this research.
- The integration of social and economic aspects, such as the triple bottom line concept, into the sustainability assessment of lightweighting is frequently insufficient or absent, with more comprehensive assessment methods using extensive dimensions like within the PESTLE (political, economic, social, technological, legal, and

environmental) analysis could not be found. The integration of social and economic aspects of sustainability could only be found in the work of Zanchi et al. (2021) that introduced the 'Life Cycle Sustainability Assessment' (LCSA) into the process of vehicle lightweighting.

- In general, comprehensive databases for materials, manufacturing processes, and joining technologies are needed, with data currency and completeness often inadequate or not consistently implemented in digital toolchains, particularly, regarding complex lightweight structures or novel hybrid materials. Additionally, integration of software solutions for sustainability or lightweighting issues is rarely efficiently compatible to other, established devices, reducing their usability and limiting their full utilization.
- Incorporating business models holds potential for future lightweight products, particularly through greater cross-company collaboration facilitating end-of-use product retrieval and handling infrastructure. Structural health monitoring in diverse application horizons within cross-company collaborations also offers opportunities to extend the lifespan of lightweight products, benefiting the circular economy.
- Addressing essential customer needs should regain focus from a sustainability perspective in system or concept lightweight design conceptualization, rather than developing and marketing performance-driven lightweight solutions that customers may not need and, thus, do overwhelm them. Alternatively, aligning functional benefits from lightweighting solutions with customer preferences through value engineering can mitigate environmental sustainability drawbacks by enhancing customer satisfaction.
- Establishing more incentives for developers, such as elements of gamification in product development, could anchor lightweighting and sustainability at the heart of the product development process. For instance, tools for topology optimization or material selection could be designed to graphically display immediate sustainability benefits from design changes and establish bonus systems for engineers when they implement environmentally beneficial design changes.

6 Conclusion and Outlook

Drawing from a meta-synthesis based on a SLR at the intersecting field of lightweight design and design for sustainability, three methodological approaches have been identified for the integration of both paradigms within the process of product development and further implications for engineering have been derived. This represents a novel perspective on symbiotically uniting typically separately operating teams in product development. This way, an appropriate answer to the research question is provided through the present work. Firstly, a sequential application of both paradigms is viable, wherein a lightweight solution can be first conceived and subsequently subjected to sustainability strategies or be harmonized with sustainability considerations. Furthermore, this sequential approach can also be reversed, by beginning with the development of a sustainable product that is subsequently fine-tuned regarding lightweighting in subsequent phases (e.g., further reduction of resource use). Secondly, the third presented approach envisions a simultaneous evolution of a product with a dual emphasis on lightweight design and design for sustainability. In this scenario, interrelationships throughout the entire process necessitate comprehensive analysis as well as synthesis methods grounding in both paradigms. However, this simultaneous approach warrants further scholarly exploration and methodological refinement, which will be realized within future research endeavors. In this regard, it is necessary to provide detailed insights into the results of the SLR and to search the identified full texts for further related works, thereby validating the presented meta-synthesis. In general, all identified approaches are needed for the development of resource-efficient products, and therefore, their validation through a specific use case example should be targeted in future research.

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