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Trade-off analysis and identification of optimization potentials between lightweight design and design for circularity

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A B S T R A C T

The pressing need for resource conservation and environmental impact reduction in sustainable development emphasizes the importance of lightweight design and design for circularity in product development. However, the complexity and multidisciplinary nature of decision-making in these areas pose a major challenge.

In the present work, a novel approach for trade-off analyses is proposed to meticulously analyze the relationships between both design disciplines, facilitating decision-making and the identification of optimization potentials throughout design. Illustrated by material selection and a case study on the development of a semi-mobile handling system, two fundamental design approaches for decision-making in view of different and shared development objectives between lightweight design and design for circularity are identified. This enables the prioritization of development objectives in early phases and enhances eco-effectivity with regard to resource conservation and environmental impact reduction in the context of complex design considerations.

Abbreviations

AFRP	Aramid-fiber reinforced plastic
BoL	Beginning-of-life
CE	Circular economy
CFRP	Carbon-fiber reinforced plastic
DfX	Design for/to X
EoL	End-of-life
GFRP	Glass-fiber reinforced plastic
LCA	Life cycle assessment
LCE	Life cycle engineering
LCIA	Life cycle impact assessment
MCI	Material circularity indicator
MoL	Middle-of-life
RO	Resource value retention option

1. Introduction

Sustainability has become a central focus in global discussions, research, and policy development across various disciplines. One of the most promising strategies to foster sustainable development is the effective utilization of resources through establishing circular economy (CE) systems (Murray et al., 2017). CE seeks to maintain a circular flow of resources replacing the end-of-life (EoL) concept (International Organization for Standardization, 2024a), aiming for environmental quality, creating economic prosperity and social equity (Kirchherr et al., 2017). Particularly in resource-scarce regions, CE is regarded as a key technology that strengthens the resilience of economic systems while addressing mounting resource scarcity and supply risk (Ghisellini et al., 2016).

In this context, lightweight design emerges as a potentially contradictory design strategy: one of its most used measure - material substitution (Herrmann et al., 2018) - poses significant challenges for CE implementation, as the usage of complex multi-material systems dramatically reduce recyclability (Liu et al., 2022; Poulikidou et al., 2015) and many lightweight metallic materials are classified as critical in terms of supply risks (Ferro and Bonollo, 2023). However, lightweighting can also be achieved by reducing the material volume of components and products. Beyond potential recycling challenges, lightweighting can compromise reusability, standardization, and the longevity of products. While the original focus of lightweighting relied on enabling or enhancing functionality, it has gained significant traction due to its potential environmental benefits. Despite the aforementioned challenges, lightweighting can contribute to reducing resource consumption and environmental impacts for mass-moved products

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(Herrmann et al., 2018). These objectives align with a second key focus of CE: reducing negative environmental impacts (International Organization for Standardization, 2024a).

To shift the focus away from mere efficiency improvements and potential problem shifting, Kara et al. (2023) propose that a greater emphasis should be placed on addressing environmental impacts, using the concept of planetary boundaries (Richardson et al., 2023; Rockström et al., 2009; Steffen et al., 2015) as absolute constraints for product development. This forms the basis for life cycle engineering (LCE), in which sustainability-oriented product development is pursued by employing methods and tools that reduce environmental impacts through changes in technologies or engineering, ensuring that products operate within an absolute safe operating space. To achieve this, it is crucial, on the one hand, to define absolute limits for product systems at the outset of the development process, and on the other hand, to guide the target-driven engineering approach in selecting mitigation options such that environmental impacts remain within these boundaries and problem shifting is avoided. The approach focuses on the product life cycle, which is divided into foreground and background systems, to identify and eliminate environmental hotspots. Kara et al. (2023) conclude that mitigation options are coupled in the sense that an improvement in one may affect others, both positively and negatively. As a consequence, problem shifting can occur between life cycle stages, the foreground and background systems as well as well between environmental impact categories. They formulate a need for further research aimed at developing and prioritizing mitigation options with respect to environmental targets.

In view of the ambiguous relationship between lightweight design and design for circularity, representing two mitigation options for environmental impact reduction within product engineering, jointly integrating both approaches in product development poses complex decision-making challenges, requiring careful balancing of the benefits of weight reduction and circularity increase. Therefore, in the present work, the analysis of the effects of lightweight design and design for circularity is operationalized through trade-off-analysis, considering their fundamental, may conflicting, objectives and their mutual alignment with shared sustainability targets. The key contribution of this work is to facilitate decision-making during the development of products, balancing the advantages of both paradigms for a sustainable product development and LCE, as illustrated in Fig. 1. Thus, we pursue the research question:

> “How can the two design options for product development, lightweight design and design for circularity, be prioritized and evaluated in the context of differing development objectives (weight reduction vs. circularity increase) and to maximize their contribution to shared objectives (environmental impact reduction)?”

In this context, the present work serves as a supporting methodology for making eco-effective decisions to reduce environmental impacts of product systems. Thereby, particular attention is given to potential conflicts as well as synergies, handled as trade-offs, between lightweight design and design for circularity. A trade-off is defined as “a balance between two opposing things, that you are willing to accept in order to achieve something” (Longman dictionary, 2024). Such trade-offs may occur with regard to environmental impacts in view of the distinct life cycle stages as lightweight design strategies primarily contribute to reducing energy consumption in the operation phase of mass-moving products and design for circularity strategies prioritize extending product lifespans and closing resource loops. According to Ross et al. (2022), a trade-off analysis involves “determining the effect of decreasing one or more key factors and simultaneously increasing one or more other key factors in a decision, design, or project.” Thus, trade-offs may arise not only in relation to environmental impacts, but also in affecting the technical value and functionality of a product system (e.g.,

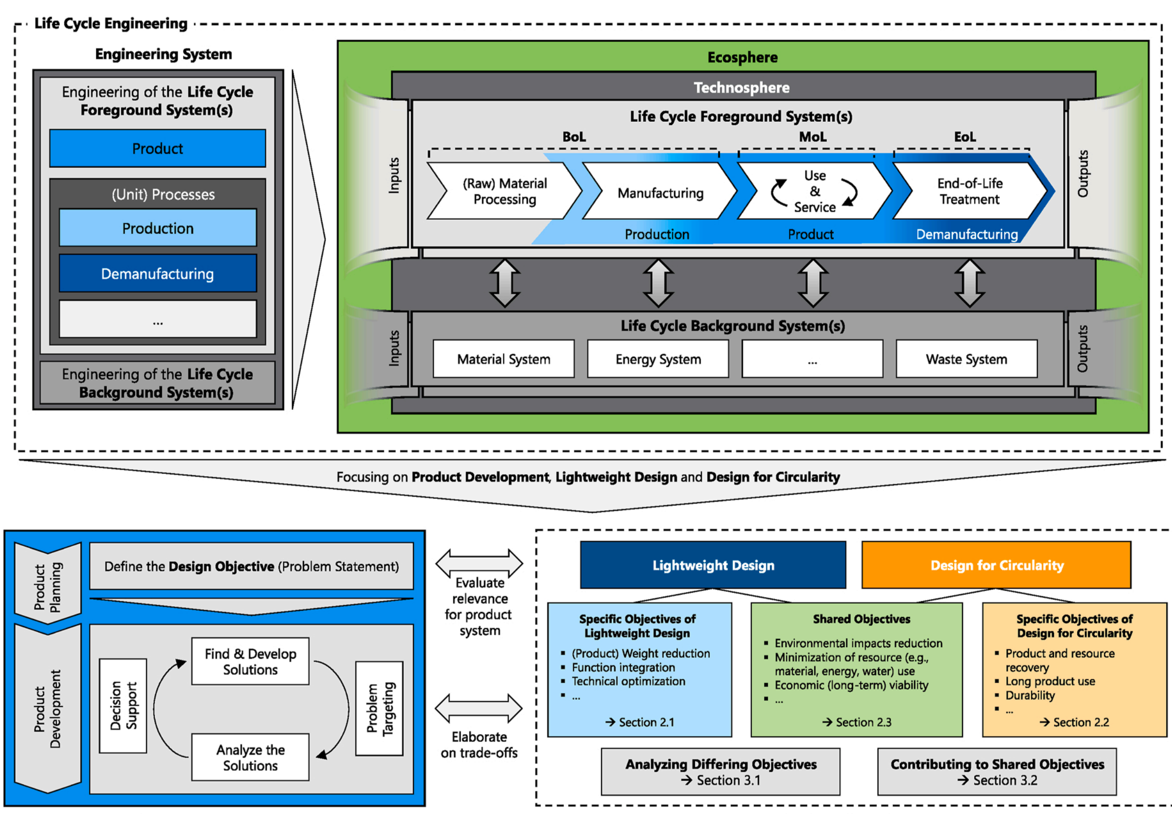


Fig. 1. Positioning of the trade-off analysis as the key contribution of the present work as a method to support decision-making in product development between lightweight design and design for circularity with a particular emphasis on the context of life cycle engineering proposed by Kara et al. (2023).

product weight vs. circularity performance).

To meticulously address the research question and the challenges in choosing between both design strategies, in Section 2, both design strategies are presented and contrasted to establish a fundamental understanding of the need for trade-off analyses. Following this, two specific approaches for trade-off analysis are introduced: first, in Section 3.1, comparing differing objectives of lightweight design and design for circularity leads to a facilitated prioritization or weighting of objectives and a raise in awareness of the implications of design decisions. Second, Section 3.2 presents a concept for trade-off analysis for a shared development objective, environmental impact reduction, implemented and validated at the example of a semi-mobile handling system. Within the discussion in Section 4, a generalization of the developed concepts aside its implementation in product development is proposed. Finally, Section 5 provides a conclusion as well as an outlook on future work and further refinement of the methodological framework.

2. Literature review

2.1. Lightweight design

2.1.1. Motivators and objectives

The motivation of lightweight design efforts in product development is driven by a range of technical, functional, economic, and environmental objectives. At its core, lightweight design is about employing the weight reduction of technical systems as the means to realize one or more of these overarching objectives (König and Vielhaber, 2024a). Originally, the focus relied on enabling and enhancing functionality (Wiedemann, 1986). By lowering structural mass, engineers can develop systems with improved performance such as reduced stress or increased stiffness. Over time, the economic perspective of lightweight design gained in importance, as it is crucial for business success and long-term profitability. This is notably evident until today within 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 weight-reduced products (Klein, 2013).

As environmental targets play a more important role in policy and

Table 1
Overview and categorization of design strategies to reduce the weight of products.

Category	Strategy	Related DfX-options (e.g.)	Description
Conditional lightweight design	**Function reduction**	Design for sufficiency, design for simplicity	Reduce or eliminate individual obligatory functions or positioning-related properties from the service provided by the physical product system (sufficiency approach).
	Requirements reduction	Design to function, requirements engineering, design for reliability, design for structural health monitoring	Lower the performance level of obligatory functions by reducing technical specifications and reduced performance demands of the physical product system.
Conceptual lightweight design	**System optimization**	Design for efficiency, design for quality	Analyze system-level interactions aimed at leveraging implicit effects through systematic and systemic design optimization.
	Integral design	Design for integration	Integrate the maximum number of active or passive functions or components into a single part made of homogeneous material.
	Function integration	Design for assembly, design for functionality, design to function	Integrate the maximum number of active or passive functions or components into a multi-material design.
	Alternative concepts/ solutions	Design for innovation	Explore and implement alternative working principles or solution concepts with a lower weight.
	Modular design	Design for modularity	Partition a product into modules with defined interfaces (function-, process-, or structure-related) and realize localized, module-specific performance optimization.
Material lightweight design	**Metals**	Design for material substitution, design to materials, design with metals	Substitute materials with metallic materials to achieve the required functionality at a lower density.
	Plastics	Design for material substitution, design to materials, design with plastics	Substitute materials with plastics to achieve the required functionality at a lower density.
	Technical ceramics	Design for material substitution, design to materials, design with technical ceramics	Substitute materials with technical ceramics to achieve the required functionality at a lower density.
	Composites	Design for material substitution, design to materials, design with composites	Substitute materials with composites to achieve the required functionality at a lower density.
	Bio-based materials	Design for material substitution, design to materials, design with bio-based materials	Substitute materials with bio-based materials from renewable sources to achieve the required functionality at a lower density.
Form lightweight design	**Shape optimization**	Design for efficiency, design for additive manufacturing, design for tolerance	Optimize material distribution within a homogeneous material component aimed at reducing material consumption while ensuring equal or improved functionality.
Manufacturing lightweight design	**Process-based optimization**	Design for manufacturing, design for additive manufacturing	Implement process-related measures (forming, shaping, separating, and altering material properties) to enable lightweight structures, enhance production efficiency and reduce part weight.
	Reversible and homogeneous material joining	Design for joining, design for assembly, design for disassembly	Substitute joining elements with reversible homogeneous material joints to reduce weight while ensuring equal or improved functionality (e.g., homogeneous material mechanical fasteners such as screws or bolts).
	Reversible heterogeneous material joining	Design for joining, design for assembly, design for disassembly	Substitute joining elements with reversible heterogeneous material joints to reduce weight while ensuring equal or improved functionality (e.g., dissimilar-material mechanical fasteners such as screws or bolts, as well as electrical connectors like plugs or clips).
	Non-reversible homogeneous material joining	Design for joining, design for assembly, design for disassembly	Substitute joining elements with non-reversible homogeneous material joints to reduce weight while ensuring equal or improved functionality (e.g., mechanical methods such as clinching, forming processes like folding, flanging, rolling, pressing, and thermal methods such as welding).
	Non-reversible heterogeneous material joining	Design for joining, design for assembly, design for disassembly	Substitute joining elements with non-reversible heterogeneous material joints to reduce weight while ensuring equal or improved functionality (e.g., thermal methods such as soldering, chemical methods like adhesive bonding, and hybrid joining processes).

society, lightweighting efforts are increasingly discussed with their environmental consequences. Therefore, Herrmann et al. (2018) emphasize the role of LCE of lightweight structures in mitigating environmental impacts across various applications, supported by recent findings from König and Vielhaber (2024b). By minimizing material usage and operational energy demand, lightweight design can contribute to environmental sustainability objectives.

2.1.2. Implementation strategies

To achieve these typical goals, five categories of strategies are distinguished in research and practice (Kopp et al., 2011): conditional, conceptual, material, form, and manufacturing lightweight design. An overview of these categories and associated sub-strategies are presented in Table 1. Thereby, conditional lightweight design sets the boundaries and requirements for each development task. By reevaluating functional requirements and eliminating unnecessary features, significant weight reduction potentials can be realized. Conceptual approaches include rethinking working principles, combining or separating functionalities via function integration or modular design. Lightweight materials, such as advanced aluminum alloys or carbon-fiber-reinforced plastics (CFRPs), offer high functionality-to-weight ratios, and can thus deliver a certain functionality by a lower density. Within this work we distinguish five material classes that may substitute a reference solution: metals, plastics, technical ceramics, composites and bio-based materials. Form lightweight design focuses on structural optimization, such as using topology optimization to minimize material usage while maintaining required mechanical stability. Manufacturing strategies leverage techniques like additive manufacturing and adhesives to reduce the amount of material used within the physical product while precisely meeting design requirements and enabling complex shapes.

2.1.3. Evaluating the lightweighting performance

Historically, lightweight design has been employed to achieve a broad spectrum of development objectives, leading to a diverse range of indicators used to measure its effects. There is no standardized approach or universal guideline for the use and selection of these indicators. Table 2 provides an overview of commonly encountered lightweight design indicators, which serve to quantify the impact of lightweighting on products.

In the context of analyzing lightweighting effects, the term lightweighting potential is frequently used. However, there is no standardized definition for this terminology. To ensure a consistent understanding, we propose defining ‘lightweighting potential’ as a measure of the capability to improve a lightweighting indicator (see Table 2) in a process, system, product, component, or material.

Table 2
Overview of performance indicators for lightweight design.

Description	Unit	Focus	Source (exemplarily)
Product mass/weight	kg	Technical	Ferro and Bonollo (2023)
Density	kg/m3	Technical	Ashby (2021)
Stiffness-to-weight-ratio	GPa/m	Technical, functional	Laufer et al. (2019)
Working performance (e.g., center-of-gravity, acceleration, ergonomics)	Various	Functional	Laufer et al. (2019)
Specific stiffness	MPa.kg/m3	Functional	Ashby (2021)
Costs per weight reduction	EUR/kg	Economical	Klein (2013)
Energy savings during usage/entire life cycle	MJ	Economical, environmental	Laufer et al. (2019)
CO2 emission reduction during usage/entire life cycle	kg CO2 eq.	Environmental	Laufer et al. (2019)
Carbon footprint per weight reduction	kg CO2 eq./kg	Environmental	Fleischer et al. (2024)

2.2. Design for circularity

2.2.1. Motivators and objectives

The CE fundamentally seeks to transition from a linear economy model to a circular one focused on multiple targets such as reducing waste, closing production loops, using resources more efficiently, or maximizing the retention of the economic value of materials and products (Morseletto, 2020). This involves three core principles according to Bocken et al. (2016): first, slowing resource loops through the design of long-life goods and product extension; secondly, ensuring resource loops are closed through recycling and other EoL strategies resulting in a circular flow of resources; and thirdly, enhancing resource efficiency via narrowed resource flows, aimed at using fewer resources per product. These fundamental concepts have profound implications for product design (Badurdeen et al., 2015), giving rise to the concept of circular design, which aligns product development with CE principles. According to De Oliveira et al. (2021), ‘circularity’ refers to the extent to which a process, product, component, energy flow, or material adheres to general CE objectives. In this context, we define ‘design for circularity’ as designing products and components for high circularity, aiming at products designed for fulfilling CE targets.

2.2.2. Implementation strategies

The implementation of a CE operates at multiple levels – macro (city, region, nation), meso (eco-industrial parks) and micro (products, companies, consumers) – to accomplish sustainable development (Kirchherr et al., 2017). De Oliveira et al. (2021) additionally define the nano-level as fourth level of CE, only focusing at products and materials while excluding an entire company perspective from the micro level. Since macro- and meso-level strategies focus on societal, sectoral, or corporate applications, the micro- and nano-level address measures targeting individual products and their materials, which is pivotal for the presented study.

Incorporating CE principles early in the design process is crucial to maximizing resource efficiency, minimizing waste and losses, and ensuring value creation throughout a product’s life cycle (Badurdeen et al., 2015). A common framework for implementing CE principles involves leveraging resource value retention options (ROs), which are classified in a R-typology (or R-imperatives) aiming to maintain the value of products, components, and materials at the EoL (Reike et al., 2018). The ISO 59010 standard (International Organization for Standardization, 2024b) adopts this concept and defines, analogously, a total of 13 resource management actions that support the transition towards a CE. These are listed in Table 3 as strategies of design for circularity. Thereby, the term ‘design for circularity’ is defined as “design and development based on the circular economy principles” (International Organization for Standardization, 2024a) and is closely linked to the concept of ecodesign. Within the ISO 59004 standard (International Organization for Standardization, 2024a), design for circularity strategies are categorized within four areas: design for product durability and long use, design for product and resource recovery, design to minimize resource use and losses, and design for performance-based approaches. In this publication, we adopt the classification and categorization proposed by Bocken et al. (2016), organizing the strategies into narrowing, slowing (referred to as design for product durability and long use in ISO 59004 (International Organization for Standardization, 2024a), and closing the loop (referred to as design for product and resource recovery in ISO 59004 (International Organization for Standardization, 2024a), in order to directly connect them to the previously outlined objectives of the CE. We further divide narrowing into the aspects of narrowing resource loops meaning minimizing resource use and losses, as well as narrowing product loops emphasizing intensifying product use (referred to as performance-based approaches in ISO 59004 (International Organization for Standardization, 2024a). Additionally, we add a fourth category, ‘recovering the loop’, which encompasses energy recovery and material recovery in line with the re-mine strategy. According to Bocken et al. (2016), this category does not directly fall under closing the loop and is thus considered separately within the present work.

An effective implementation of CE requires understanding the current circularity of operations, value creation models, and associated risks. This understanding informs targeted actions to improve circularity, beginning with a robust circularity assessment, as emphasized by ISO 59020 (International Organization for Standardization, 2024c). Once weaknesses are identified, products can be re-engineered through specific Design for/to X (DfX) approaches, such as 'design for remanufacture', 'design for repairability', or 'design for disassembly'. Comprehensive overviews of DfX strategies for enhancing product circularity are provided in the contributions of Mesa (2023) and Sassanelli et al. (2020).

2.2.3. Evaluating the circularity performance

In contrast to lightweight design, there is an extensive range of reviews on metrics for assessing the circularity of a product or material. Notable examples include the works by De Oliveira et al. (2021), De Pascale et al. (2021), Kristensen and Mosgaard (2020), Patil and Ramakrishna (2023), and Rossi et al. (2020). A selection of indicators that frequently appear in these reviews is listed in Table 4. In this study, the analysis of circularity indicators is not a primary focus. Instead, we rely on the foundational insights provided by the aforementioned reviews.

Table 4
Overview of circularity indicators for assessing the circularity performance of product systems.

Description	Unit	Focus	Life cycle stage	Source
Material circularity indicator (MCI)	–	Flow of materials, lifetime, intensity of use	Full life cycle	Ellen Mac Arthur Foundation (2015)
Longevity indicator (or resource duration indicator)	Years	Duration of active resource use	MoL, EoL	Franklin-Johnson et al. (2016)
Global resource indicator	kg Fe eq.	Recycling, resource scarcity, geopolitical availability	Full life cycle	Adibi et al. (2017)
Product circularity indicator	–	Similar to MCI, but more comprehensive regarding supply chains	Full life cycle	Bracquené et al. (2020)
Material efficiency metric	kg	Material inputs and outputs	BoL, EoL	Brändström and Eriksson (2022)

Table 3
Overview and categorization of design strategies to increase the circularity performance of product systems.

Category	Strategy	Related DfX-options (e.g.)	Description
Narrowing product loops (**intensify product use**)	**Refuse**	Design for demand or on availability, design for PSSs, design as a service	Make solutions redundant by abandoning its function or by offering the same function with a radically different solution.
	Rethink	Design for sustainability, design for modularity, design for standardization and compatibility, design for environment, design as a service	Reconsider design and manufacturing decisions. Make service use more intensive (e.g. through sharing or by putting multi-functional products on the market).
Narrowing resource loops (**minimize resource use**)	**Circular sourcing**	Design from recycling, design for entire value chain	Select recovered or renewable, sustainably sourced or produced resources. Use resources that can be easily recycled or returned to the biosphere. Reconsider formulations.
	Reduce	Design for reduce resource consumption, design for light weight/miniaturization, design for energy efficiency	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials.
Slowing product and resource loops	**Repair**	Design for repairability, design for dis- and reassembly, design for easy maintenance and repair, design for long use	Restore a defective or damaged product so that it can be used in its original function.
	Re-use	Design for reuse, design for long use, design for (product, physical, emotional) durability, design for reliability, design for longevity	Re-use a discarded product which is still in working condition and fulfils its original function.
	Refurbish	Design for refurbishing, design for long use, design for (product, physical, emotional) durability, design for easy maintenance and repair, design for reliability, design for longevity, design for standardization and compatibility	Restore to a useful condition during expected service life with similar quality and performance characteristics.
	Remanufacture	Design for remanufacturing, design for long use, design for dis- and reassembly, design for (product, physical, emotional) durability, design for reliability, design for longevity, design for standardization and compatibility	Return an item, through an industrial process, to a like-new condition from both a quality and performance perspective.
	Repurpose	Design for long use, adaptable design, design for adaptability, design for dis- and reassembly, design for (physical, emotional) durability, design for reliability, design for standardization and compatibility	Adapt a product or its parts for use in a different function than it was originally intended without making major modifications to its physical or chemical structure.
Closing resource loops	**Cascade**	Design for cascade use, design for EoL, design for biological cycle, design for technical/technological cycle, design for disassembly, design for material recovery	Shift recovered materials from one loop to another to optimize feedstock flows through additional cycles, often with decreasing quality and quantity. When adopting for biobased material, cascading implies repeated use of renewable resources at decreasing quality, with final treatments such as composting, energy recovery or biodegradation, and safe return of the material to the environment.
	Recycle	Design for recycling, design for end of life, design for biological cycle, design for technical/technological cycle, design for biodegradability, design for material recovery, design for disassembly	Recover and process material to obtain the same (high grade) or lower (low grade) quality through activities such as recovery, collection, transport, sorting, cleaning and re-processing.
Recovering resource loops	**Recover energy**	Design for energy recovery	Generate useful energy from recovered resources.
	Re-mine	Design with waste, urban mining	Mining or extraction from landfills and waste plants can be possible in some cases if mining or extraction activities are sustainably managed.

2.3. Incorporating lightweight design and design for circularity

Lightweight design has historically been considered independently of ecodesign strategies. With the rising importance of sustainable development and CE, it is increasingly recognized as a possible strategy for resource conservation (Desing et al., 2021). This highlights the opportunity for a synergistic integration of lightweighting with CE principles.

However, alongside synergies, challenges arise from reduced recyclability of sophisticated lightweight materials, difficulties in non-destructive disassembly of lightweight joining techniques and impact shifting from usage benefits to manufacturing and EoL impacts. In addition, key strategies of design for circularity as repairability, ease of disassembly and maintenance (Vanegas et al., 2018) as well as modularity, are at odds with lightweight design. An overview of the results of a meticulous methodological analysis of both design strategies on the objectives of each discipline is presented in Fig. 2, whereby detailed information and supporting literature can be found in Supplementary material 1.

From the analysis we found as key conclusions for the lightweight design strategies with regard to the CE objectives:

Narrowing. Strategies for weight reduction can reduce resource consumption (in particular, material and energy) depending on the specific type and characteristics of the physical product system. Functionality and, consequently, may the intensity of product use, gets improved through lightweighting; however, the feasibility and practical implementation must be carefully evaluated as rebound effects are not addressed and the actual intensity of product use is not verified (Herrmann et al., 2018). Depending on the type of measure, resource consumption may shift between the type of resources, potentially resulting in unintended environmental trade-offs (Das, 2021; Sato and Nakata, 2021). To avoid problem shifting, lightweighting measures should be assessed through a holistic and life cycle-based analysis.

Slowing. Lightweight design strategies tend to reduce product lifespans by resulting in less robust systems and by limiting or complicating the implementation of resource management options aimed at extending the useful life even if a functional improvement may result in a broader adaptability and flexibility regarding second use cases (Amezquita et al., 1995; Hooton and Bickley, 2014; Mboule et al., 2019; Spreafico, 2022).

Closing. In particular, lightweight design through function integration, material substitution using plastics or composite materials, and the use of non-destructively reversible or material-heterogeneous joining elements significantly reduces the performance of closing resource loops (Das, 2021; Sato and Nakata, 2021). The other lightweighting measures from Table 1 tend to have a secondary or ambivalent impact, depending on how they are implemented in the specific physical product system and must be evaluated on a case-by-case basis.

Vice versa, for the design for circularity strategies with regard to the resulting product weight, it can be concluded:

Weight reduction. Product systems designed for the CE tend to exhibit a higher product weight due to the need for greater functional flexibility, increased dimensions resulting from higher safety factors and material reserves required for a variety of resource management options, as well as constraints on the selection of materials (e.g., circular sourcing, remine), manufacturing processes, and (reversible) joining techniques (Carruth et al., 2011; Kokorikou et al., 2016; Lewis et al., 2019; Maia

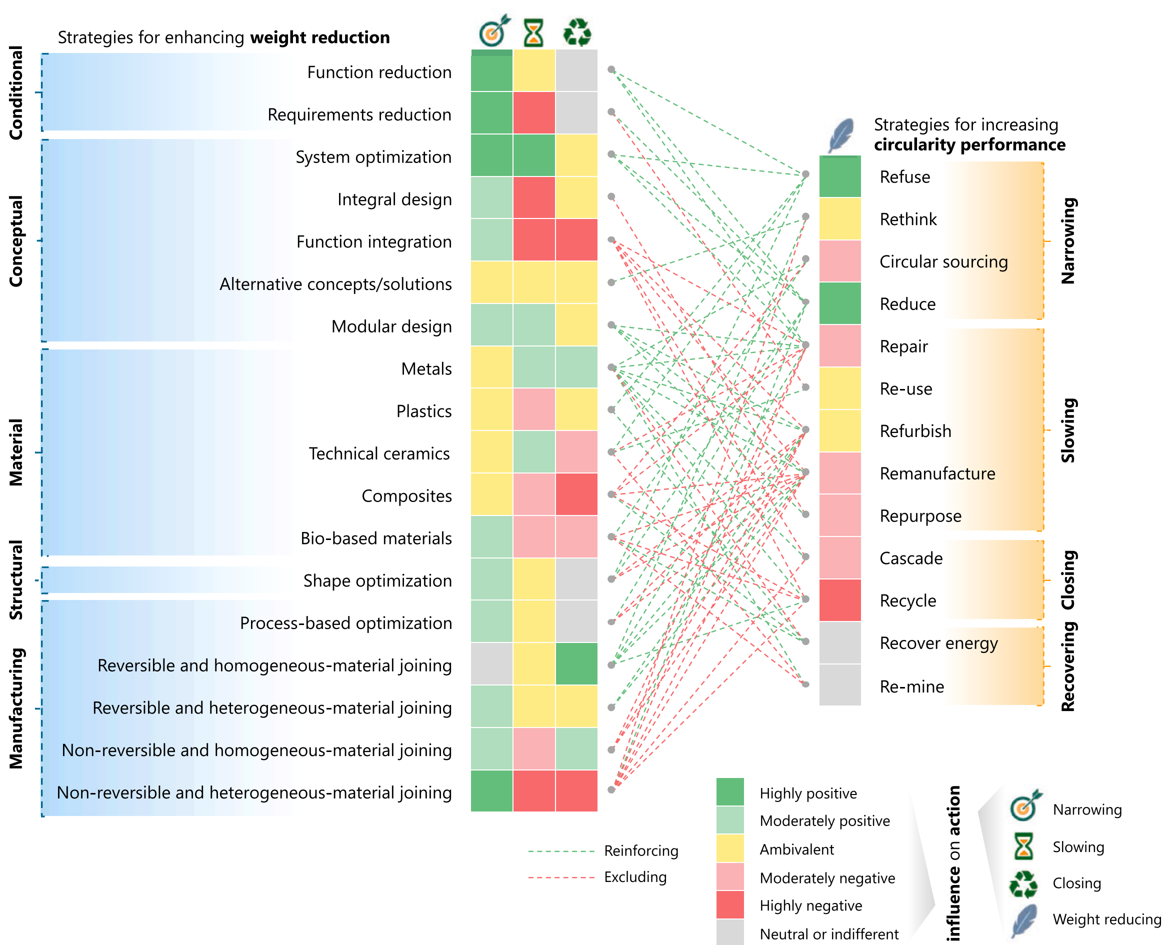


Fig. 2. Visualization and qualitative assessment of the mutual influences between lightweight design and design for circularity as well as their fundamental objectives. A detailed explanation of the color-coded qualitative assessment can be found in Supplementary material 1.

et al., 2019; Mesa, 2023; Monteiro et al., 2022; Witik et al., 2011; Yang et al., 2017). Exceptions to this are the 'refuse' and 'reduce' options, which can have a significantly positive impact on reducing product weight (Figge and Thorpe, 2023).

As Bocken et al. (2016) proposed a hierarchy for implementing CE principles in products – prioritizing slowing and closing loops, while narrowing loops may be more prone to trade-offs – this methodological analysis supports that perspective. Thus, we treat lightweight design and design for circularity as two distinct strategies, each contributing to product optimization for environmental impact reduction (shared objectives) and enhancement of technical value (differing objectives). Depending on the context, their relationship can be synergistic, conflicting, or neutral.

One shared focus of both design strategies relies on selecting materials and has been identified as exceptionally critical from the methodological analysis in Fig. 2. At this intersection, Ferro and Bonollo (2023), building on Ashby's (2005) methodology for material selection, proposed an trade-off analysis considering product mass as a lightweighting indicator and the criticality of raw materials, particularly driven by the growing demand for rare earth elements in the context of electromobility. Ashby's material selection charts have long been adapted for sustainability considerations in raw material extraction. For example, Allwood et al. (2011) compared the specific stiffness of materials against the energy consumption required for primary material production.

With the increasing focus on CE principles, energy transitions, and lightweight design, there is a growing need to explore such interrelations in a more diversified manner and to avoid problem shifting. Existing approaches lack a comprehensive evaluation of CE measures against lightweighting measures for enhancing environmental sustainability. To address this gap, this paper proposes a novel decision-making methodology.

3. Analyzing trade-offs between lightweight design and design for circularity

Dealing with lightweight design and design for circularity in product development, design objectives can be different, such as to minimize weight vs. enhancing circularity, or mutual. A critical decision lies in determining whether both design strategies aim to address such distinct goals or to achieve a shared development objective.

For shared objectives, the greatest overlap between both strategies centers on minimizing resource consumption and reducing negative environmental impacts. In this context, the decision-making process seeks to identify the most effective strategy for achieving the shared objective in the design process.

When considering distinct objectives, the decision-making process involves balancing the functional improvement of a product through weight reduction against the goal of circularity, for example, to enhance resource availability. Ultimately, potential trade-offs between advancing one dimension at the expense of the other can be evaluated.

Having this distinction in mind, we fundamentally differ between these two perspectives in the following subsections.

3.1. Evaluating different development objectives

3.1.1. Theoretical considerations

In the context of differing development objectives, a trade-off analysis is conducted to facilitate a fundamental design decision between implementing a lightweighting measure to achieve lightweighting goals against a measure for circularity aiming at fulfilling CE objectives. Thereby, the approach can be used to quantify the effects from optimizing one strategy on the other, to find an optimal balance. Thus, a trade-off analysis is implemented to support strategic design decisions, for instance, regarding the prioritization of requirements, a weighing of development objectives or adjusting business orientation.

For this case, we propose a comparative analysis between lightweighting (Table 2) and circularity indicators (Table 4). The selection of an appropriate lightweighting indicator in this scenario can be performed by the original motivators for lightweighting efforts (e.g., technical, functional, economical, or environmental improvements) described earlier. An appropriate circularity indicator can be determined, for example, following the methodology presented by Saidani et al. (2019) or based on the criteria discussed by Luthin et al. (2024).

3.1.2. Implementation example: material selection

As an example for analyzing trade-offs when involving differing development objectives, material selection as part of product development is chosen. Referring to the approach of Ashby (2005), materials are typically selected for physical components during the embodiment design cycle, following conceptual design and preceding detailing the components. Material selection plays a critical role in the development of any physical product and is pivotal for both lightweighting and CE. To enable comparability between materials for their intended applications, functional requirements such as structural integrity for mechanical components must be met by each design alternative. Therefore, in this example, the bending of a beam with a fixed length, a variable cross-section, and an unrestricted material selection, which still must not failure, serves as the basis for comparative material selection. To establish a starting point, in Table 5, ten different materials along with their common properties and effects relevant to lightweighting are listed. These materials cover metals, composites, and natural (bio-based) materials.

To identify a suitable circularity indicator for the material selection example, we followed the methodology outlined by Saidani et al. (2019). Therefore, the indicator should operate on the micro level, enabling an immediate evaluation of concepts (reflecting shorter implementation timelines). It should intrinsically focus on the performance of circular loops (analogous to how lightweighting indicators directly target lightweighting objectives). Furthermore, it should consider all circularity improvement options ('all the loops'), be represented as a single indicator, serve the purpose of providing actionable information (facilitating subsequent decision-making), be generic in its application, and be computable using a software tool.

Based on these criteria, the MCI developed by the Ellen Mac Arthur Foundation (2015) was selected. The MCI values are calculated for one ton of each material listed in Table 5 using the calculation template provided by thinkstep (2024). The results are summarized in Table 6. For the calculation, standard values for the recycled content of metals were assumed based on global averages. The recycling efficiency for metals was generally set at 80 %. For steel components, it is assumed that remanufacturing requires about 5 % virgin material for remanufacturing purposes. All other metals will be handled with material recycling at the EoL. In contrast, regarding the traditional composite materials, no widely accepted and implemented ROs were identified aside from energy recovery. As energy recovery represents one of the least desirable options of CE implementation (Reike et al., 2018), it is not rewarded in the MCI calculation for these non-bio-based materials. Consequently, we treat the composites with landfill at the end-of-use to avoid misunderstanding. The selected bio-based composite option consists of 60 % PLA and 40 % bamboo fiber from regenerative sources. This composite material is assumed to be biodegradable and free from any toxic substances. Spruce and plywood, handled as representative construction woods, are entirely sourced from regenerative origins, such as FSC-certified forests. In this case, efficient energy recovery at the EoL is considered a positive contribution to the MCI calculation.

A utility factor can be included in the MCI calculation, which originally accounts for a longer lifespan and intensity of material usage. In general, we distinguish two scenarios. In the first scenario, no benefit from the utility function is considered. In the second scenario, the utility function $F(X)$ is applied to quantify the savings achieved through lightweighting. Thereby, the weight-saving factor is determined by the ratio of the material index for steel M_{St} used as the reference scenario, to the material index $M(X)$ for another material X. The inverse of this factor serves as the utility function for the MCI calculation, reflecting the contribution of lightweighting to circular performance:

$$F(X) = \frac{M(X)}{M_{St}}$$

Essentially, this implies that substituting steel with an alternative material may require a reduced material quantity compared to steel while still meeting the functional requirements. In the MCI calculation, this deviation is regarded as a positive contribution to a CE, as it reflects a reduction in material consumption from an absolute perspective.

The two resulting trade-off analyses between both MCI scenarios representing design for circularity and the material index M for evaluating the lightweighting performance of a bending loaded beam are illustrated in Fig. 3.

When examining the results without considering the utility function (Fig. 3 (a)), it becomes evident that composites, which perform well from a lightweighting perspective, only exhibit a low circularity. In contrast, metals show a significantly higher MCI but perform considerably worse in terms of their material index compared to composites. This highlights a strong trade-off (meaning conflict in targets) between lightweighting and circularity for traditional lightweighting materials. Regenerative and environmentally friendly materials, such as bio-based composites and the two woods, are generally preferable from a circularity perspective. Among these, spruce stands out, displaying only a weak trade-off in terms of lightweighting performance. Thus, the combination of a good lightweighting potential and a strong circularity performance makes spruce a preferred choice for the application. However, these considerations should be validated against additional material selection criteria, such as cost, water consumption, and durability before final decisions are made.

When the utility function is incorporated (Fig. 3 (b)), no significant trade-off between lightweighting and circularity targets emerges that would indicate a strong conflict between the two strategies. Notably, traditional composites are more favorably represented due to their functional performance. In this scenario, wood continues to be the preferred material choice.

3.1.3. *Opportunities and limitations*

In general, the methodology facilitates the evaluation of trade-offs between development objectives related to lightweighting and circularity performance. By comparing lightweighting indicators with circularity indicators, it becomes possible to directly identify the interrelationships between these disciplines and assess their respective impacts.

However, it was only able to demonstrate the approach for a limited number of materials, as comprehensive material data are necessary. Therefore, a comprehensive and reliable material database is required to evaluate all material options in a more complete manner. From the authors' perspective, the assessment of circularity in generic databases is particularly critical, as possibilities for material recovery varies from region to region.

In our example, we did not impose extensive boundary conditions on material selection, which would be far more comprehensive in actual practice (e.g., see the use case example in Section 3.2.2). For instance, the wood options would require a significantly larger cross-sectional area compared to the other materials, while tolerances must be set larger, questioning their applicability.

The positive weighting of efficiency gains through lightweighting for a linear product flow, using the utility function, is generally not advised for MCI calculation by the Ellen MacArthur Foundation (Ellen Mac Arthur Foundation, 2015). It is discouraged since lightweighting often occurs for economic reasons, typically enabling only minor material savings, and because defining an average reference value (in our example M_{St}) is challenging due to the diversity of product sizes and types. This viewpoint is confirmed by the presented example, as the composite materials without any favorable RO at the end-of-use are positively evaluated from a CE perspective when the utility function is considered. Nevertheless, depending on the product type, it may be worthwhile to still incorporate the utility of lightweighting.

Having a look at strong and linear trade-offs, it is necessary to establish either priorities (e.g., "Is material circularity more important than functionality through lightweighting?") or offsets (e.g., "How much material circularity is equivalent important as which amount of weight reduction?") between lightweighting and circularity to systematically justify design choices. For such purposes, the methodology offers fruitful insights into consequences along the decision-making process. Nevertheless, there are no direct implications regarding environmental impacts.

3.2. *Optimizing shared objectives*

3.2.1. *Theoretical considerations*

3.2.1.1. *Resource conservation and environmental impacts reduction.*

Referring to the pursuit of a shared development objective, this shared target must first be determined prior to performing an analysis. From an environmental perspective, resource conservation and the reduction of negative environmental impacts represent the greatest overlapping objective between the two design strategies.

The discussion about resources is extensive in the field of CE. There are numerous distinctions regarding the types of resources (such as natural, bio-based, recoverable, renewable, or recovered). Furthermore, there are classifications regarding what can be considered a resource (e.g., virgin material, waste). For the purpose of this contribution, we follow ISO 59004 (International Organization for Standardization, 2024a) and define the term 'resource' as an asset from which a solution (in our case a physical product or component) is created or implemented. Therefore, we classify as essential resource any form of material that, in the context of natural resources, has been or will be transferred from the ecosphere to the technosphere. Additionally, any form of energy is regarded as another resource of fundamental importance. According to Ashby (2021), energy is not fully separable from material considerations, as it is required for the production of materials (embodied energy), their processing, usage, and EoL recovery, thus being relevant throughout the entire life cycle.

A third important resource is water. While CFRPs require a water consumption of around 1400 l/kg for material production, the water consumption for the more circular steel option (as per Tables 5 and 6) is only about 40 l/kg, making it significantly lower. Therefore, the consideration of water as a resource in the context of lightweighting and CE is fundamentally relevant. Given the usage phase of energy-intensive products, varying amounts of water are also required for providing energy depending on the source (IEA, 2016).

Thus, a correlation exists between materials, energy, and water. In light of this, we recommend focusing on energy considerations (calculating cumulative energy demand) as simplified methodological process for early phases of product development.

As mentioned at the outset, the focus of LCE lies in allocating and limiting environmental impacts for product systems within the absolute boundaries of the Earth's carrying capacity. Therefore, the consideration of environmental impacts and an allocation to these absolute limits gets necessary in subsequent steps of the methodological process of trade-off analysis to avoid problem shifting. Within the operationalized framework to LCE, Kara et al. (2023) put their emphasis on life cycle assessment (LCA). To include absolute boundaries, Bjørn and Hauschild (2015) proposed a carrying capacity-based normalisation in LCA. Additionally, Ryberg et al. (2018) introduced a planetary boundary-based life cycle impact assessment (LCIA) methodology based on the planetary boundary framework (Richardson et al., 2023; Rockström et al., 2009; Steffen et al., 2015). To take an initial step in this

Table 5
Lightweighting materials and some of their functional properties as well as their economical, and environmental effects with glass-fiber reinforced plastic (GFRP) and aramid-fiber reinforced plastic (ARFP).

Material type	Density ρ [kg/dm-3]	Stiffness E [GPa]	Specific Stiffness E/ρ [$GPa{\cdot}m^3/kg$]	$M = \frac{\sqrt{E}}{\rho}$ [$GPa{\cdot}m^3/kg$]	Price [EUR/kg]	Embodied Energy [MJ]	CO2 footprint material [kg/kg]	Water usage [l/kg]
Steel	7.9	211	26.7	1.84	1.47	34	3.5	45
Aluminum	2.7	73	27.0	3.16	3.48	190	13.7	1115
Magnesium	1.8	43	23.9	3.64	8.08	369	23.0	990
Titan	4.8	111	23.1	2.19	27.80	1030	63.0	560
CFRP	1.6	142	88.8	7.45	39.50	727	50.9	1410
GFRP	1.8	40	22.2	3.51	29.35	116	7.2	162
AFRP	1.4	70	50.0	5.98	63.25	226	12.4	461
Bio-Composite	1.3	10	7.7	2.43	8.00	41	3.1	1735
Spruce	0.4	11	27.5	8.29	1.01	16	0.3	700
Plywood	0.6	6.5	8.1	3.19	0.58	27	0.7	700

Table 6
Estimated values of MCI for different lightweighting materials with regard to their end-of-life-treatment.

Material type	Regenerative source [%]	Mass reduction factor	Utility function $F(X)$	Treatment at EoL	MCI	MCI with utility
Steel	0	1.00	1.00	Remanufacturing	0.53	0.53
Aluminum	0	0.58	1.72	Recycle	0.46	0.69
Magnesium	0	0.50	2.00	Recycle	0.46	0.73
Titan	0	0.84	1.19	Recycle	0.46	0.55
CFRP	0	0.25	4.00	Landfill	0.10	0.78
GFRP	0	0.52	1.92	Landfill	0.10	0.53
AFRP	0	0.31	3.23	Landfill	0.10	0.72
Bio-Composite	40	0.76	1.32	Compost	0.73	0.79
Spruce	100	0.22	4.55	Energy recovery	0.75	0.95
Plywood	100	0.58	1.73	Energy recovery	0.75	0.86

direction and to reveal the relevance of environmental impacts for both design strategies, we incorporate, alongside energy evaluation, an assessment of impact categories from LCA in the following steps, when more data is available and concepts are at least initially elaborated. Thereby, the gap to environmental concerns is bridged and the objective to reduce environmental impacts is considered through the trade-off analysis. This approach makes a contribution to eco-effectiveness while not substantially increasing methodological complexity and leaving space to include the absolute boundary concepts in further steps of methodological refinement.

3.2.1.2. Assigning shared expenditures. With regard to reducing environmental impacts, it becomes necessary to allocate the overall impacts separately to both individual strategies and perform trade-off analysis within this separation. Its outcome enables the quantification and assessment of the benefits derived from optimizing in a specific design strategy toward the overarching development goal. Research and advancements in both lightweight design and design for circularity consistently emphasize the importance of distinguishing between life cycle stages. Building on this foundation, we make the following assumptions for the allocation of resource consumption and environmental impacts to the design strategies:

- Lightweight design primarily focuses on energy reduction during the middle-of-life (MoL), specifically for mass-moving products. Based on the data in Table 3 and the graphical visualization in Fig. 3 (a), we assume that measures such as material lightweighting may result in problem shifting to other life cycle stages (beginning-of-life, BoL, and EoL).
- Design for circularity emphasizes resource-efficient use, the reintegration of materials into cycles, and measures to extend product lifespan. These aspects can be allocated within an environmental

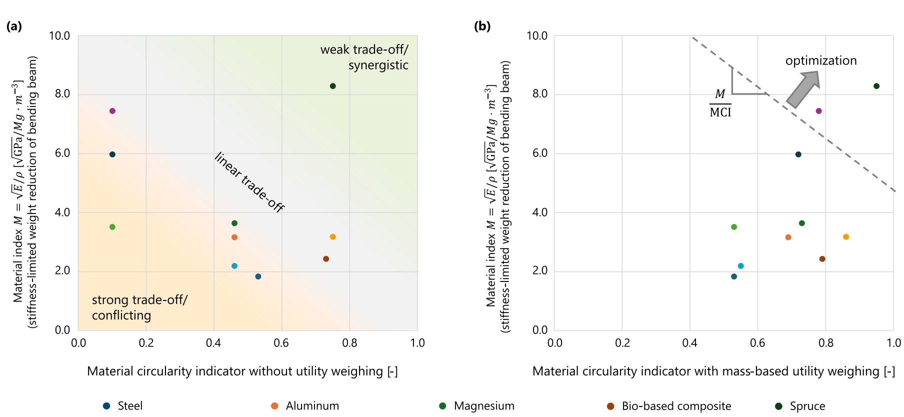


Fig. 3. Trade-off-based material selection between lightweighting and circularity targets; a) material selection without utility weighing in MCI calculation; b) with utility weighing in MCI calculation.

assessment to the BoL and EoL stages of a product's life cycle – either directly through the input and output flows within the product system or via an extended functional unit, which, in comparative analyses, leads to more resource-efficient BoL and EoL processes for equivalent periods of usage. However, the use of more circular materials may mitigate the positive effects of lightweighting, as circularity-oriented designs tend to be disadvantageous regarding impacts during the MoL for mass-moving products due to an increased product weight resulting in higher energy consumption.

3.2.2. Implementation example: a semi-mobile handling system

To provide a practical illustration of these theoretical considerations, we use the identification of optimization potentials for a semi-mobile handling system as case study, which has been discussed in earlier works (König et al., 2024, 2025; König and Vielhaber, 2025). The system illustrated in Fig. 4 features a gantry-mounted portal robot that travels along a track 25 m in length, transporting tools from a storage to four operating machines. Key components of the reference system, along with their major subassemblies, are detailed in terms of their main materials and associated life cycle energy consumptions Table 7. The system operates with a cycle time of approximately 1 min per tool change.

Considering our assumptions and cumulative energy demand as the selected indicator for early phases of development, a diagram can be constructed as shown in Fig. 5. In this diagram, the x-axis represents the relative energy consumed by each component during the usage phase, mainly offering lightweighting potentials. On the y-axis the sum of the relative energy expenditures of the BoL and EoL stages serve as the indicator of the potential for implementing design for circularity. The primary subassemblies of the system are depicted as individual points, with their total life cycle energy consumption represented as the sum of the energy used across all three life cycle stages.

An example of implementing optimization potentials is material selection, where materials (e.g., recycled steel, aluminum, and CFRPs) were evaluated alongside EoL strategies (e.g., re-use, remanufacturing, recycling, landfill). These were analyzed to enhance resource conservation through lightweight design and design for circularity, compared to the reference system that primarily uses virgin steel for components and landfill at the EoL (data in Table 7). Natural materials and bio-based composites were excluded from further investigation due to potential accuracy issues in long-term applications. Conceptual solutions are developed and illustrated in Fig. 5 for four energy-intensive assemblies: the gantry, pillars, carriage, and gripping unit.

In Fig. 6, environmental impacts are analogously allocated to the components of the system based on damage assessment at the midpoint level according to the ReCiPe 2016 method (Huijbregts et al., 2016, 2017). The trade-off diagrams for all 16 midpoint indicators can be found in Supplementary material 2. Fig. 6 presents the impacts for (a) global warming, (b) ionizing radiation, (c) fine particulate matter formation, (d) terrestrial acidification, (e) terrestrial ecotoxicity, and (f) mineral resource scarcity.

Table 7
Calculation results for the cumulative energy demand of the status quo of the semi-mobile handling system.

Part/ Assembly	Material (mainly)	Mass [kg]	E^{BoL} [GJ]	E^{MoL} [GJ]	EoL stategy	E^{EoL} [GJ]
A1 axle	Steel	442.1	288.1	5.2	Landfill	0.072
A2 axle	Steel	448.6	292.3	15.9	Landfill	0.074
A3 axle	Steel	386.0	251.5	89.3	Landfill	0.063
A4 axle	Steel	45.5	29.6	54.3	Landfill	0.008
A5 axle	Steel	22.8	14.9	39.1	Landfill	0.004
A6 axle	Steel	7.0	4.6	10.4	Landfill	0.001
Carriage	Steel	677.0	41.7	368.5	Landfill	0.090
Gantry	Steel	6139.7	209.7	0.0	Landfill	1.022
Energy chain	Steel	573.7	42.9	0.0	Landfill	0.068
Energy chain connection	Steel	197.5	10.8	0.0	Landfill	0.016
Gripping Unit	Steel	45.8	7.4	773.8	Landfill	0.011
Oil sump	Steel	1313.5	101.5	0.0	Landfill	0.331
Pillars	Steel	4144.4	252.2	0.0	Landfill	0.557

3.2.3. Opportunities and limitations

The analysis indicates that, from an environmental perspective and when balancing the entire life cycle, the implementation of sophisticated lightweighting measures is preferable to other design for circularity strategies only for highly dynamic components (e.g., gripping unit). In contrast, the opposite is true for static components: recycled materials (e.g., using recycled steel for the pillars as well as the gantry) drastically improve a product's environmental performance. Thereby, also enhancing the closed loop nature is largely preferrable: designing the pillars to be re-useable after their first life cycle in the presented plant, requires an estimated amount of five percent more material, but benefits the entire system in view of their circularity. For semi-mobile components (e.g., carriage), one-dimensional optimizations (only lightweighting or only circularity enhancement) may cancel each other out or do not yield the optimum, resulting in local trade-off surfaces that need to be evaluated in detail to achieve minimal environmental impacts while maintaining functionality. In the case study, the aluminum option with material recycling at the end-of-use enhances the lightweighting effects as well as the circularity performance of the carriage.

By analyzing environmental impacts with the proposed trade-off-analysis, it becomes possible to directly evaluate the overarching

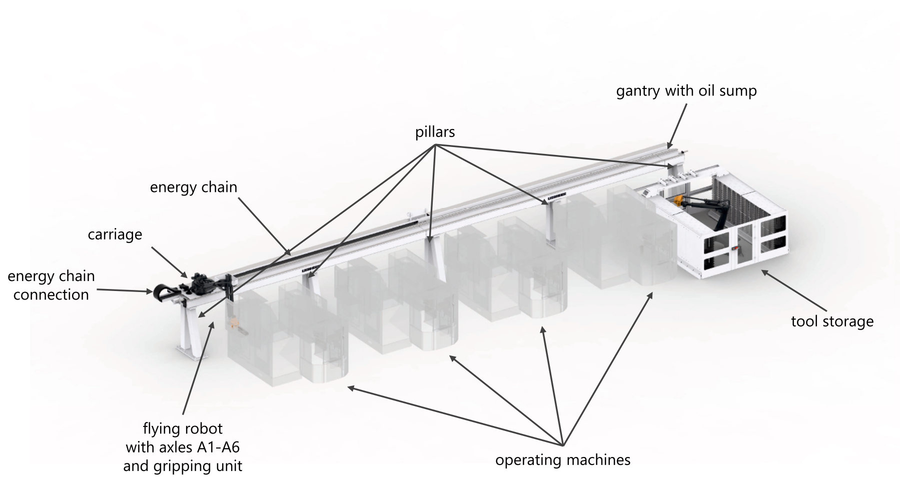
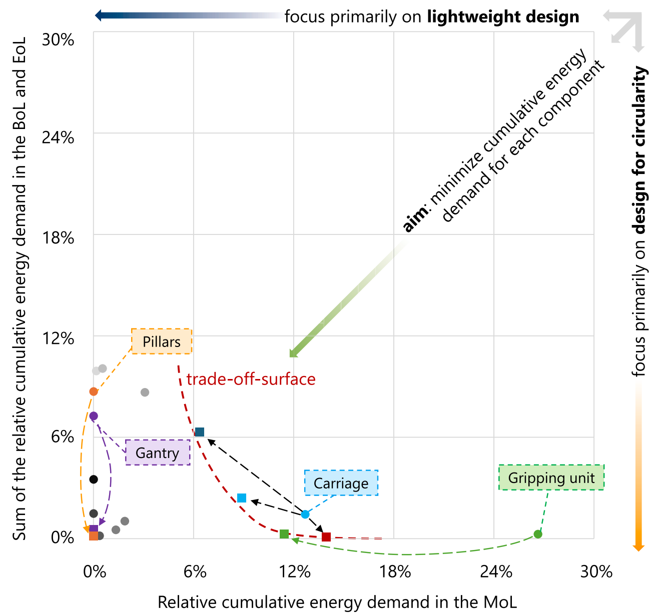


Fig. 4. Semi-mobile handling system and its main components.



Identified optimization potentials

Type	Material	Weight	EoL	E_{B+E}	E_M	ΔE_{PLC}
Gripping unit						
Ref.	Steel	98.6 kg	Landfill	7.4 GJ	773.8 GJ	Δ
LWD	CFRP	56.2 kg	Landfill	7.6 GJ	331.6 GJ	- 56.6 %
Pillars						
Ref.	Steel	4,144.4 kg	Landfill	252.8 GJ	0 GJ	Δ
DfC	Recycled steel	4,351.0 kg	Re-use	4.0 GJ	0 GJ	- 98.4 %
Gantry						
Ref.	Steel	6,139.7 kg	Landfill	210.7 GJ	0 GJ	Δ
DfC	Recycled steel	6,446.7 kg	Remanu-facture	15.2 GJ	0 GJ	- 92.8 %
Carriage						
Ref.	Steel	677.0 kg	Landfill	41.8 GJ	368.5 GJ	Δ
LWD	CFRP	192.2 kg	Landfill	182.9 GJ	184.2 GJ	-10.5 %
DfC	Recycled steel	710.9 kg	Remanu-facture	2.6 GJ	405.3 GJ	- 0.6 %
Opt.	Aluminum	393.0 kg	Recycling	69.9 GJ	257.9 GJ	- 20.1 %

Other components

A1 axle, A2 axle, A3 axle, A4 axle, A5 axle, A6 axle, Energy chain, Energy chain connection, Oil sump

Fig. 5. Positioning of trade-off-solutions between lightweight design and design for circularity with regard to their life cycle energy consumption.

benefits of implementing both lightweight design and design for circularity. As supported by other articles, material lightweight design does not address an impact reduction simultaneously within a wide range of impact categories. For instance, with regard to global warming and ionizing radiation (Fig. 6 (a) and (b)), this is the case. However, as illustrated for terrestrial acidification and mineral resource scarcity in Fig. 6 (e) and (f), design for circularity consistently emerges as the superior choice of design strategy for impact reduction. In addition, there are several impact categories – e.g., fine particulate matter formation and terrestrial acidification, as shown in Fig. 6 (c) and (d) – for which design for circularity also appears to be the more effective option, although lightweighting can likewise contribute to significant impact reductions in these cases. In general, increased circularity can yield an impact reduction in all aspects, whereas weight reduction only seems crucial for a limited number of environmental impact categories.

However, attributing environmental life cycle data or impacts to specific strategies can be challenging, particularly when there is no clear causality (e.g., water usage). This ambiguity risks oversimplifying the interrelationships between two disciplines, potentially resulting in misleading conclusions. In this study, we have focused on a life cycle stage-based allocation of lightweight design and design for circularity aspects. Taking into account the assumptions and limitations of our study and methodology, Fig. 7 schematically illustrates a generalization of the trade-off-analysis for resource conservation and environmental impact reduction, highlighting the potential for optimization when comparing design for circularity and lightweight design based on the findings of our case study. There are four possible directions in which a component's resource consumption or environmental impact might shift in our proposed diagram. This generalization is valid and applicable to other product systems only if the LCA places a strong emphasis on mass-related aspects and if the environmental impacts during the use phase are primarily driven by the dynamic movement of a physical product.

4. Discussion

The trade-off analysis between differing development objectives yielded results that are both coherent and actionable. These insights can be leveraged in the early phases of product development to inform the weighting of design objectives and requirements, thereby contributing to a more systematic, goal-oriented, and operationalizable development process.

Nonetheless, the general applicability of the methodology for differing objectives is constrained by a critical limitation: the availability and granularity of material-specific data, particularly concerning circularity indicators. While lightweighting products is common and established practice, including circularity metrics in product design has not been focused on a variety of development projects yet. This highlights the urgent need for standardized, high-quality, and regionally differentiated datasets to ensure quick and meaningful trade-off assessments. Furthermore, the analysis conducted in this study focused exclusively on material selection. As outlined in Section 2.3, potential synergies and conflicts between lightweight design and design for circularity extend well beyond material selection. Especially relevant are trade-offs between functional integration and joining technologies towards circularity performance and CE measures aimed at extending product lifespans with regard to their impact on weight reduction. Future research should therefore focus on two key areas: first, a critical examination of the suitability and sensitivity of available metrics for capturing such multidimensional trade-offs; and second, the development of methodological approaches to appropriately account for and manage uncertainties in the underlying data.

From a component-based analysis of energy consumption as one indicator for resource conversation, a general conclusion with regard to analyzing trade-offs for shared objectives is that lightweighting with resource-intensive materials is only environmentally advantageous for exceptionally energy-intensive, mass-moved products during the usage phase. Trade-offs with CE principles can emerge for less mobile products or components. In such cases, it may be environmentally preferable to focus more on design for circularity rather than pursuing lightweighting targets. Lightweight materials that are also circularly compatible (e.g., aluminum) offer substantial benefits when considering both strategies simultaneously. This is also a valid statement for some environmental impact indicators focusing on changes in the land system and resource availability. In future work, handling multiple environmental impacts simultaneously while avoiding problem shifting within should be addressed based on an absolute perspective of the Earth's carrying capacity as outlined in Section 3.2.1.1.

In general, energy consumption with cumulative energy demand as

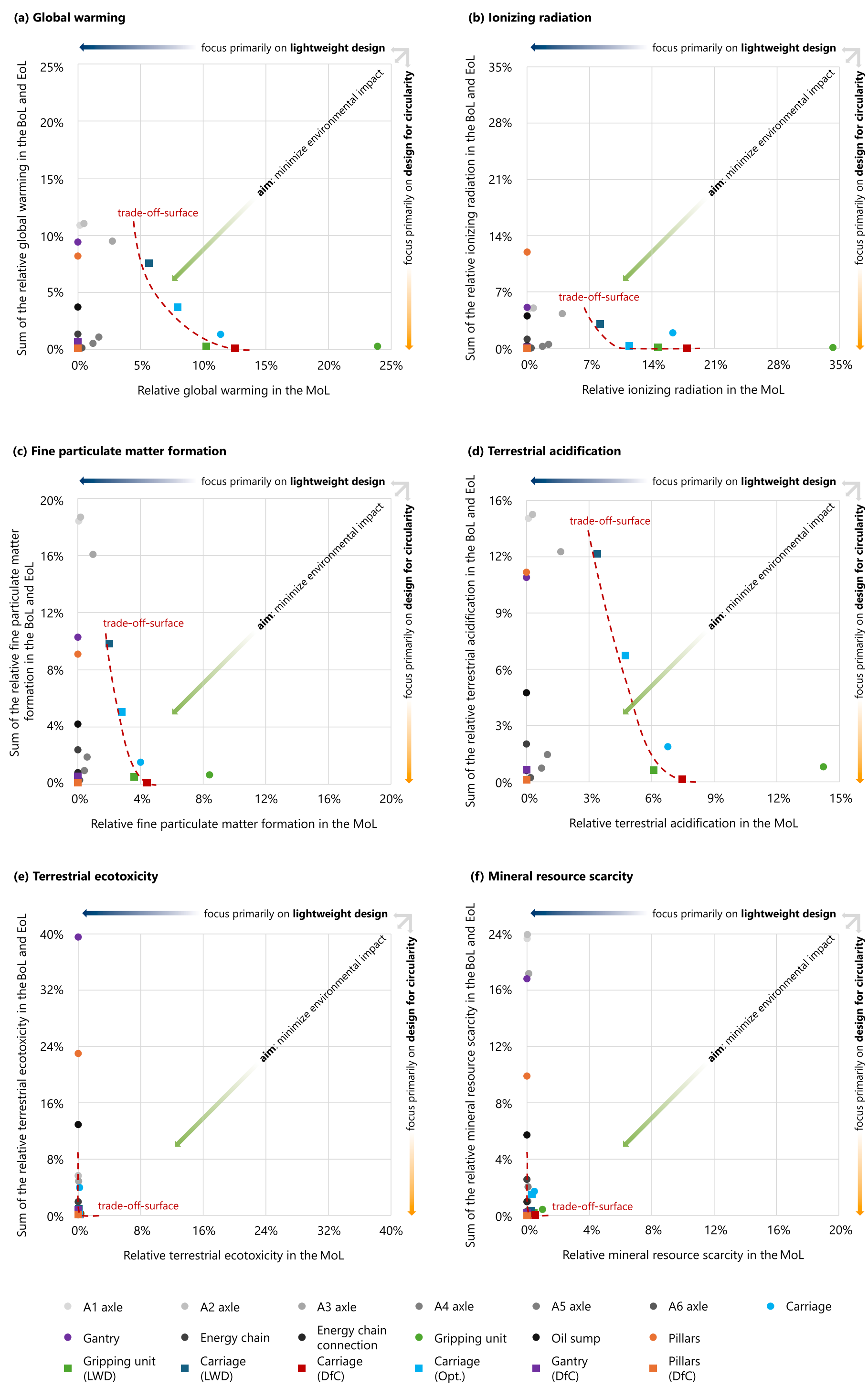


Fig. 6. Avoiding problem shifting between lightweight design and design for circularity based on an excerpt of life cycle impact assessment of the semi-mobile handling system using the ReCiPe 2016 method at the midpoint level. The entire impact assessment and all trade-off diagrams can be found in Supplementary material 2.

the indicator can be regarded as a valid for decision-making, particularly for identifying optimization potentials during the early phases of product development. The analysis conducted within the impact assessment reveals that both design strategies – lightweight design and design for circularity – do not contribute equally to the reduction of environmental impacts across all damage categories. In fact, over 80 % of potentials for environmental impact reduction in the categories terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, and mineral resource scarcity can be attributed almost exclusively to measures associated with design for circularity strategies.

In contrast, for categories such as global warming, stratospheric ozone depletion, ionizing radiation, ozone formation (human health), freshwater eutrophication, marine eutrophication, and fossil resource scarcity, both design for circularity and lightweight design prove to be similarly effective in reducing environmental impacts. Here, both energy savings through lightweight design and improved circularity performance can serve as significant levers for enhancing the

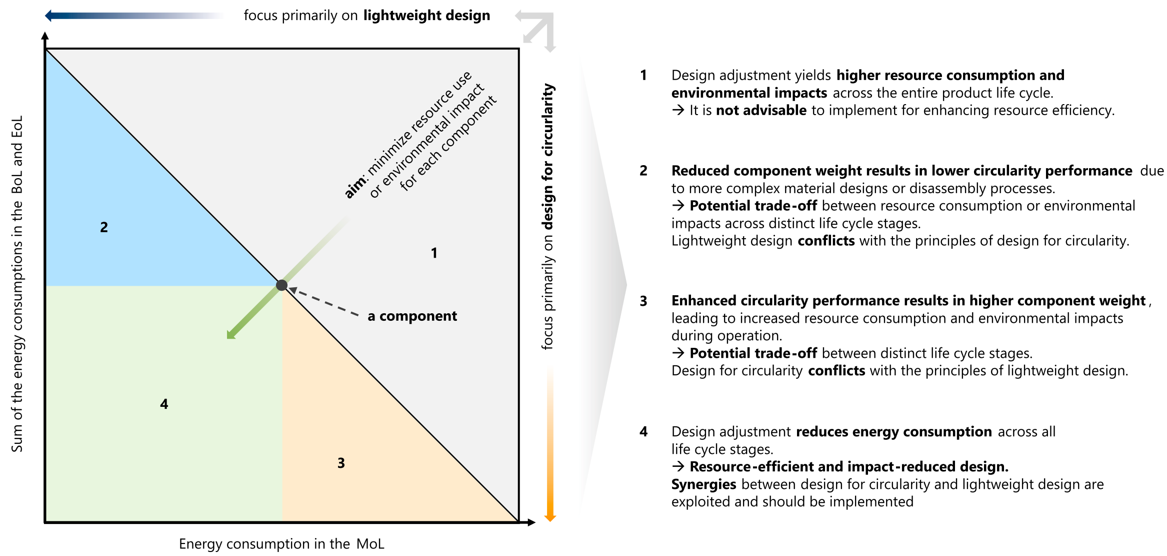


Fig. 7. Generalization for the identification of optimization potentials in a trade-off analysis with shared development objectives, e.g. minimization of resource use and environmental impact reduction.

environmental performance of products.

For the remaining impact categories – fine particulate matter formation, ozone formation (terrestrial ecosystems), terrestrial acidification, land use, and water consumption – design for circularity demonstrates slightly greater potential for impact reduction. However, improvements can also be achieved through lightweighting in these categories.

From a cost perspective, the methodology overlooks the economic considerations that drive the actual implementation of any optimization measure in products. In view of life cycle costing, it is conceivable to adapt the methodology to emerging costs along the product life cycle instead of resource consideration or impact reductions. Opportunities may arise to position businesses in a way that mitigates conflicts between both design strategies based on our proposed trade-off analysis with distinct development targets (e.g., material recycling of CFRPs). With regard to the strong definition of sustainability, giving the hierarchy of environment, society and economics, it is advisable to first evaluate and place the design options within absolute boundaries and then perform optimization based on the other aspects of sustainability.

Fundamentally, implementing CE principles is environmentally more promising in the long-term but requires significant infrastructural changes. In contrast, lightweighting measures are easier to implement in the short term while they are supposed to be less environmentally effective in the long-term. Therefore, the methodological approach has limited applicability regarding long-term comparability. However, it is possible that better options for preserving the value of lightweight materials will become available at an industrial scale, again questioning this limitation.

Overall, the trade-off analyses focused on material aspects. When considering other design aspects such as modular component design, shape optimization, and conceptual design elements, different conclusions may arise regarding the synergies or conflicts between

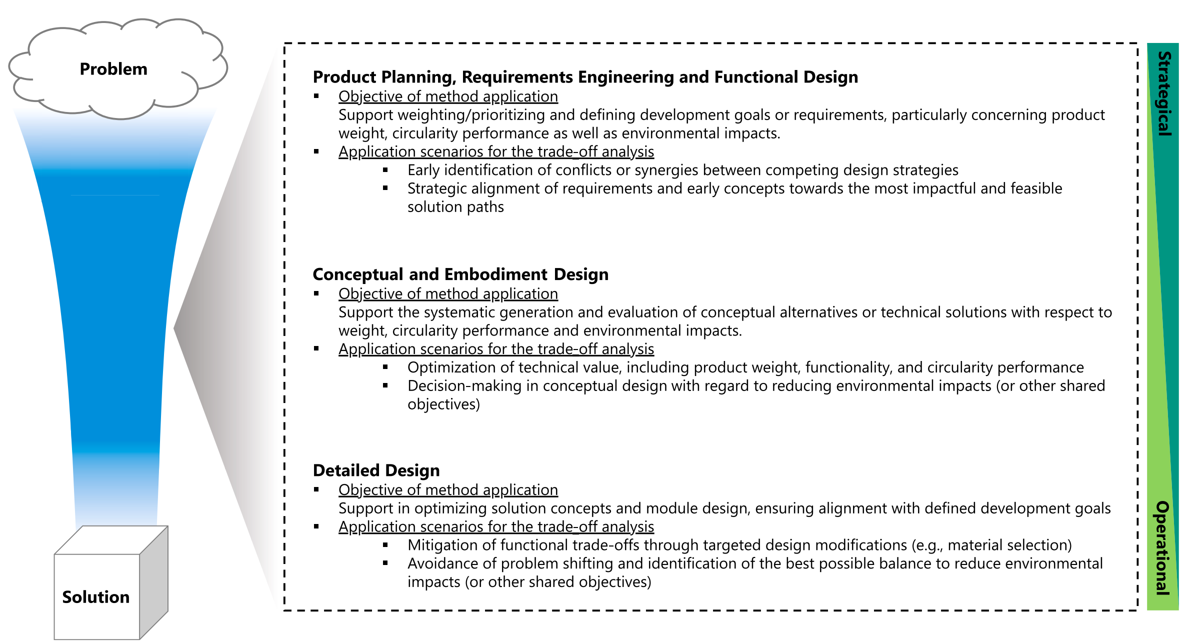


Fig. 8. Implementation of trade-off-analyses with regard to lightweight design and design for circularity throughout the product development process.

lightweighting and CE principles as illustrated on theoretical foundations in Fig. 2. Generalizing the findings from material-focused analyses to these other design aspects is not necessarily straightforward and may not yield comparable results. Therefore, the proposed generalization must be further validated across different design strategies and application sectors.

With regard to the process of product development a step-by-step approach as illustrated in Fig. 8 will be necessary to support effective operationalized implementation. Trade-offs commonly arise during product development, requiring decisions among multiple design alternatives. In the earlier phases and to support decision-making, goals are typically weighted based on requirements, corporate philosophies, or development objectives (Byggeth and Hochschorner, 2006). Therefore, in the intersecting field of lightweighting and CE strategies, understanding possible trade-offs seems crucial. We propose using the trade-off-analyses in the early phases for weighting, prioritizing and defining development objectives. In later phases, trade-off-analyses can be useful to support decision-making between conceptual alternatives and to achieve effective environmental impact reduction.

5. Conclusion and outlook

Driven by the global imperative to enhance resource conservation and environmental impact reduction for sustainable product development, the present work was motivated by contributing to insights into the relationship of two fundamental design strategies: lightweight design and design for circularity.

Therefore, a methodology to identify trade-offs between these strategies was proposed. Based on theoretical foundations, two approaches were examined: first, when different development objectives are pursued, lightweighting and circularity indicators can be compared to set priorities in decision-making for early phases of development and to evaluate the effects of one strategy on the over.

Secondly, when aimed at implementing both strategies for a shared development objective, in our case the reduction of environmental impacts, a methodology for allocating the impacts of each design strategy is necessary but enables systematic choices between design alternatives. This supports avoiding problem shifting between life cycle stages and environmental impacts in view of lightweight design and design for circularity and sets a methodological basis also for analyzing problem shifting between other mitigations options during product development.

Recognizing the limitations of the methodological framework, future research should focus on enhancing the robustness of the trade-off analyses by applying the approach to other industries, integrating economic factors and quantifying environmental benefits in relation to absolute boundaries. Such advances will further support eco-effective product development within LCE and contribute to sustainable development.

CRediT authorship contribution statement

Kristian König: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Simon Mörsdorf:** Writing – review & editing, Conceptualization, Visualization. **Michael Vielhaber:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clet.2025.101068.

Data availability

The data that has been used is confidential.

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