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Resource conservation by means of lightweight design and design for circularity—A concept for decision making in the early phase of product development

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ABSTRACT

Lightweight design can contribute to savings of consumed material in products and enhancing their energy efficiency during the use phase but also to a higher resource consumption at the beginning- and the end-of-life, challenging the implementation of a circular economy. Hence, this publication methodologically addresses the synergies and conflicts of lightweight design and design for circularity. The concept of the 'functional life cycle energy analysis' is presented, which foresees the division of a product architecture into functions with allocated energy consumptions as cross-stage indicator for the expected resource consumption along the entire product life cycle. Holistic optimization potentials within three life cycle stages can thus be derived as recommendations for action for future product generations. This allows engineers to rethink functional principles and supports decision making in the early design phases of implementing lightweight design and design for circularity. The methodology is illustrated by means of a robotics use case.

1. Introduction

In today's globalized world, product development is significantly characterized by generation development, meaning that reference products are commonly available (Albers et al., 2015). Besides building a reference knowledge basis, the previous generation also provides a benchmark for the target system in new development cycles. This evolutionary process relies on the interplay of analysis and synthesis methods to exploit a variety of optimization potentials in the best possible way (Haberfellner et al., 2019). While analysis methods serve to evaluate the effects of existing products or concepts on various objectives (e.g., costs or sustainability), synthesis methods facilitate the implementation of new solutions (e.g., creativity techniques or design catalogs) (Verein Deutscher Ingenieure, 2019).

As development objectives got more complex over the years, various 'design for X' (DfX) approaches have emerged to address on the one hand the achievement of (measurable sub-)goals ('design to X', DtX, e.g., costs or quality) or on the other hand the facilitation of further processes along product development (DfX, e.g., manufacturing or assembly) (Verein Deutscher Ingenieure, 2019). Influenced by political and social advancements regarding growing awareness about climate change and associated consequences for nature and human health, 'design for environment' (ecodesign) and 'design for sustainability' have emerged as the leading research topics in contemporary studies of discipline-specific product development (Ahmad et al., 2018; Brenner and Pflitsch, 2017; Wang et al., 2015). This primarily involves conscientiously balancing the three pillars of sustainability (environmental, economic, and social aspects), also known as the triple bottom line concept (Elkington and Rowlands, 1999; Ghisellini et al., 2016; Hacking and Guthrie, 2008; Hosseinpour et al., 2015). The environmental dimension of sustainability at the focus of the present work aims at the responsible use of resources and the reduction of negative environmental impacts (Glavič and Lukman, 2007; Hauschild, 2015; International Organization for Standardization, 2006). Among others, two implementation strategies that can enhance the achievement of these objectives of environmental sustainability are 'lightweight design'

Abbreviations: BoL, beginning-of-life; CE, circular economy; CFRP, carbon fiber reinforced plastics; DfC, design for circularity; DfX, design for X; DtX, design to X; EDA, energy distribution analysis; EoL, end-of-life; ETWA, extended target weighing approach; FLCEA, functional life cycle energy analysis; FMA, function mass analysis; LCA, life cycle assessment; LCE, life cycle engineering; LCEO, life cycle energy optimization; LWD, lightweight design; MBSE, model-based systems engineering; MoL, mid-of-life; PLC, product life cycle; RO, (Resource value) retention option.

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(LWD) (Herrmann et al., 2018; Kaspar and Vielhaber, 2017; König et al., 2023; Kupfer et al., 2022) and 'design for circularity' (DfC) (Ghisellini et al., 2016; International Organization for Standardization, 2023; Winans et al., 2017). The present work will focus on the intersecting field of these two strategies as shown in Fig. 1.

Researchers and practitioners consider the circular economy (CE) as the most significant lever since it operationalizes sustainable product development (Ghisellini et al., 2016; Murray et al., 2017), making it less vague for implementation (Naudé, 2011). Section 2 takes a deeper look at this topic, but CE basically capitalizes on the life cycle thinking of products. It emphasizes achieving environmental sustainability benefits by conserving resources through closing product and material loops as well as extending the useful life of products (Bocken et al., 2016; International Organization for Standardization, 2023). The philosophy of LWD can also reduce resources across the entire product life cycle (PLC) by on the one hand reducing consumed material in components through optimized structures (Choudry et al., 2018) or novel manufacturing technologies (Junk and Rothe, 2022; Priarone et al., 2023; Wegmann et al., 2022) as well as on the other hand minimizing emissions particularly in the product's use phase as a result of less required energy in dynamic products (Alonso et al., 2012; Caldwell et al., 2013; Delogu et al., 2016; Gonçalves et al., 2022; Koenig and Friedrich, 2011). However, advanced lightweight solutions like multi-material designs or composite structures entail increased efforts in production and challenge recovery processes in contrast to the benefits during the use phase (Liu et al., 2022; Poulikidou et al., 2015). This poses a challenge for LWD from a life cycle perspective within the context of the CE and raises the question whether or not the effort of lightweighting solutions is worth their savings of resources in products or rather an entirely circular design is preferable, especially in view of the rapidly increasing use of electric drives and renewable energies.

Focusing on the early development phase of a new product generation, the design freedom is at its greatest, with the result that the decisions made at this point strongly determine the environmental effects of any product. As it is expressed in the ecodesign paradox (Bhander et al., 2003; Chebaeva et al., 2021), in later development phases the possibility of exerting influence decreases sharply making changes highly laborious and thus uneconomical, particularly regarding DfC (Diaz et al., 2022). This emphasizes the importance of the early design phase for the implementation of the CE as also observed by Hapuwatte et al. (2022). To address this issue, this paper focuses on the functional aspects as part of the conceptual design allowing the following research question to be formulated:

'How can optimization potentials be identified to facilitate decision making when applying LWD or DfC to the development of new product generations and to offer insights into synergies and potential conflicts of both strategies aiming at an expected resource conservation over the entire PLC?'

To address this question, the present work proposes the 'functional life cycle energy analysis' (FLCEA) methodology that builds upon the current state of art and research in LWD and DfC. The methodology systematically supports engineers in decision making by clearly visualizing optimization potentials function-wise in a bar plot for strategically allocating development efforts between LWD and DfC to efficiently optimize future product generations towards a more responsible use of resources. Insights into synergies and potential conflicts between LWD and DfC can subsequently be found by the iterative application of the proposed analysis methodology and the subsequent comparison of results during product development. The FLCEA is presented within a methodological framework to ensure its proper implementation in the product development process.

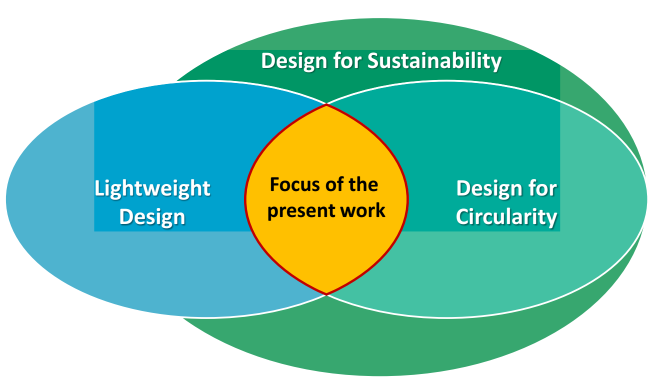

Fig. 1. Thematic arrangement of the present work in the intersecting field of LWD, DfC, and design for sustainability.

The following five steps were undertaken to develop the proposed framework and methodology for identifying optimization potentials and insights into synergies and conflicts of LWD and DfC:

Step 1: Identification of the state of the art as well as fundamental principles of both fields LWD and DfC.
Step 2: Identification of research gaps in the intersecting field of LWD and DfC, particularly regarding the trade-off analysis between LWD and DfC for decision making in conceptual design to exploit optimization potentials.
Step 3: Synthesis of a conceptual framework for the identification of optimization potentials providing insights into synergies and conflicts of LWD and DfC.
Step 4: Elaboration of the framework with specific methodological support along the process of product development.
Step 5: Validation of the methodology on a use case example including derivation of further improvement possibilities as methodological optimization potentials.

The following Section 2 presents the methodological background and state of the art of LWD and DfC within the context of product development (step 1), also highlighting its limitations (step 2). Section 3 illustratively presents the proposed methodology on the use case example of a semi-mobile handling system in three steps. In this section, the methodological framework is proposed first (step 3). Subsequently, the specific methodological support is explained in detail (step 4), followed by its validation on the use case example (step 5). Finally, a brief summary of the main outcomes and an outlook to future work is provided in Section 4.

2. State of the art

As this publication aims to propose a methodology for the identification of optimization potentials providing insights into synergies and conflicts of LWD and DfC, this section first introduces both disciplines in terms of their fundamental principles and methods, followed by a concretization of the research gap.

2.1. Design for circularity

Due to the growing significance of CE in politics and society, scientific research, particularly in product development, is increasingly focusing on how products can be designed to align with the concept of circularity (Kirchherr et al., 2017). Basically, DfC is defined in the upcoming ISO standard 59004 as *"design and development based on the circular economy principles"* (International Organization for Standardization, 2023, p. 18) and, therefore, operationalizes the implementation of at least parts of the CE within product development. It is strongly related to ecodesign (International Organization for Standardization, 2006) enhancing life cycle thinking and sustainable development. To clarify right from the start, in accordance with other authors (Kalmykova et al., 2018; Niero and Rivera, 2018; Rizos et al., 2016), DfC by itself won't be sufficient to fully realize a CE. Nevertheless, it is a key instrument. To establish a shared understanding, this subsection will first introduce the core principles of the CE before deriving implications for product development as the main objective of DfC.

2.1.1. The concept of circular economy

The fundamental aim of CE is to shift away from the linear economy paradigm (*'take, make, use, dispose'*) and, instead, focus on closing, slowing, and narrowing the loop of products and materials (Bocken et al., 2016). This has profound implications for product (re)design, as it necessitates considering stakeholders of all PLC stages in the early phase of development (Badurdeen et al., 2015; Boothroyd and Alting, 1992). Thereby, impacts typically encompass socio-technical aspects (Diaz et al., 2021). This implies that a mere technical (re)design is insufficient; society, industry and product users must also rethink their behavior. Thus, different levels of applying the principles of CE within the society are considered (De Oliveira et al., 2021; Patil and Ramakrishna, 2023; Saidani et al., 2017):

- *Macro level.* The advancement of the CE in spatial areas (cities, countries, regions or international groups) or sectors (such as mining or manufacturing) is regarded as the macro level. This involves redesigning and integrating industrial systems, the service delivering infrastructure as well as the social system and the cultural framework.
- *Meso level.* On the meso level, the focus is placed on groups or networks of collaborating industries enabling industrial parks and symbiotic relationships between diverse cross-sector companies, particularly focusing on the reuse of material waste.
- *Micro level.* The micro level pertains to CE progress for consumers, individual companies or organizations.
- *Nano level.* Due to the expansive scope of the micro level, many metrics identified as micro level circularity indicators may not appropriately cover the complexity of a CE for a specific product. This may lead to different interpretations and challenges in evaluating the effective performance of CE implementation in a product (De Oliveira et al., 2021). Therefore, the nano level was introduced to describe the circularity of products (including product as a service), components and materials along the value chain and throughout their entire PLC (Saidani et al., 2017).

Within this paper, we focus on the nano level of CE, primarily considering the environmental effects of products and their circularity. At this level of CE implementation, the so called 'xR typology' plays a central role. While numerous definitions of the R-imperatives exist, in this work, we draw from the comprehensive research conducted by Reike et al. (2018). In their contribution, they introduce a 10R typology that outlines 'resource value retention options' (ROs) based on two distinct literature reviews. Their typology encompasses two preventive options ('refuse' and 'reduce') and eight reutilization options (ranging from short to long loops: 'reuse', 'repair', 'refurbish', 'remanufacture', 'repurpose', 'recycle materials', 'recover energy', and 're-mine'). We propose one modification to this typology only for this contribution and our methodology: given that the 're-mine' option, within the context of a circular approach, typically follows a landfilling process, it may not be performed component-specific, and represents a distinct form of resourcing lost values, we further add the end-of-life option 'landfilling'. We are aware, that this end-of-life option does not align with the concept of a CE. However, it allows us to evaluate ROs of genuine CE against resource loss in landfilling. Thus, in our R typology, the option 'landfilling' corresponds to the linear economy paradigm allowing for a comparison of product design in both contrasting types of economy.

In addition to the current state of research and academia, the upcoming ISO standard 59004 (International Organization for Standardization, 2023), which is still in draft form, places a stronger emphasis on implementing CE in businesses. This standard bridges the gap between academia and industrial practice. While Reike et al. (2018) only differentiate between two categories (preventive and reutilization options), the ISO standard distinguishes a total of five categories: actions that create value (i), that contribute to value retention (ii), that contribute to value recovery (iii), that rebuild lost values (iv), and actions to support the transition to a circular economy (v). The last option (v) operates at a social and political level, thus shifting the focus away from products and associated opportunities. Consequently, this category is not further considered. Actual value creation (i) is facilitated through the implementation of, for example, DfC in the product development process. It serves as an overarching category that describes the operationalization of CE implementation possibilities for the different described levels. The remaining categories (ii – iv) are mostly comparable to Reike's et al. (2018) 10R typology but offer much greater detail and depth.

2.1.2. Integration of circular economy principles in product development

The integration of the fundamental principles of CE into product development is outlined conceptionally but remains rather vague to the specific possibilities of implementation. Hence, we would like to delve into this topic more deeply in this subsection, as we mentioned at the outset that for a CE, products need to be entirely reconceptualized. In the upcoming ISO standard 59004 (International Organization for Standardization, 2023), the category actions that create value (i) encompasses DfC and consolidates product development activities that implement the fundamental principles of CE within products, highlighting four key aspects:

- *Design for product and material recovery.* The focus of this implementation strategy lies in creating value at the end of a product's use by closing product and material loops. This typically involves distinguishing between biological and technical loops or cycles (McDonough and Braungart, 2010; Reike et al., 2018). In essence, a straightforward product disassembly, including material and component labeling, is necessary.
- *Minimize resource use.* While closing loops is considered as the primary and most impactful option for implementing the CE, the optimization of loops in terms of resource use should follow. This encompasses the use of secondary materials, the implementation of reduced material diversity, or LWD principles.
- *Design for product durability and long use.* This implementation strategy aims to design products for an extended lifetime, both from a physical and emotional perspective, with the goal of minimizing obsolescence in any form.
- *Design as a service.* This implementation strategy primarily emphasizes reducing the total number of products through the adoption of new business models that encourage sharing (e.g., product as a service).

The mentioned implementation strategies can be found in similar forms in numerous works such as Campbell-Johnston et al. (2020), Den Hollander and Bakker (2012), Yoshida et al. (2007) as well es Rahman et al. (2019). For instance, Desing et al. (2021) also describe strategies for resource conservation in a CE, including both improving value retention at the end of the PLC and extending product lifetimes while conserving resources during the manufacturing phase. However, only the globally recognized approach 'Cradle-to-Cradle' design by McDonough and Braungart (2010) presents a somewhat contrasting view. They advocate for waste as long as it serves as nutrition for other products, systems or nature. Resource minimization in terms of energetically optimized products is not focused on as long as renewable energy sources are in use.

In summary, in the field of CE, there is a growing presence of DfX approaches over the years, which transfer one or more fundamental principles into product development. Thereby, the terminology 'design for X' is consistently mentioned, illustrating that approaches of CE not only determine development goals (as opposed to DtX) but also necessitate a fundamental rethinking of interrelated processes (e.g., reverse logistics (Julianelli et al., 2020) or component recycling (Moraga et al., 2019)) and business models (e.g., product service systems (Kjaer et al., 2019)).

2.1.3. Methodologies to implement design for circularity

But how should these fundamental ideas of CE be methodologically implemented in the product development process, and what would be a starting point? Reike et al. (2018) distinguishe two life cycles. Whereas the '*produce and use*' life cycle focuses on material and product flows in the PLC and visualizes therein the ROs, within the '*concept and design*' life cycle, the ROs are mapped to product development activities, showcasing how they may influence design phases. It is notable that the development phase at which CE implementation occurs is crucial for the choice of the adequate DfX sub-strategy of DfC. If a RO influences the business model (e.g., reuse, repurpose), a strategic decision needs to be made explicitly before what is referred to as 'strict design' by Reike et al. (2018) encompassing embodiment and detailed design. Subsequently, e.g., 'design for circular business models' (e.g., product service system, industrial symbiosis) can be applied. In this context, the creative exploration of new solutions may be beneficial, so it can be conducted in advance of the typical product development process. This perspective is also shared by other authors such as Antikainen and Valkokari (2016), Potting et al. (2017) or Blomsma et al. (2019). Further ROs can be implemented in line with discipline-oriented DfX approaches, whereas, for almost every RO, there exist associated DfX approaches. For instance, sub-strategies like 'design for remanufacturing' (remanufacture), 'design for disassembly' (among others, e.g., re-use), or 'design for recycling' (recycle materials) come to mind. Thereby, it is essential to ensure that there are no contradictory implications for other methods and principles of CE resulting in an impact shifting. For comprehensive insights into discipline-specific DfX approaches for CE, references like Mesa (2023), Sassanelli et al. (2020) or Bocken et al. (2016) can be consulted. Recently, Riesener et al. (2023) published a paper outlining intersections of nine selected DfX sub-strategies of CE with ecodesign regarding the impacts on the different PLC stages, thus, enabling the derivation of fields of action. However, it is important to note that their work represents only a portion of the implementation possibilities of CE at the nano level.

Considering that a substantial proportion of product development activities encompasses generation engineering, Diaz et al. (2021) discerned the importance of directing particular attention to the early phases of the development process (notable in task clarification and product planning) emphasizing that decision support is pivotal in these phases. This is exactly the problem we want to address with our methodology to be presented in Section 3 by facilitating decision making in focusing on the two strategies LWD and DfC in the early phase of the development by offering practical methodological support to exploit optimization potentials and reveal insights into synergies and conflicts of LWD and DfC. To better delimit LWD from the other described strategies related to DfC, we will take a closer look at its fundamental principles and methodologies in the following subsection.

2.2. Lightweight design

Historically, the implementation of LWD was driven by the imperative of realizing product functionalities, such as enabling flights in the aviation sector by material substitution (Shanley, 1952) or ensuring structural integrity in buildings (Leonhardt, 1940). Subsequently, the engineering paradigm found utilization based on economic considerations (Ehrlenspiel, 1980; Lanner and Malmqvist, 1996), aimed at reducing operational costs, notably in aviation (Tsai et al., 2014) and the automotive industry (Artinian and Terry, 1961; Revfi et al., 2018; Sakundarini et al., 2013). In contemporary contexts, LWD has gained prominence, primarily driven by environmental reasons, particularly concerning emissions in the automotive sector (Kelly and Dai, 2021; Lewis et al., 2014). For instance, in Germany, LWD, together with the CE, is recognized as a key technology for achieving resource efficiency in various industries (Bundesministerium für Wirtschaft und Klimaschutz (BMWK), 2021).

The fundamental principle of LWD concerns the weight reduction of technical products or systems achieved through various measures, encompassing conceptual approaches (conceptual or system LWD), structural design (form LWD), material selection and (re)design (material LWD), or regarding manufacturing processes (manufacturing LWD) (Ellenrieder et al., 2013; Kopp et al., 2011). The following paragraphs require a basic understanding of these lightweight strategies, which can be acquired, for example, in Henning and Moeller (2020) or Klein (2013).

We focus in the following subsections on how to methodically identify lightweighting potentials along the product development process, since our proposed methodology shares the same purpose. Therefore, the most relevant analysis methods to exploit lightweighting potentials for resource conservation are presented. Synthesis methods as for example the LWD creativity method of König et al. (2023) as well as methods of DfC lacking a lightweighting perspective such as the function-oriented ecology analysis proposed by Riesener et al. (2023) are excluded. The explanations of the theoretical background build upon a thorough literature review in the context of LWD and design for sustainability (as a strategy overarching DfC). From this, we have identified the systemic LWD frameworks of Kaspar et al. (2022), König et al. (2023) and Hermann et al. (2018) as particularly relevant. Therefore, the following explanations are based on their works.

2.2.1. Function mass analysis and extended target-weighing approach

A significant step in the field of LWD methodology along the functional design was made by Posner et al. (2013, 2012) via the 'function mass analysis' (FMA). Since the method was upgraded a little later by the 'extended target weighing approach' (ETWA) (Albers et al., 2017), now also incorporating costs and CO2 emissions, the methodological approach of the ETWA is shown in Fig. 2 and explains also the principles of the FMA in analogy.

In the spirit of product generation engineering, the ETWA sets out from a reference system for which an optimization is aimed at a reduction of consumed mass, costs, or CO2 emissions (which together can be summarized as effort). The underlying concept of this method is that a technical function should not cause more relative mass, costs, or CO2 emissions as it is important for the fulfillment of the overall system function. For this purpose, existing components of the previous generation are matched to the technical functions enabling the allocation of efforts to the functions themselves. Therefore, a project team of experts is assembled, which evaluates the proportional contribution of a component to a technical function and enters it in the table shown in Fig. 2. Here, the experts are responsible for defining the level of detail. Analogous to the different levels of function modeling (from system function via subsystem functions to individual technical functions), there are also different levels of detail at the physical level, with either analyzing individual components or smaller assemblies that are functionally interrelated. Hence, the term subsystem is used for the division on the physical level, referring to either individual components or functionally related component groups.

To ultimately perform the analysis, the functions must be weighed against each other in terms of their importance to the overall system. The weighting of functions likewise takes place in a team of experts, for example, using a pairwise scheme. As a result, the functions can now be visualized in a bar plot with their effort in increasing functional importance order. After entering the regression line, which represents a visualization of the functional weighting within the bars, LWD potentials can be identified at areas where the efforts in mass and CO2 emissions lie above the regression line, but additional costs can still be accepted (e.g., function 1 and 2 in Fig. 2). The result of the methodology is thus a recommendation of action represented in a ranking of functions which should be optimized first in the next iteration within product

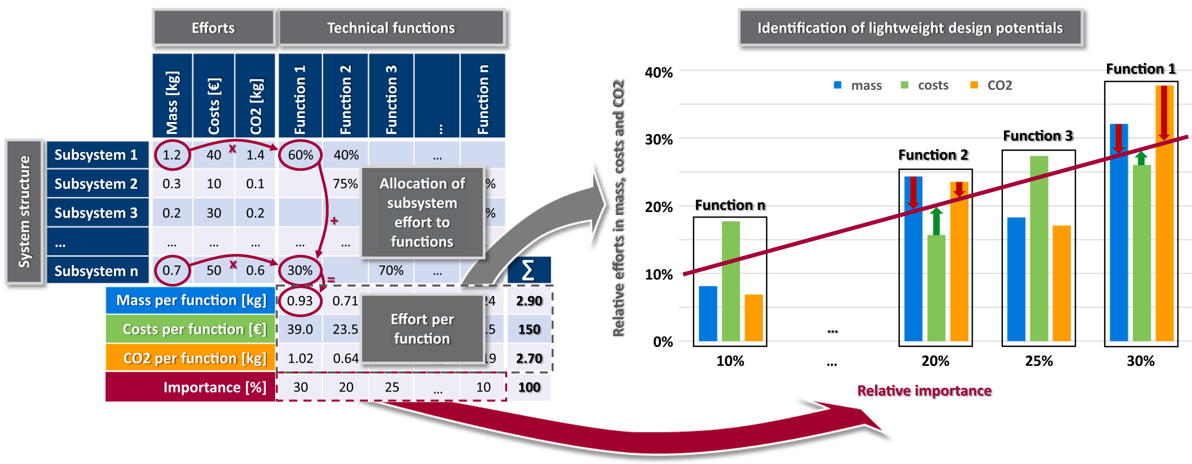

Fig. 2. Methodical procedure of the ETWA respective FMA, based on (Albers et al., 2017).

generation engineering in terms of mass and CO2 emissions.

However, the method is limited insofar as it gives no absolute improvements, but merely provides illustrative recommendations for action for subsequent optimization loops from a LWD perspective as outcome. The data collection for costs is based on a greenfield approach, whereas CO2 emissions can be determined by the previous product generation, for example via the 'life cycle assessment' (LCA) (International Organization for Standardization, 2006). Thereby, the environmental analysis focuses on the manufacturing and disposal processes of the individual components or functions, whereas no precise specification for determining the impact of the use phase is available for the same ones with a particular LWD focus. In general, a detailed view into the individual life cycle stages is missing. Instead, a decrease in CO2 emissions due to the implementation of LWD is assumed in each case. Apart from this, the impact of each component is in fact triple counted since the consumed mass influences the costs as well as the CO2 emissions to a similar degree (Revfi et al., 2018).

2.2.2. *Energy analysis for lightweight design*

From a LWD perspective, the mass of individual components and its concrete distribution generally dominate the environmental effects during the use phase of mobile products. In general, energy represents a comprehensive cross-stage indicator for this, as it is possible to consider influences from all life cycle stages and components, regardless of whether they are moving or not. Moreover, it is important to highlight that every material is associated with a certain amount of embodied energy, establishing a direct relationship between mass and energy. In general, this allows the potential of LWD concepts to be better exploited, as a compensation between distinctive life cycle stages is realized, which is especially important in regard to the significantly more extensive production and recycling effort of sophisticated lightweight solutions and materials such as 'carbon fiber reinforced plastics' (CFRP). In terms of the use phase, this is particularly interesting with respect to electric vehicles, since more efficient powertrains shift energy expenditures to manufacturing and the end-of-life treatment (Hannon et al., 2020). In terms of semi-mobile production systems, which Laufer et al. (2018, 2019) examined, lightweight potentials can be weighed up between moving and non-moving parts. A methodological framework is given with their 'energy distribution analysis' (EDA). A key aspect of their methodology is to include the state of motion of mass as well as its distribution for selecting the primary component for design optimization with respect to a weight reduction. This way, LWD ensures that the center-of-gravity as indicator for the mass distribution on the system level is considered preventing undesired effects of weight reduction within the mechanical system behavior and allowing LWD to be implemented at the most effective locations for each product. Hence, the methodology systematizes the idea of lightweight zones as described, for example, for car design by Haldenwanger (1997) or Friedrich (2013). In the EDA, the mass of a component, its moment of inertia and the energy of the movement are analyzed from a functional perspective of design to determine the mass-fraction factors resulting in a recommendation for an optimization order from a LWD point of view. However, even if cost effects of the product's use phase are newly included within the 'cost-benefit analysis' (Laufer et al., 2020), other effects due to materials and manufacturing processes or more comprehensive aspects such as a cross-component joining selection (Kaspar et al., 2019) are as of yet still not considered.

In contrast, O'Reilly et al. (2016) provide a comprehensive life cycle view in their 'life cycle energy optimization' (LCEO) methodology for vehicle development. The methodology supports in observing trade-offs between vehicle production, its operational performance, and its end-of-life from an energy perspective. Therefore, all energy consumptions in each life cycle stage are assessed, whereas the use phase is evaluated by simulating a car regarding the main driving resistances within different driving maneuvers in a system simulation. The methodology faces the material selection in automotive body components and enables their reasoned substitution as it assumes that the energy consumption among the entire life cycle dominates the environmental impact of a vehicle. Even if this would not be the matter, energy reduction over the entire life cycle certainly exploits benefits regarding the environmental impact of a product and conserves resources. For vehicles, this conclusion is obvious, since the use phase dominates the LCA and mass reduction offers a remedy, particularly for cars with combustion engines (Mayyas et al., 2012; Nemry et al., 2008). However, these potentials may not be logical for other products, which can have a lower degree of mobility during the use phase. For this purpose, a generalization for other industries and products of O'Reilly's et al. approach is missing. Therefore, the following subsection focuses on the life cycle engineering (LCE) of lightweight components in order to derive a generally valid statement.

2.2.3. *Life cycle engineering of lightweight structures*

Fundamentally, there is a correlation between LWD and the environmental sustainability of a product since LWD often provides a powerful tool for improving the product's resource efficiency in terms of material or energy consumption. An in-depth overview of the benefits in individual industries of LWD from a life cycle perspective covering different fields of application can be found in Herrmann's et al. review (2018). They formed a framework around LCA for the analysis of lightweight products and the subsequent exploitation of potentials for environmental sustainability. In general, LCA can be used for such processes of decision making in product development from a sustainability perspective (Schneider et al., 2019) emphasizing the usefulness of his approach. However, the LCA methodology has one major challenge, as it is only applicable in the later phases of development since environmental effects of products can only be determined at these later phases (Chang et al., 2014).

Another difficulty is that LWD has various impacts that cannot be evaluated against each other in a standardized way, even in LCA. For example, Laufer et al. (2019b) derived various criteria that can be used as indicators to exploit lightweighting potentials. Unfortunately, it is not clear which indicators are appropriate for which product. A familiar example is the automotive sector, where LWD is used to reduce greenhouse gases caused by the use of fossil fuels, as shown, for example, in the publications of Del Pero et al. (2017), Hillebrecht et al. (2014) and Lewis et al. (2014). However, this relationship becomes less obvious when looking at electric mobility and a broadened life cycle view (Mayyas et al., 2012, 2017). The LCE of lightweight components is therefore not yet fully refined from a methodological point of view and still requires further research in certain areas, which are summarized in the following subsection.

2.3. Circular economy and lightweight design

2.3.1. Distinction and assumptions

Taking the insights from the various scholarly contributions discussed, we can synthesize that LWD, as an engineering philosophy today increasingly aiming at enhancing resource efficiency, fundamentally represents a sub-strategy for the implementation of the CE in products. This thesis is underscored by the upcoming ISO standard 59004 (International Organization for Standardization, 2023) listing LWD as a means of implementing the ‘minimize resource use’ strategy of DfC. Similarly, the 10R typology of Reike et al. (2018) can be interpreted by subordinating LWD to the R1 ‘reduce’ option. In addition, for instance, Desing et al. (2021) also consider LWD as a means of conserving resources in manufacturing processes for a CE.

We share this viewpoint that emphasizing resource conservation through LWD, either by a reduced material consumption and consequently less required energy in manufacturing (Allwood et al., 2011), or reduced impacts (energy and emissions) during the use phase of dynamic products, implies synergies with CE. Thus, we allow to interpret LWD as a sub-strategy of DfC in accordance with other authors (Mestre and Cooper, 2017). Besides these aspects, extending product lifetimes through increased emotional value associated with technically outstanding lightweight products may encourage users to handle products more carefully and use them for an extended period (related to ‘design for product durability and long use’). In essence, there are fundamental positive interrelationships between LWD and DfC, as both strategies can align with similar objectives.

However, alongside these synergies, contradictions are also known. For example, highly sophisticated lightweight solutions can lead to end-of-life issues (Das, 2021; Lewis et al., 2019; Witik et al., 2011). Functionally integrated, lightweight products pose a challenge for developers, as structures may not be separable into pure components or materials, contradicting the principle of product and material recovery for closing loops (Chatziparaskeva et al., 2022). Furthermore, lightweighting solutions might shift beneficial resource savings during the use phase to other stages of the PLC, implying that a lightweight product may require more effort in production or at the end of its useful life (Delogu et al., 2018; Dér et al., 2019; Herrmann et al., 2018; Hottle et al., 2017; Kaluza et al., 2017). Considering individual lightweight materials like CFRP, not only is the end-of-use and material recycling challenging, but also measures to extend the lifespan, such as repairability, easy maintenance and modularity, may be at odds with lightweight solutions (Allwood et al., 2011; Gumpinger et al., 2016; Herrmann et al., 2018; Timmis et al., 2015). This includes lightweight-oriented manufacturing and joining techniques like adhesives, which can complicate easy product disassembly (Kellens et al., 2017; Peng et al., 2018; Soo, 2018; Soo et al., 2014). In the past, the lightweight strategies were historically implemented independently of such considerations related to the CE. Notable illustrations of such instances include their implementation in motorsport (Ellenrieder et al., 2013) and aviation (Timmis et al., 2015). The growing effort to integrate them into the CE becomes increasingly significant, especially given the criticality of lightweight materials (Czerwinski, 2021; Ferro and Bonollo, 2023). Basically, they have to be fundamentally reconsidered to align with the specific requirements of CE.

Given these interrelationships, we believe that LWD and DfC can fundamentally coexist in products synergistically. However, in the use phase resource-efficient and outstanding lightweight solutions may increasingly hinder the closing of product and material loops compared to conventional designs on the one hand, and potentially contradict a design for increased physical durability regarding repairability, easy maintenance, and modularity on the other hand. At the same time, a DfC can result in a rebound effect (Zink and Geyer, 2017), in the sense of an increased energy consumption during the use phase due to an increase in weight as a result of re-dimensioning for longer durability or the use of circular materials with higher specific weights. Therefore, we address both design disciplines, LWD and DfC, within this publication. We consider - with our methodology described in the following section - only products that exhibit a certain degree of mobility during the use phase, so that potential energy savings and emission reductions can be achieved through increased lightweighting efforts in product development. At the same time, we assume that DfC primarily aims to close loops at the end of a product’s use. To specify our research gap, we will summarize the identified shortcomings in the next subsection.

2.3.2. Deficits and research gap

The findings of the scientific works in the intersecting field of LWD and DfC discussed in the preceding state of the art are summarized in Fig. 3. The fulfillment of aspects that we consider particularly relevant for the FLCEA methodology are highlighted. It is evident that the presented contributions primarily focus on isolated aspects within the disciplines of functional design, energy analysis, LWD, or DfC.

A concept combining these aspects to particularly specify optimization potentials within the functional design based on an energy analysis over the entire PLC for revealing insights into potential synergies or conflicts of LWD and DfC in the early phases of product development is subsequently missing. This would support engineers in deriving strategies for the efficient employment of LWD and DfC strategies during the development and thus ensure the design of energy-optimized product generations effectively improving environmental effects and resulting in an expected resource conservation across all life cycle stages. To fill this gap, the FLCEA methodology within the methodological framework is presented in the following section.

3. The concept for the functional life cycle energy analysis methodology

This section presents the general concept of the proposed methodology and discusses the proceeding during application. Fig. 4 displays the proper integration into the product development process in the early design phase at the level of functional design.

3.1. Methodological framework

The underlying concept of the presented methodology is the treatment of the design task as a holistic energy efficiency problem for which an optimum has to be found incorporating all life cycle stages by using the principles of LWD and DfC within product development. Therefore, the FLCEA methodology intervenes within the functional design and utilizes valuable life cycle data across the entire PLC. Among these are data of manufacturing and transport processes at the beginning-of-life (BoL), usage data in the mid-of-life (MoL), as well as key data from

Level of fulfillment: ● ◔ ◑ ◕ ● (low → high)

	Functional design	Specific metho-dical support	Life cycle engineering: Beginning-of-Life	Life cycle engineering: Mid-of-Life	Life cycle engineering: End-of-Life	Focus on light-weight design	Focus on design for circularity	Discussion of syn-ergies and conflicts	Energy analysis	Generalizaton across industries
FMA (Posner et al., 2012, 2013) & ETWA (Albers et al., 2017)	●	◕	●	◑	●	●	●	◑	◑	◕
EDA (Laufer et al., 2018, 2019a)	◑	●	◔	◕	◕	◕	◕	●	●	◔
LCEO (O'Reilly et al., 2016)	◑	◑	◕	●	◕	◔	◔	●	●	◔
Herrmann et al. (2018)	◔	◕	●	●	●	●	◔	◔	◔	●
Kaspar and Vielhaber (2017)	◔	◔	◕	◑	◑	●	●	◔	◔	◔
König et al. (2023b)	◑	●	◑	◑	◑	●	◔	◔	◔	●
Cradle-to-Cradle (Braungart and McDonough 2021)	◑	●	●	●	●	●	●	◔	◔	◕
Desing et. al (2021)	◑	●	●	●	●	◔	●	◔	◔	◔
ISO/DIS 59004 (2023)	◑	◑	●	●	●	◔	●	◔	◔	●

Fig. 3. Identification of the research gap by reviewing existing approaches.

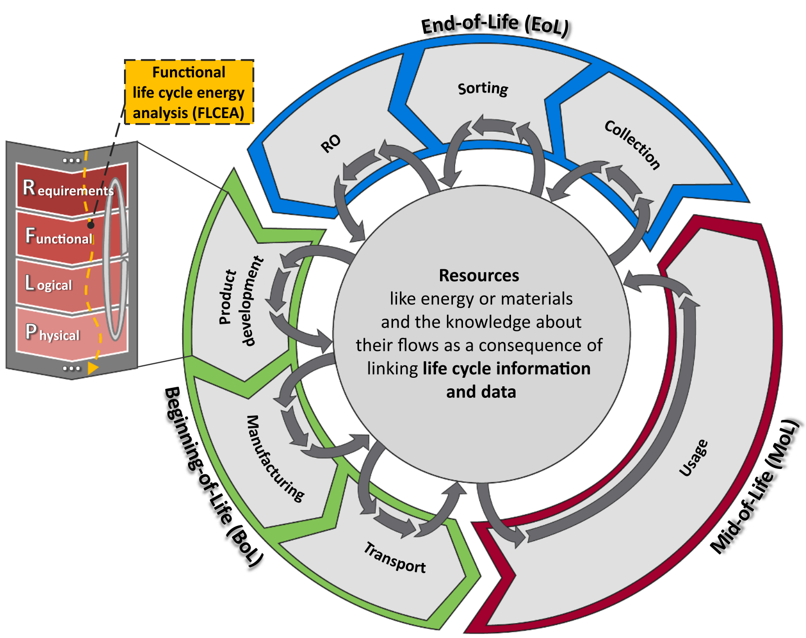

Fig. 4. Methodological framework for the application of the proposed FLCEA methodology in product development.

the handling of the product at its end-of-life (EoL, also indicated as end-of-use as mentioned by Nasr and Russell (2018) or Hapuwatte (2022)). These data, within their respective contexts, represent the basic information for the implementation of the FLCEA methodology. Thereby, a fundamental principle of the methodological framework is that each product is in exchange with the environment at every stage of its life cycle. Hence, it allows the product to consume a variety of resources across the PLC (e.g., materials in manufacturing processes or energy in use), but also to recirculate them back into the same or perhaps to a completely different product and its life cycle at any time (e.g., material waste from manufacturing or energy recovery in EoL). Thus, based on the acquisition of the life cycle data and their linkage with the life cycle stages (processes and efforts they generate), a fundamental information basis is created. From this, knowledge regarding the optimization of resource flows can emerge through the implementation of the FLCEA methodology. When this information with the respective data can be meticulously collected, as discussed in Section 2.2.3, LCA emerges as a widely employed approach for assessing environmental impacts of products. Typically, its application occurs in the later phases of development and is not feasible for the early design phase (Broeren et al., 2016), thus, complicating the implementation of optimized concepts due to the ecodesign paradox (Bhander et al., 2003; Chebaeva et al., 2021; Ehrlenspiel and Meerkamm, 2013). Additionally, the resource-intensive data and information collection process incurs substantial costs. In contrast, the proposed FLCEA methodology is specifically designed for next generation products and is thus applied in the early phases of development, drawing upon information and data from reference products (outlined in Section 3.2). For efficiency reasons and LWD as one of the main research topics, the FLCEA methodology requires only mass-related energy data. If such data have already been gathered during a LCA for a reference product, it is advisable to leverage this existing dataset. The LCA is done component-wise, which significantly limits the space for finding solutions. In order to preserve the interface with engineering ingenuity and creativity, the FLCEA is conducted at a functional level in advance of a typical LCA implementation. For a comparable visualization and presentation of the results, the FLCEA uses a function-wise bar plot. This builds the foundation for a comprehensive comparison of different reference products or concepts which are analyzed with the FLCEA methodology allowing for offering insights into synergies and potential conflicts of LWD and DfC to specify the best possible solutions for the respective use case.

3.2. Definition of reference products

The fundamental requirement, as shown as the first step of the application of the methodology in Fig. 5, is the availability of a reference product, which can be an earlier product generation, a competitor product or the result of a previous iteration of development. Alternatively, when multiple concepts for the new product generation are available during development, these could also be specified as reference products. This is particularly relevant when analyzing synergies or conflicts between LWD and DfC. For example, when comparing a sophisticated lightweighting concept with one containing circular materials as a consequence of the implementation of DfC, an interesting question arises: whether the use of sophisticated lightweight materials nullifies the resource savings from a closed material loop, despite significant savings in the use phase, or if more circular materials are more favorable.

Based on the analysis of the reference product with the proposed methodology, recommendations for action can be derived. Subsequently, the definition of at least one reference product represents the first step. At this point, the system boundaries as well as the EoL strategy as ROs of the product and its components must be specified.

3.3. Decomposition into functions

The main part of the methodology focuses the data and information acquisition and allocation to functions as part of the product architecture. First, in order to create assessable units, the product is divided into technical functions in analogy with Albers et al. (2017) and Posner et al. (2013, 2012). This decomposition of a product into functions is a common process step in product development and serves the purpose of opening up the solution space by enabling an abstract thinking within functional domains. To emphasize the importance of functional design, it is declared as a separate phase in the well-known RFLP approach (an acronym for requirements engineering 'R' as well as functional 'F', logical 'L', and physical 'P' design) of 'model-based systems engineering' (MBSE) (Kleiner and Kramer, 2013). In general, a function is considered as a standalone building block that can be integrated into a larger system. This can either be a component, divisions of a component, but also a complete subsystem or system. The significant advantage considering functions is the possibility of completely redefining the concept of implementation along with the operating principle if the requirements fulfillment for the respective function is still guaranteed. In addition, a better quantification of the contribution to possible customer requirements or benefits is realized since the MBSE approach ensures traceability between the 'R' and 'F' view of design. Furthermore, the evaluation of functions aligns with a key principle of environmental analysis in LCA, where functional units serve as the reference units for quantifying the performance of a product system. In this context, technical functions represent a corresponding subcategory at the subsystem level for evaluating the performances of individual components within a product system. This enables the assessment of reference flows from the existing product generation to be compared with new operational principles for technical functions in future, optimized product generations in a standardized way.

Before analyzing the consumed energy among the entire PLC, the relative importance for each of the functions with respect to their contribution to the overall system functionality is calculated, as, for example, with a pairwise scheme. For illustrating this, the decomposition is shown at the example of a gripping system for a portal robot in Fig. 6. Thereby, the function (i) fulfills the purpose of realizing the structural integrity of the whole assembly by providing mounting points and absorbing the forces during movement, whereas unit (ii) ensures the correct positioning of the whole subsystem. Function (iii) holds the tool in place and unit (iv) compensates any vibrations or offsets for realizing an accurate positioning.

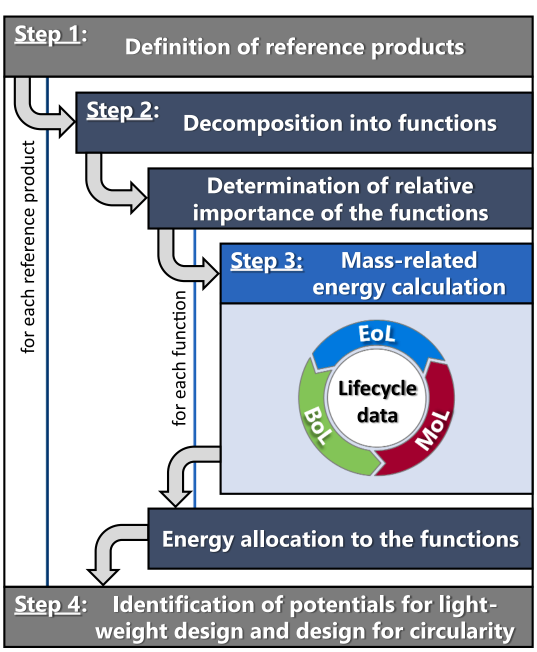

Fig. 5. Application method of the FLCEA methodology within the functional design of product development.

3.4. Mass–related energy calculation

From a sustainability viewpoint, the methodology foresees the division into the three main life cycle stages 'BoL', 'MoL' and 'EoL', as it is in analogy with Kiritsis et al. (2008) or Terzi et al. (2010). The BoL stage is characterized by the product development, the production processes like raw material extraction and manufacturing as well as the transport of both the materials to the manufacturing plants and the final product to its location of use. The product's use is the main focus of the MoL stage, which is also characterized by service as well as maintenance of the product. Within the EoL stage, the implemented RO of the product consisting out of its components is observed in detail. Therefore, a variety of ROs such as disposal with or without thermal energy recovery, a material recovery or the reuse of the refurbished product itself, certain subsystems, or components can be conceivable. For a reasonable assessment of the efforts in the individual life cycle stages for each

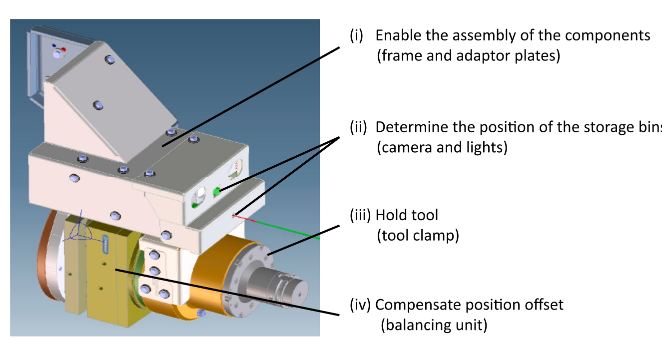

Fig. 6. Decomposition of a gripping system into technical functions.

function of a lightweight solution with one another, the cumulated energy consumption was chosen as the central cross-stage life cycle indicator. Energy and mass, which are essential from a LWD point of view, are in the use phase directly related to each other via the energy equations as proposed by Laufer et al. (2018, 2019). In the case of mass reduction, this directly decreases the amount of consumed energy in the MoL. In addition, a general correlation between the values of CO2 emissions, costs, and energy consumption has been identified by Ashby (2021) for material extraction and production processes emphasizing the importance of the BoL and MoL and eliminating the need to consider multiple distinct values for these life cycle stages. Due to the ongoing research in terms of efficiency gains in existing processes as well as the development of novel production technologies, a reasonable degree of uncertainty is undeniable, especially in the early phases of product development (see the ecodesign paradox). Subsequently, the procurement of reliable data and information plays an essential role at this point, since this is the only way to realize a meaningful comparison of concepts and the resulting determination in the early phase can only be corrected in later phases to a limited extent and at great expenditure according to the ecodesign paradox (Bhander et al., 2003; Chebaeva et al., 2021; Ehrlenspiel and Meerkamm, 2013). Thus, the use of defined data acquisition is essential to ensure the quality of the results. The overarching objective of this methodology is to preserve the total energy demand throughout the entire PLC. Given the anticipation of applying this methodology during the early phases of product development, which are characterized by high levels of uncertainty, it becomes viable to leverage global correlations with other environmentally and CE relevant variables, such as CO2 emissions. This can be achieved by employing energy as a comprehensive cross-stage indicator, as previously elaborated upon in Section 2.2.2. For this purpose, various calculations are performed within step three of the methodology, which are specified in the following paragraphs. The proposed equations serve as a basis and are highlighting important aspects which should be considered for a reasonable implementation of the FLCEA methodology. The considered level of detail may also depend on the available data and information.

Beginning-of-Life: The energy calculation in the BoL is carried out based on the decomposition of the analyzed product into functions. Hence, the calculated energy E_i^{BoL} for the BoL of each i-th function is assessed according to Eq. (1) and thus consists of the energy required for material procurement, the unit manufacturing, the transportation of each unit to the location of assembly mounting and the assembly of the whole product itself. If several components act as a group in a functional subsystem, the manufacturing steps of each component must be considered with respect to their energy expenditures. If functions share assemblies or components, energy fractions have to be assigned to both functions accordingly.

$$E_i^{BoL} = E_i^{material} + E_i^{manufacturing} + E_i^{assembly} + E_i^{transport} \quad (1)$$

The material energy consumption $E_i^{material}$ depends on whether recycled or new primary material or a combination is used and needs to be defined accordingly. If a specific recycling fraction is precisely determinable due to circular material life cycles, this can be accounted accordingly. Alternatively, comprehensive material databases can provide a remedy for this. The manufacturing energy $E_i^{manufacturing}$ is required to quantify the efforts of the manufacturing processes and steps, whereby the processes are typically divided based on the cohesion of particles of a solid body (Deutsches Institut für Normung e.V, 2022). The cohesion is either created (primary forming), maintained (forming, rearrangement of material particles), reduced (separation, separation of material particles) or increased (joining, coating, inclusion of material particles). Material losses should be considered proportionally in the calculation and should generally be minimized as much as possible. Whereas $E_i^{manufacturing}$ function-wise considers all energies required to manufacture the individual components, $E_i^{assembly}$ accounts for the effort required to integrate each component into the product assembly. The latter includes particularly energies for joining processes or assembly mounting. The transportation energy $E_i^{transport}$ is derived from the respective form of transportation, i.e., by train, truck, or plane regarding the volume or mass of each component. All the included energies are highly mass dependent and thus relevant for exploiting LWD and DfC potentials.

Mid-of-Life: The energy calculation in the MoL, according to Eq. 2, consists of the estimated cycles of usage based on the typical user behavior, while each cycle includes the expenditures of kinetic energies (E^{kin}) for translation (t) and rotation (r) as well as the resulting effort as a consequence to changes in the potential energy (E^{pot}) for each function. A cycle of usage is defined as a closed sequence of movements with a matching start and end position. The use phase of a product can be composed of several different sequences of movements (indicated as m) and their respective number of cycles (indicated as n). Unless a specific cycle is known, a simplified replacement model can be used to provide a representation of the product's dynamics in the use phase. For example, the WLTP ('worldwide harmonized light vehicles test procedure') cycle for the fuel consumption of cars can serve for this purpose (Fontaras et al., 2017). Besides, factors influencing the efficiency of any energy transformation at the product and the possibility of energy recovery must also be considered within the calculation. Depending on the available data, the consumed energy in the MoL E_i^{MoL} can either be calculated based on physical testing, numerical simulation, or analytical calculation. Measurement during physical testing is the best option regarding accuracy but is also the most elaborate method and requires a physical product, which is not feasible in any case and challenges the allocation of energy consumptions to functions. An analytical calculation can be used as a rough estimate, while numerical simulation provides a best of both worlds' solution. Particularly for mobile products like motor vehicles this phase is essential due to the high dependency of mass and mass distribution.

$$E_i^{MoL} = n \cdot \sum_m \left(E_{i,m}^{t-kin} + E_{i,m}^{r-kin} + E_{i,m}^{pot} + E_{i,m}^{recovery} + E_{i,m}^{loss} \right) \quad (2)$$

End-of-Life: The energy consumption of each function in the EoL E_i^{EoL} is calculated according to Eq. 3 and describes the energy return of the components as a consequence of their EoL treatment. Thereby, the energy for disassembling the product into each function, the sorting energy for each unit to its specific RO-process as well as the energy required for the implementation of the RO are consulted. Depending on the RO, the sorting energy for the unit as well as the RO energy might differ.

$$E_i^{EoL} = E_i^{disassembly} + E_i^{sorting} + E_i^{RO} \quad (3)$$

System view: Since the implementation of a RO can extend at least a component's life cycle (as for example within the ROs 'reuse', 'repair' or 'remanufacture') by its integration in another or the same product's life cycle, this influence has to be taken into account within the energy calculation of the system-in-development. At the same time, a component may need to be replaced during product use, for example, due to wear. For this purpose, a lifetime estimation must be made for both the entire product as well as its individual functions and corresponding components. In turn, this can be used to calculate a number that indicates the lifetime of each function i relative to the lifetime of the entire product. Therefore, we define the factor k_i as the quotient between the estimated lifetime of the entire product and the potential lifetime of each function i. The greater k_i is (at least greater than one), the longer the product will last in comparison to the physical solution of the corresponding function i. As a result, the physical component that is responsible for realizing function i must be replaced (including another cycle of production, transport and installation) or repaired at least once throughout the product's useful life if the function should still be performed by the system. The larger k_i becomes, the more frequently these kinds of service occur. Only if k_i exactly equals one, a component will last as long as the product. It can thus be decisive for the product's useful lifetime. Vice versa, the smaller k_i is (at least smaller than one), the greater is the potential useful life of the component of the i-th function in comparison to the actual useful life of the product. Then, at the end of the product's use phase, the product as a whole unit is actually at its EoL, whereas the component of the i-th function could still operate, resulting in a theoretical remaining useful lifetime for the component. Hence, if k_i is less than one, a function-preserving RO (short to medium loops) should be implemented for the system-in-development if possible, allowing the component to continue operating in another product after its use in a first product's life cycle. In contrast, if k_i is greater than or equal to one, this triggers measures to extend the component's and, as a consequence, function's lifetime. In principle, k_i ensures an integer multiplication of the effort of the i-th function in the BoL and EoL, since the component has to be repaired or replaced (manufactured, removed, and reinstalled) each time. For the calculation in Eq. 4, k_i is defined as always greater than one, because each component is used in the product under investigation within the FLCEA methodology at least once. This represents only a constraint in the calculation for the energy expenditures over the PLC and should be seen separately to the explanations for handling components in terms of value retention depending on the actual amount of k_i.

Besides, the energy for the transportation process in the BoL for transporting the assembled product from the production to its location of use as well as the consumed energy for its return to the location of disassembling has to be calculated and then assigned to the functions.

In total, first the cumulated energy over the entire PLC including all stages is calculated as the sum of the consumed energy for each function with respect to their number of demands k_i. The calculation method of the cumulated energy for the assembled product is shown in Eq. 4.

$$E^{product} = \sum_i E_i^{PLC} = \sum_i \left(k_i \cdot E_i^{BoL} + E_i^{MoL} + k_i \cdot E_i^{EoL}\right) \quad (4)$$

3.5. Result visualization and interpretation

As part of the last step of the FLCEA methodology, the results of all preceding calculations are visually presented in a uniform way, that engineers can identify optimization potentials and gain insights into synergies and potential conflicts of LWD and DfC to subsequently derive recommendations for action. Therefore, the energy consumptions of each life cycle stage associated to the functions are depicted in a bar plot, as shown in Fig. 7 for the use case of a semi-mobile handling system. The system-in-development in the case study involves the transportation of heavy tools between manufacturing machines and a tool storage using a flying robot. This robot features a 6-axis system and a gripping unit. During its operational phase, the robot transitions between a tool storage and four processing machines, with a cycle time of approximately one minute. Transportation is achieved using a carriage mounted on a duct consisting of guide rails and an oil sump. The entire unit is supported by a structure consisting of pillars with an energy chain. This setup introduces varying levels of dynamics. While the support structure remains stationary throughout usage, both the carriage and the robot, including its gripping unit, move dynamically. The estimated useful lifetime of the system is approximately 25 years. For a more detailed discussion of this use case, please refer to the work of Scholz et al. (2023). The objective of this case study is to strategically distribute forthcoming development efforts utilizing our methodology. This approach aims to optimize the design of the plant to be conceptualized in the context of future implementation, particularly within the discourse encompassing LWD and DfC for the system's functions.

Within the bar plot, the energy consumptions corresponding to each life cycle stage are distinguished (yellow for BoL; blue for MoL; green for EoL), and the values are cumulated over the entire PLC (orange frames). Optimization potentials can be identified by observing the black regression line, which represents the relative importance of each function on the vertical axis, since each function is only allowed to consume proportionally as much energy as it is important to fulfill the overall system function (comparable to principles of the FMA (Posner et al., 2013, 2012) or ETWA (Albers et al., 2017) approaches). Negative relative energy consumptions in functions in the EoL can result by value retention in certain ROs. In this case, recovered energy is calculated as negative in the EoL but has a positive effect to the total energy consumption regarding the entire lifecycle. Thus, the orange frame in Fig. 7 represents the signed sum of the three life cycle stages. One of the simplest forms of energy recovery is thermal material recycling, whereby energy is directly released.

For example, the function 'provide stability' is attributed with a negative value due to an estimated partial reuse of the architecturally constituent pillars. Here, the manufacturer estimates that three of the five pillars used in the semi-mobile handling system could also be reused

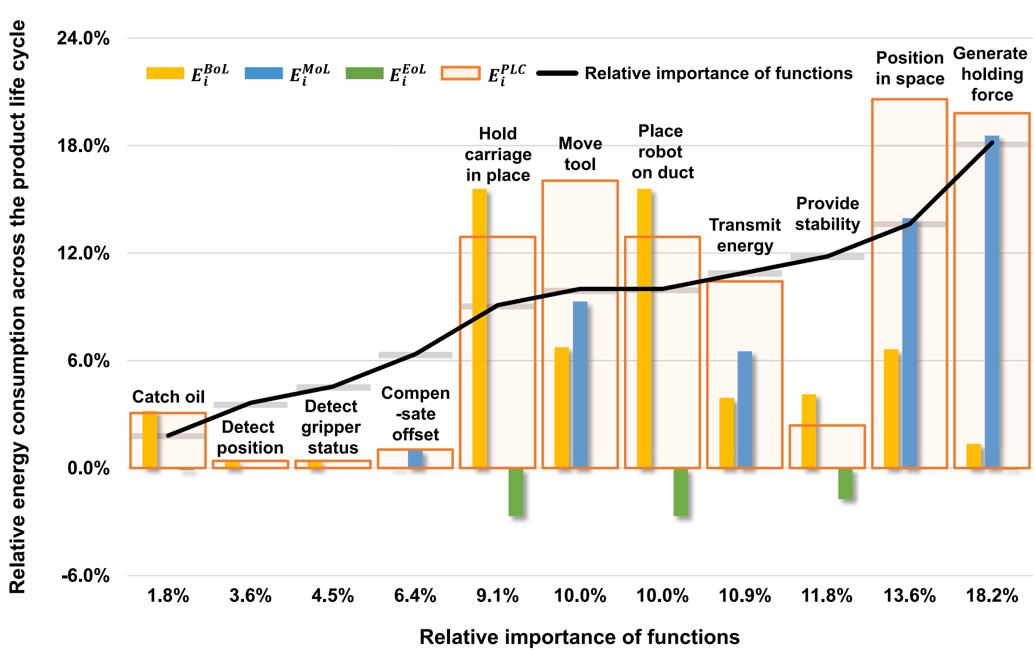

Fig. 7. Results of the application of the FLCEA methodology on the use case of a semi-mobile handling system.

in another product in the same form in 25 years. Thus, after subtracting energy expenditures for disassembly and reverse logistics, the BoL energy of the three pillars (66.456 GJ) is partially re-credited in the EoL as a negative energy amount (–27.921 GJ). This negative amount mostly contains the efforts for raw material extraction and manufacturing processes of the components. In principle, it cannot be greater in amount than the energy of the BoL, since there are unavoidable energy consumptions in the product's course along the three life cycle stages (e.g., losses in material processing, wear and tear in the use phase, in particular also effort in transport and assembly/disassembly). In relative terms, the value added through reusing the pillars at the end of the product's use thus credits about 42 % of the 'provide stability' BoL energy to the system again.

In contrast to the reuse of the pillars, the oil sump, likewise composed of metal, physically solves the abstract function 'catch oil' and creates value in the EoL in the sense of material recycling (longer loop as the RO 'reuse'). Just less than 4 % of the energy expended in the BoL (51.366 GJ) is recovered in the EoL as a result of the material reprocessing steps. This is the result of expensive recycling processes (among others: transport, disassembly, cleaning, re-melting) as well as a medium percentage of material remanufacturing (about 50 %). In principle, the more negative the energy amount of the EoL is, the more positive it is for the overall system, since it describes recovered energy, which is included in the overall energy calculation with a negative sign.

The graphical visualization clearly highlights functions in need of improvement in energy consumptions while allowing to directly trace back increased energy consumptions to the different life cycle stages. In further development steps, synergies and potential conflicts between LWD and DfC can be derived. The individual energy bars of the life cycle stages are used for this purpose. If the MoL is energy intensive, LWD should primarily be considered as an optimization strategy. Vice versa, in the case of an energy intensive BoL without or just a low energy recovery in the EoL, strategies for closing product and material loops, extending the useful life of individual components, or designing with secondary materials are preferable. In principle, the implementation of DfC might offer more potentials for resource conservation regarding the entire PLC in this case. As long as all life cycle stages exhibit energy efforts, trade-offs between LWD and DfC can possibly evolve. A primary optimization strategy in one of the two disciplines can then shift energy expenditures to other life cycle stages. For example, if a measure to improve product disassembly (e.g., screwing instead of welding) is implemented including the application of a material circularity strategies (e.g., recycle material), the product may become heavier in weight. Then, due to the closing of the material loop, the sum of the energy expenditures in the BoL (positive amount) and EoL (negative amount) can be reduced, but the energy consumption in the MoL of the product can become higher as a consequence of more mass to be moved in the use phase. To uncover these possible conflicts, it is either necessary to compare multiple reference products or to apply the methodology iteratively for different concepts (LWD vs. DfC) so that the shifts in energy consumptions in the bar plot represented by the bars of the life cycle stages can provide insights into possible compromise solutions. However, this does not necessarily imply a conflict of objectives. Depending on the implementation strategies, synergetic effects between LWD and DfC may also emerge (e.g., topology optimization of a steel component).

For instance, regarding the presented case study, certain functions, such as 'hold carriage in place' or 'position in space', reveal increased energy consumptions relative to their functional importance. The function 'hold carriage in place' describes the purpose of cinching the carriage in position on the support structure, enabling the robot to move along the guide rail between the tool storage and the processing machines. The function demonstrates no potential for improvement in terms of the MoL, since all components remain stationary during the operational phase. In contradiction the 'position in space' function necessitates a thorough reassessment with regard to the product's use phase. The constituent components of this function are extensively moved during operation, as the function is an abstract description of the 6-axis robot moving on the guide rail. In contrast, the 'hold carriage in place' function displays significant effort in the BoL with just a low energy recovery in the EoL. However, the function 'transmit energy' (energy chain for providing the energy between the energy connection of the entire plant and the robot) seems to be well designed since the relative energy consumption matches the relative importance of the function.

Basically, an increased emphasis on LWD is promising during the use phase, particularly when redesigning rapidly and extensively moving components, as part of the function 'position in space'. Here, even a small weight reduction can result in significant efficiency improvements across the entire PLC. However, highly sophisticated lightweight materials such as CFRP often have higher resource consumptions than conventional alternatives especially in BoL and EoL. When reevaluating new design concepts with the FLCEA methodology, these normally overlooked aspects, can be included and an optimal concept for the specific use case can be identified. In this robotics use case, one could analyze whether the use of carbon fiber parts within the function 'hold carriage in place' indeed reduce resource consumption or if secondary impacts in BoL and EoL void the efficiency gained during the MoL (potential trade-off). Here, in view of lightweighting strategies, measures other than material selection to conserve resources that do not negatively affect the EoL treatment may also be appropriate (concept or form LWD). This includes, for example, structural optimizations improving physical stability and structural integrity, while still allowing for reuse in the future at the end of the product's use.

DfC aspects may also be implemented for the 'position in space' function. However, due to poorer material characteristics, which can for example be caused by a higher recycling fraction due to secondary materials or the use of short- instead of long-fiber reinforced plastics, would lead to more material consumption to match the structural properties when using non-recycled material. As a result, the energy consumption would increase due to the dynamics of the constituent components in the use phase, thus implementing a DfC measure is less advisable at the outset but can be beneficial in the second step of optimization. Basically, the energy consumed by the additional weight must be lower than the energy saved using the more circular material. The FLCEA can subsequently be used to grasp insights in synergies and potential conflicts between energy savings across the three life cycle stages.

DfC is particularly promising for optimizing functions containing non-moving parts and a high material consumption such as 'hold carriage in place', which have major energy consumptions in BoL and EoL. Here, the reduction of transport route or the implementation of a valuable RO can thus significantly reduce the effort for BoL and EoL without an increase in energy consumption in the MoL.

However, the best-case scenario would be the combined use of LWD and DfC principles. This could be the case, when using a strong, easy to manufacture and circular material for the function 'generate holding force' such as aluminum and additionally employing a topology optimization for further weight reduction. Depending on the use case this solution is then more sustainable then a slightly lighter highly sophisticated CFRP solution as a result of a lower material circularity.

Since the FLCEA allows for solution finding in the functional design space more creative solutions for example a rope construction instead of steel guide rails to serve the 'hold carriage in place' functionality can be specified. The rope structure would not only have significantly less weight but is also easier to transport which enables additional savings in the BoL and EoL. This empowers engineers to think outside the box and find completely new solutions which are beneficial in lightweighting as well as regarding the product's circularity.

4. Conclusion and outlook

The presented methodology enables the life cycle-spanning optimization of new product generations with regard to their energy consumption at functional design phase. Through the implementation of the methodology, optimization potentials as well as insights into synergies and potential conflicts for decision making in between LWD and DfC can be identified, thus providing an answer to the formulated research question. The methodology foresees the energy consumption as cross-stage indicator for exploiting lightweighting and circularity potentials regarding the entire PLC as it significantly affects other key factors for lightweighting and CE, such as costs or CO2 emissions. This is supported by the fact, that the electricity mix is not entirely renewable until now and significantly varies from country to country. In general, the authors expect fossil energy sources to be replaced in the medium term with most of the mobility then becoming electrified or based on other energy resource types. Thereby, a reduction in energy consumption is inevitable, whether fossil fuels or renewable energy sources are used. In terms of sustainability, however, this is not an impact endpoint parameter, meaning that specific effects to nature, climate, or human health in the case of energy minimization or increase are undefined and cannot be considered. Therefore, further environmental impacts should be kept in mind, which remains the responsibility of the adopters of the methodology. The authors recommend considering more comprehensive and detailed approaches, such as LCA, as complementary methodologies in later phases of development. This is particularly advisable when more precise data and information become available. Additional factors for including secondary effects, including CO2 emissions, water consumption, and location-specific considerations across the entire value chain and throughout the PLC, should be incorporated at this juncture. Furthermore, the FLCEA methodology can be validated to ascertain whether resource conservation was indeed achieved by using the energy in the early development phase as a cross-stage indicator.

A still challenging point of the FLCEA methodology is the reliance on data for the energy calculation and expert knowledge for determining the importance of the functions, which might lead to the deliberate induction of wrong results. Furthermore, depending on the region, a large portion of the energy demand may still be covered from fossil resources, making a differentiation between fossil and renewable energies reasonable in future research. This can potentially be realized with a weighing factor as it has been done in the software Granta (ANSYS, Inc., 2022).

Current work focuses the process of validation of the proposed framework on cross-industry use cases in order to ensure a generalizable statement regarding its practical applicability. In future work, we will provide a detailed presentation of the literature review process and the flows of information, data, and knowledge within our framework.

Additionally, future work can generalize the FLCEA methodology outside of the LWD scope to also include non-mass related energy consuming functions relevant for DfC. This would be the case when analyzing products such as a hair dryer or coffee machine where a large energy-fraction is attributable to thermal energy.

CRediT authorship contribution statement

Kristian König: Conceptualization, Methodology, Software, Validation, Formal analysis, Data curation, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Janis Mathieu:** Methodology, Validation, Writing – review & editing, Visualization. **Michael Vielhaber:** Writing – review & editing, Supervision, 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.

Data availability

The data that has been used is confidential.

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Appendix A

Table A1
Calculation results of the FLCEA methodology for the semi-mobile handling system.

Part/assembly	Mass [kg]	E^{BoL} [GJ]	E^{MoL} [GJ]	EoL stategy	E^{EoL} [GJ]
Pillars	4144.4	66.456	0.000	Reuse	–27.921
Oil sump	1313.5	51.366	0.000	Recycle materials	–1.857
Energy chain	573.7	45.997	0.000	Landfill	0.004
Duct	6139.7	502.871	0.000	Remanufacture	–86.734
Carriage	677.0	105.707	150.342	Landfill	0.004
Energy chain connection	197.5	15.509	107.253	Landfill	0.003
A1 axle	442.1	34.818	14.717	Landfill	0.002
A2 axle	448.6	36.526	30.636	Landfill	0.002
A3 axle	386.0	30.255	45.314	Landfill	0.002
A4 axle	45.5	3.574	63.759	Landfill	0.002
A5 axle	22.8	1.788	74.253	Landfill	0.002
Gripping Unit	45.8	23.128	314.554	Recycle materials	–1.672

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