Decision Support for Lightweight Design and Design for Circularity: A Trade-Off Analysis

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Abstract. The need for resource efficiency in sustainable development and environmental responsibility 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. Therefore, the present work proposes a novel approach for trade-off analysis to facilitate decision-making in conceptual design. Illustrated by a case study on the development of a semi-mobile handling system, five fundamental design strategies for decision-making are identified and discussed. This enables a nuanced understanding of resource optimization in the context of complex design considerations and environmental requirements.

Keywords: Lightweight Design · Design for Circularity · Trade-Off Analysis · Ecodesign

1 Introduction

In response to mounting environmental challenges and resource constraints, the design paradigms 'lightweight design' and 'design for circularity' have emerged as key strategies for resource conservation. Lightweight design aims to reduce the weight of structures, enhancing material efficiency and energy savings [1]. Conversely, the circular economy (operationalized in design for circularity) seeks to extend product lifetimes as well as to narrow and close product and material loops [2]. Integrating these sustainability approaches presents complex decision-making challenges, requiring careful balancing of the benefits of weight reduction and circularity. Effective decision support systems are essential but often face obstacles, such as accurately assessing trade-offs between weight reduction and recyclability, lacking comprehensive frameworks for holistic environmental impact evaluation [3]. Focusing on the nano level of circular economy [4] for comparing products and components, in this paper, the following research question is addressed: 'how can trade-offs between lightweight design and circular economy principles be determined to optimize a product's environmental performance?'.

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2 Literature Review

2.1 Evaluating Lightweight Design for Environmental Sustainability

Lightweight design plays a pivotal role in enhancing environmental sustainability, particularly in dynamic products such as automobiles, aerospace, trains, or ships [1, 5]. The primary focus of lightweight design lies in reducing energy consumption throughout the dynamic usage phase centering on its potential to mitigate CO2 emissions [6]. However, other life cycle issues such as recyclability, repairability, or the technical lifespan of a product may also play a significant role in comprehensive evaluations [7]. Considering these aspects, lightweight design is not only seen as a means to reduce environmental impact but also as a measure to enhance functionality. Therefore, sustainability assessments should consider not only CO2 reduction potential but also technical robustness and the extent to which functional requirements are met in product development in order to more effectively satisfy customers. A holistic approach thus ensures that lightweight solutions contribute to environmental targets while maintaining or improving product performance, all within acceptable cost limits [8].

2.2 Methodologies for Assessing the Circularity of Products

The fundamental principles of circular economy for products and components are rooted in extending product lifespans as well as closing and narrowing product and material loops [2]. Consequently, assessment methodologies for circularity aim to systematically evaluate these principles either qualitatively or quantitatively. As this publication focuses on the nano level of circular economy, an overview of potentially relevant circularity indicators at this level can be found in the articles by De Oliveira et al. [9] and Patil and Ramakrishna [4]. To detail two specific examples, the 'material circularity indicator' [10] focuses on restoring material flows and assesses the degree of linearity or closed-loop nature of material flows within a product, leveraging life cycle assessment data for a straightforward determination. Conversely, the 'resource duration indicator' [11] (also known as the 'longevity indicator') evaluates not only the circularity of a resource but also its duration of active utilization. In essence, circularity indicators necessitate a departure from traditional sustainability metrics associated with the linear economy paradigm.

2.3 Decision Making Between Lightweight Design and Design for Circularity

Historically, lightweight design has been predominantly discussed independently of other design for environment strategies. However, within frameworks of circular economy development, lightweight design is often identified as a partial solution to minimize resource consumption [12], as exemplified in the 'resource pressure' method proposed by Desing et al. [13]. Specific methodologies for evaluating circular economy design strategies against each other are sporadic and suffer from methodological deficiencies. A common approach to decision-making and evaluation involves considering the so called 'Ashby Maps' proposed by Michael Ashby [14], comparing performance indicators of lightweighting (e.g., specific strength or stiffness) against environmental impacts (e.g.,

CO_2 emissions of primary material production), partly relevant for product circularity. For instance, Allwood et al. [15] assessed the technical lightweight performance (e.g., specific strength or stiffness) against the energy input of primary material production. Additionally, Ferro and Bonollo [16] examined the lightweight potential concerning raw material criticalities using 'criticality indicators', centering on product mass while neglecting environmental impacts throughout the entire product life cycle. Addressing the entire product life cycle represents the gap targeted in the 'functional life cycle energy analysis' by König et al. [3], which, however, exhibits weaknesses in identifying global optimization potentials and trade-offs due to the underlying mechanism in their bar plot [17]. In this context, the subsequently proposed methodology aims to complement these existing approaches addressing the research question.

3 Trade-Off Analysis for Supporting Decision Making in Product Development

3.1 Assumptions and Distinctions

In this publication, we consider the implementation of a circular economy and lightweight design as two essential strategies for enhancing resource conservation. Therefore, our methodology primarily targets products with dynamic usage phases, which can environmentally benefit from weight reduction. In contrast, realizing a circular economy may be relevant for all types of physical products. Thus, the proposed methodology may also be applied to non-dynamic products, although the identification of optimization potential may be limited. Given this background, we assume that dynamic products predominantly offer lightweighting potentials to minimize environmental impacts during their usage phase (mid-of-life, MoL). In contrast, the potential of implementing a circular economy lies in reducing environmental impacts at the beginning-of-life (BoL, e.g., by consuming secondary materials) as well as at the end-of-life (or end-of-use, EoL, e.g., by implementing a resource value retention option).

Our methodology is intended to be applied at the functional level of product development. Therefore, measurable impacts of physical components are methodically allocated to technical functions, for example, through a pairwise scheme, as these represent the functional unit at the smallest level in terms of performance comparison [3]. This approach evaluates the value of a product and allows questioning the necessity of each function. It also offers the greatest optimization potential, as entirely new solutions may subsequently be found using systematic solution-finding methods [18].

3.2 Quantifying and Assessing Trade-Offs

The fundamental objective of this research lies in determining the trade-offs between lightweight design and design for circularity. Therefore, the respective positive environmental benefits (or amount of reduced negative impacts) of both design approaches have to be evaluated. In general, a fundamental principle is that both design approaches can be implemented either in conflict, synergistically or with subordinate influence on each other, as discussed by König et al. [3]. Therefore, to determine potential trade-offs, it is essential to select indicators that enable a decision-making process effectively.

In this publication, we select energy consumption across the three main life cycle stages (BoL, MoL and EoL) as the indicator and measurement criterion for quantifying the environmental effects of both lightweight design and design for circularity, as previously done in an earlier work [3]. We attribute the sum of energy consumptions from the BoL and EoL (regained energy at the EoL stage is credited negatively in the calculation) stages to the circularity of a product (respectively technical functionality). Conversely, for assessing the benefit of lightweight design over the product's usage, we select the energy consumption during the MoL as the indicator.

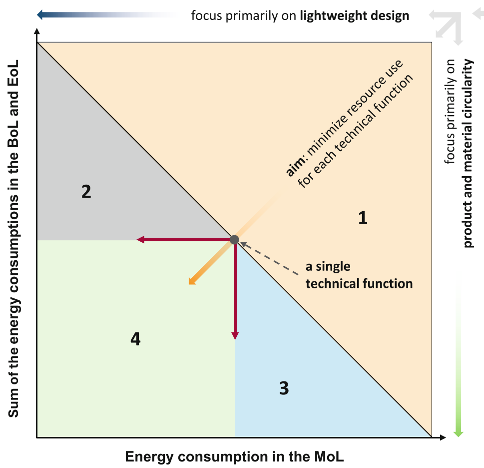
As energy consumption represent life cycle data and not an impact assessment indicator, it is fundamentally possible to choose indicators other than energy. The rationale for using energy consumption lies in its nature as a physically measurable quantity, which, as part of the life cycle inventory, has many useful implications for a product's environmental impacts (e.g., CO2 emissions) or costs (e.g., less energy consumption may mean lower costs). However, it is not a direct measure of a product's environmental impact and circularity. Probably, it is also more challenging to determine in supply chains compared to costs (direct exchange medium) and the CO2 footprint in future (within the framework of the 'corporate sustainability reporting directive'). Fundamentally, the choice of an indicator is ultimately up to the user of the methodology. The approach to determining trade-offs remains unaffected.

Conversely, particularly the circularity indicators discussed in Sect. 2.2 could be a meaningful choice for assessing the circularity of a product and thus its environmental sustainability. In that case, a different indicator would need to be chosen to evaluate the environmental benefit of implementing lightweight design. Here, potential CO2 savings during the usage phase of a lightweight product design could be considered. However, such an approach quickly becomes enormously challenging, as nearly infinite implications and potential impact shifting to other dimensions of sustainability (social and economic aspects) would need to be considered (and an evaluation of the indicators against each other may get necessary: 'is material circularity more important than CO2 footprint reduction?'). The resulting increase in complexity would then not be proportionate to the added value of the methodology, which is why we refrain from this for the time being. Simplicity and low complexity with goal-oriented insights are symbolic goals for the early phase of product development. The concept of trade-off identification does not fundamentally exclude such considerations and also includes a possible cost analysis in future iterations of methodological adjustments.

3.3 Determining Strategies for Reducing Resource Consumption

Considering our assumptions and the selection of indicators, a diagram can be constructed as illustrated in Fig. 1. In our case, we have indexed the energy consumption of the usage phase on the x-axis, representing the environmental potential of lightweight design. On the y-axis, the sum of the energy expenditure of the BoL and EoL stages is plotted as the indicator of the potential for implementing a circular economy. Each technical function is represented as a single point in the diagram, with its total energy consumption calculated by summing the energy expenditures of all three life cycle stages.

There are four possible directions in which a function can shift in terms of energy expenditure in the diagram. Increasing energy consumption without exploiting any



#	Description
1	Design adjustment yields higher energy consumption across the entire product life cycle → it is not advisable to implement for enhancing resource efficiency
2	Reduced component weight results in lower circularity as a consequence of a more complex material or disassembly → potential trade-off between the distinct life cycle stages LWD conflicts with the idea of DfC
3	Enhanced recyclability results in higher product weights, thus more energy is consumed during operation → potential trade-off between the distinct life cycle stages DfC conflicts with the idea of LWD
4	Design adjustment reduces energy consumption across all life cycle stages → Optimal resource-efficient design, synergies between DfC and LWD are exploited and should be implemented

Fig. 1. Concept for trade-off analysis methodology to support decision making between lightweight design and design for circularity.

potential benefits should generally be avoided (option 1) as it may lead to higher environmental impacts. The primary development goal of engineering should be to reduce energy expenditures by optimizing the product considering the surrounding product system across all life cycle stages (options 2–4). Thereby, each function may enhance a potential of implementing a circular economy (option 2) or a lightweighting measure (option 3), with the other strategy might be negatively impacted. The aim should be to ensure that the benefit of implementing the environmentally superior solution in one strategy does not result in a greater negative impact in the other. Ideally, lightweight design and design for circularity should be synergistically implemented (option 4).

3.4 Identifying Trade-Off as Local and Global Optimizations

From a global perspective, the most environmentally friendly product is the one that is not needed, as it requires no resources. Such a function would ideally combine lightweight design and circular economy principles (option 4) and would be positioned at the origin of the diagram. Thus, to find an absolute global minimum, it is crucial to first determine whether a function is truly necessary or if it can be dematerialized to minimize resource use, invoking the concept of sufficiency.

Many products inherently have negative environmental impacts. These impacts do not necessarily need to be completely offset, as long as operations remain within the Earth's biophysical limits [19]. Therefore, for essential functions that ensure customer satisfaction and are of high importance to the product, global minima cannot be at the origin. Such functions will always use resources (e.g., material and energy) throughout the product life cycle and may return them to the Earth's ecosystem. Depending on the function's characteristics, their impacts are more pronounced on either the BoL/EoL axis or the MoL axis. The goal is to find an acceptable level of resource consumption and identify the lowest impact while ensuring functionality along options 2–4. Local minima can also be identified within iterations: an existing solution is initially optimized slightly in one strategy; rethinking the functionality entirely and searching for an altered solution principle may harness greater potential.

One way to move beyond the depicted quadrant, which only illustrates negative environmental impacts, and instead, achieve positive effects across all life cycle stages may be through the application of the 'positive impact product engineering' methodology proposed by Mörsdorf and Vielhaber [20]. Their approach suggests compensatory measures in each impact category (in our example: energy) to mitigate impacts.

4 An Application Example: Optimization Potentials of a Semi-mobile Handling System

4.1 Description of the Use Case

To ensure that the preceding considerations are not purely theoretical, we discuss the potential identification in a semi-mobile handling system as an illustrative application example. This use case has been previously explained in earlier works [3, 21] and is revisited here. The system involves a portal robot mounted on a carriage that travels along a gantry (approximately 25 m in length), transporting tools from a tool storage to operating machines with a cycle time of about one minute per tool change.

4.2 Results of the Use Case Implementation

For Fig. 2, the proposed methodology was applied to the functional structure of the described system and the associated energy expenditures previously determined in an earlier study [3]. The results depict five possible implementation strategies along with illustrative descriptions. As an example of optimizations, material selection was considered, whereby different materials (recycled steel, aluminum, carbon fiber-reinforced plastics) were proposed for improving energy consumption for various technical functions compared to a baseline scenario (new primary steel for the respective components). 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 circular economy strategies for highly dynamic functions or components (e.g., 'generate holding force'). In contrast, the opposite is true for static components: closed-loop systems or materials (e.g., using recycled steel for the function 'place robot on duct') drastically improve a product's environmental performance, while lightweight measures seem elaborate and might only be minimally beneficial. For semi-mobile functions (e.g., 'move tool'), one-dimensional optimizations may cancel each other out, resulting in local trade-offs that need to be evaluated in detail to achieve minimal environmental impacts while maintaining functionality.

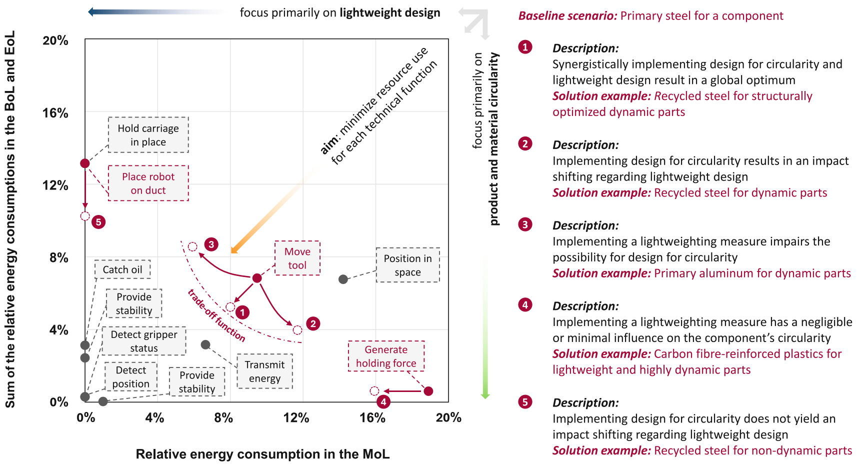


Fig. 2. Results of the implementation of the trade-off analysis on the use case example of the resource-efficient design of a semi-mobile handling system.

5 Conclusion and Outlook

Driven by the global imperative to reduce resource consumption, this study was motivated by the exploration of two fundamental strategies: implementing lightweight design and design for circularity. Therefore, the research question focuses on developing a methodology to identify trade-offs between these strategies. Based on theoretical foundations, a proposed methodology was presented and validated at the functional level of product development, specifically through material selection for technical functions of a semi-mobile handling system. This validation process yielded five distinct optimization strategies, which were examined and discussed. Future work may involve the usage of other indicators as well as exploring the methodology's applicability to physical components to enhance comprehension and application in practical contexts.

References

1. Herrmann, C., Dewulf, W., Hauschild, M., Kaluza, A., Kara, S., Skerlos, S.: Life cycle engineering of lightweight structures. CIRP Ann. **67**, 651–672 (2018)
2. Bocken, N.M.P., De Pauw, I., Bakker, C., Van Der Grinten, B.: Product design and business model strategies for a circular economy. J. Ind. Prod. Eng. **33**, 308–320 (2016)
3. König, K., Mathieu, J., Vielhaber, M.: Resource conservation by means of lightweight design and design for circularity-a concept for decision making in the early phase of product development. Resour. Conserv. Recycl. **201**, 107331 (2024)
4. Patil, R.A., Ramakrishna, S. (eds.): Circularity Assessment: Macro to Nano: Accountability Towards Sustainability. Springer, Singapore (2023)
5. König, K., Vielhaber, M.: Incorporating lightweight design and design for sustainability in product development - a meta-synthesis based on a systematic literature review. In: Proceedings of the NordDesign (2024, in press)
6. Kaspar, J., et al.: SyProLei - A systematic product development process to exploit lightweight potentials while considering costs and CO2 emissions. Procedia CIRP **109**, 520–525 (2022)

7. König, K., Vielhaber, M.: Analysis of the interrelationships between lightweight design and design for sustainability. Procedia CIRP **122**, 324–329 (2024)
8. Klein, B.: Leichtbau-Konstruktion. Springer Fachmedien Wiesbaden, Wiesbaden (2013)
9. De Oliveira, C.T., Dantas, T.E.T., Soares, S.R.: Nano and micro level circular economy indicators: assisting decision-makers in circularity assessments. Sustain. Prod. Consumption **26**, 455–468 (2021)
10. Ellen Mac Arthur Foundation: Circularity indicators: An approach to measuring circularity (2015)
11. Franklin-Johnson, E., Figge, F., Canning, L.: Resource duration as a managerial indicator for Circular Economy performance. J. Clean. Prod. **133**, 589–598 (2016)
12. International Organization for Standardization: ISO/DIS 59004:2023 (E) Circular Economy - Terminology, Principles and Guidance for Implementation (2023)
13. Desing, H., Braun, G., Hischier, R.: Resource pressure – a circular design method. Resour. Conserv. Recycl. **164**, 105179 (2021)
14. Ashby, M.F.: Materials Selection in Mechanical Design. Butterworth-Heinemann, Amsterdam (2005)
15. Allwood, J.M., Ashby, M.F., Gutowski, T.G., Worrell, E.: Material efficiency: a white paper. Resour. Conserv. Recycl. **55**, 362–381 (2011)
16. Ferro, P., Bonollo, F.: Lightweight design versus raw materials criticalities. Sustain. Mater. Technol. **35**, e00543 (2023)
17. König, K., Mathieu, J., Vielhaber, M.: A sustainability-driven comparison of methods for the identification of lightweight design potentials in product generation engineering. Procedia CIRP **122**, 145–150 (2024)
18. König, K., Zeidler, S., Walter, R., Friedmann, M., Fleischer, J., Vielhaber, M.: Lightweight creativity methods for idea generation and evaluation in the conceptual phase of lightweight and sustainable design. Procedia CIRP **119**, 1170–1175 (2023)
19. Steffen, W., et al.: Planetary boundaries: guiding human development on a changing planet. Science **347**, 1259855 (2015)
20. Mörsdorf, S., Vielhaber, M.: Positive impact product engineering (PIPE) model - the way to net-positive sustainable products. Procedia CIRP **116**, 474–479 (2023)
21. Scholz, J., Kaspar, J., König, K., Friedmann, M., Vielhaber, M., Fleischer, J.: Lightweight design of a gripping system using a holistic systematic development process - a case study. Procedia CIRP **118**, 187–192 (2023)