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ORIGINAL ARTICLE

Ensuring low carbon-emission and circular product design through reverse engineering: consideration of a robot gripper frame

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Abstract

This study presents a reverse engineering approach to improve product circularity, considering CO_2 emissions and costs across the full product life cycle, demonstrated using a robot gripper frame. The proposed approach closes a research gap by providing a practical, systematic method that links quantitative results with reverse engineering thinking to identify product-specific circularity bottlenecks and derive concrete design improvements without causing environmental or economic trade-offs. Starting from a state-of-the-art aluminum structure, the study develops a novel lightweight design that utilizes carbon fiber–reinforced tubes and 3D-printed polyamide-based nodes. Life Cycle Assessment, Life Cycle Costing, and Life Cycle Gap Analysis are used to assess the environmental, economic, and circularity performance of the concepts. While the lightweight composite structure significantly reduces energy demand in the manufacturing (− 51.18%) and use phases (− 19.46%), it simultaneously worsens circularity performance, reflected by a 30.17% increase in the Life Cycle Gap. By applying the reverse engineering approach to the lightweight composite structure, non-reversible material and process choices are identified and replaced, specifically by using thermoplastic materials instead of thermosets to enable recyclability. The optimized composite structure leads to a 19.44% reduction in the life cycle gap, with simultaneous further reductions in carbon footprint of 0.23% and costs by 0.2%.

Keywords Reverse engineering · Life cycle assessment (LCA) · Life cycle costing (LCC) · Life cycle gap analysis (LCGA) · 3D skeleton winding (3DSW)

1 Introduction

The use of fully automated production systems and manipulators significantly contributes to efficiency. However, due to their energy consumption, they also present opportunities for improving resource efficiency in the use phase. The ecological potential of such systems is gaining importance in light of political goals, such as the Sustainable Development Goals (SDGs) (United Nations 2015), with SDG 12 focusing on sustainable consumption and production (e.g. cradle-to-cradle designs), as well as regulatory frameworks like the Paris Climate Agreement, which aim to limit global warming. To quantify environmental impacts, Life Cycle Assessment (LCA), conducted in accordance with ISO 14044 (2006) and ISO 14040 (2009), can be used to evaluate the entire life cycle of a product, process, or service. Life Cycle Gap Analysis (LCGA) (Dieterle 2023) is used to evaluate the ecological Life Cycle Gap (LCG), while Life Cycle Costing (LCC) applies cash-flow analysis over the product life cycle to determine costs. LCA and LCC are suitable for quantification, however they do not provide guidance on how a system can be modified to decrease carbon footprint or costs, nor do they directly indicate which components or process steps hinder circularity. Despite the availability of prescriptive eco-design tools (e.g. DfX) and data-based methods, the current literature lacks a practical and systematic approach that links quantitative life-cycle results to concrete, product-specific design modifications for improving circularity.

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The key findings of the literature review presented in Sect. 1.2 can be summarized as follows: existing tools either provide general principles without analytical depth, or generate detailed assessments without specifying where and how design changes should be implemented. Moreover, no established method operationalizes the core idea of RE for identifying circular product development as outlined in the following section. This gap highlights the need for a structured, design-oriented methodology that starts from an existing product and systematically identifies circularity bottlenecks while avoiding environmental and economic trade-offs.

In the present research, a lightweight robotic handling system (as shown in Fig. 6b) is developed as a demonstrator. This use case was selected as the energy consumption during the use phase dominates the life cycle assessment, both ecologically and economically, which may render circularity considerations seemingly negligible. Nevertheless, the demonstrator illustrates that minor design adjustments can substantially enhance circularity, thereby contributing to achieving a Circular Economy (CE). The lightweight materials allow for reduced energy consumption during the use phase compared to a state-of-the-art handling system using aluminum profiles, but they reveal shortcomings in terms of circularity at the product's end of life (EoL). In a second development step, a reverse engineering (RE) approach is applied to derive circularity optimizations for the lightweight solution under consideration of environmental and economic assessment, addressing the identified methodological gap. The approach does not primarily aim at substantial improvements in LCA or LCC, but at enhancing circularity without shifting burdens to other life-cycle phases and without adverse effects on LCA or LCC. At the same time, it identifies the manufacturing steps that negatively affect the product's EoL performance and directs the practitioner to them.

1.1 Background on reverse engineering

RE refers to the reversal of the conventional process chain in engineering—also known as front-end engineering (FE)—in which development typically progresses from conceptual design to logical design and finally to physical implementation (Aqeel et al. 2023). RE originated in mechanical engineering in the field of aviation in 1899 (Wang 2010) and further historic RE applications can be found in the literature; see (Kumar et al. 2013; Levins 2017; Gaskill 2018). In publications from 1990 to 2010, RE is frequently described as the process of capturing or scanning a physical object to obtain its geometric data (Daschbach et al. 1995; Hong-Tzong 1997; Chen and Lin 2000; Raja and Fernandes 2008). While there is no universally accepted definition of RE, the core idea across various applications is the derivation of information from an existing object. Technological advancements in the 20th century have transformed the landscape of RE (Wang 2010). RE enables industries to respond to rapidly shortening innovation cycles of modern machines and instruments, thus intensifying competitive pressure (Kumar et al. 2013). Initial efforts to harness RE for sustainability have focused on repairs through replacement part solutions for damaged or worn components for which no data exists (Kumar et al. 2013). Thus, RE can contribute to closing technical loops, a key principle of the CE, for example, by producing spare parts through additive manufacturing processes (Chiriță et al. 2024). The primary motivation for RE in replacement applications stems from inadequate spare-parts availability rather than ecological considerations. Therefore, these applications are not considered as RE contributing to sustainability in the present work.

Approaches that apply the core idea of RE, learning from existing products to the optimization of sustainability can be traced back to two educational studies. A visionary approach from Van Doorsselaer and Koopmans (2021) that seeks to harness the core idea of RE explicitly to enhance sustainability proposes to begin product planning from a desired future scenario and reason backwards to the present, a strategy referred to in the publication as "reverse engineering", "backcasting", or "reverse scenarios", albeit without providing any further methodological framework or concrete elaboration. The approach presented by Dempere (2010) uses RE in a university teaching context to introduce students to sustainability by having them disassemble technical devices, analyze component functions and materials, and examine underlying design and material selection criteria. Students propose more "sustainable" alternative materials or designs and justify them from ecological, social, and economic perspectives. Although the focus lies on material and chemistry aspects and lacks a structured methodology with clear circularity criteria, it is one of the few documented cases where RE is explicitly applied to enhance sustainability.

1.2 Background on eco design tools

In the context of the CE, the so-called R-strategies, named after the initial "R" of each strategy (e.g., refuse, reduce, recycle) emerged in the 1990s (Cooper 1994; Graedel and Allenby 1997) and have since been integrated into environmental policies and programs, where they now serve as a basis for action. While the original 3Rs-reduce, reuse, recycle—remain central in new research, efforts are underway to expand them to 9Rs, which are (R0-R9): recover, recycle, repurpose, remanufacture, refurbish, repair, reuse, reduce, rethink, refuse (Kirchherr et al. 2017).

To support the implementation of sustainability in products, both qualitative and quantitative tools exist, commonly referred to as eco-design tools (EDT). Eco-Design (ED), as defined in ISO 14062 (2019), is a design approach aimed at reducing the environmental impacts of products and services throughout their entire life cycle while ensuring equal or improved performance for customers. These tools can be categorized into prescriptive, data-based, and analytical methods (Casamayor and Su 2010).

The most common prescriptive tools are guidelines, such as Design for X (DfX), helping to implement specific engineering objectives early in product development (Tusch et al. 2025). Guidelines for implementing the R-strategies are referred to as where X may represent an R-strategy or a life cycle phase (Andereasen and Mortensen 1997). Within the EDT landscape, DfX belongs to the prescriptive methods, which provide indicative, principle-based design guidance. To enable circularity at the product's EoL, various DfX approaches exist, such as design for recycling (DfR), design for reuse and repurposing (DfRR) (Sassanelli et al. 2020). These offer fundamental guidance, for instance, on material selection (e.g., favoring thermoplastics over thermosets (Tech 2004), avoiding black pigmentation (Lizenzero 2023), or applying joining technologies that allow for large-scale disassembly and material sorting). In EDT, users must therefore define a DfX goal and select the appropriate approach. The choice of which R-strategy to apply is subject to the user's subjective selection. Such a subjective preselection inherently narrows the solution space, which might otherwise have been expanded through the consideration of alternative R-strategies. According to Mesa (2023), DfX approaches are not formally oriented to a CE and lack pathways to apply the design rules.

The data-based EDT includes quantifying methods, primarily LCA, which are criticized for their limited link to product design, as they leave unanswered how quantitative results can be translated into improvements at the product level. The methodological framework for conducting an LCA is defined in ISO 14044 (2006) and ISO 14040 (2009) and has been extensively described in the literature, to which this work also refers (Sánchez-Burgos et al. 2025; Mohan 2024; Singh and Agarwal 2025). LCC is understood as the cumulative aggregation of all costs associated with a product from its initial development phase through to the EoL, including disposal. The application guide IEC 60300-3-3 (2017) provides a standardized procedure for conducting LCC analyses and is widely used as a methodological reference. The origins of LCC can be traced back to Harriman (1928), and the method has since been extensively discussed and refined in the literature, therefore, this work refers to existing work for details (Osborne 2010; Hunkeler et al. 2008; Muthu 2023). Conventional methods for evaluating product costs remain purely accounting tools and do not directly propose improvement measures.

The LCGA can also be classified as a data-based EDT, as it utilizes the results of an LCA and LCC with a clear focus on CE. The LCG (see Eq. 1) results from the efforts associated with raw material acquisition (RMA) and production (P) minus the credits (C) recoverable at the product's EoL. Thus, from a CE perspective, the LCG evaluates how much of the original efforts cannot be recirculated. To enable better comparison of the gap between different products, Dieterle (2023) introduced the relative gap (see Eq. 2), expressed as a percentage by dividing the LCG by the original efforts of RMA and P.

Analytical methods serve to find optima as well as for presenting and comparing results. Established examples of such data-based tools include the Material, Energy, and Toxic Emissions Matrix (MET Matrix) (Brezet and van Hemel 1997), and the Material, Energy, Chemicals, and Others Matrix (MECO Matrix) (Wenzel et al. 1997). Analytical methods often contain subjective elements through the assignment of priorities, as in the ABC-Analysis (A = problematic, action required, B = medium, to be observed and improved, C = harmless, no action required) by (Byggeth and Hochschorner 2006). Mathematical optimization tools require an understanding of the underlying algorithms, as can be seen in the works of (Ercan et al. 2015; Cerri and Terzi 2016; Schwartz et al. 2016). A shared point of criticism of EDT tools is that they generally focus on the absolute assessment of environmental impact rather than on promoting the circularity of products.

In summary, there exists a methodological gap between prescriptive EDTs, which provide general, product-independent design principles but do not allow for quantitative evaluation and data-based methods such as LCA and LCC, which quantify impacts in detail but do not offer a translation into concrete design modifications. Existing approaches do not explicitly address CE principles and either rely on subjective categorization or require mathematical optimization knowledge that goes beyond the LCA and LCC instruments commonly used in practice. Consequently, there is a lack of a practical approach that starts from an existing product and guides practitioners directly to the components and process steps where CE improvements can be achieved with respect to trade-offs in LCA and LCC.

To address this gap, Sect. 2.5 presents a novel RE approach that analyzes an existing product and derives improvements. The method demonstrated using a robot gripper frame integrates LCA, LCC, and LCGA to pinpoint product-specific EoL bottlenecks and to guide actionable design changes that increase circularity without inducing burden shifting in environmental or economic performance.

2 Materials and methods

2.1 Considered demonstrator and application

For the handling of components, such as in pick-and-place operations, actuators are required to establish temporary force-fit or form-fit connections for manipulation. These include linear, suction, or magnetic grippers for rigid components, and needle grippers for flexible or deformable materials. Articulated robots used in pick-and-place applications are typically delivered by manufacturers with a round flange, often compliant with ISO 9409-1, designed to interface with actuators. Depending on the specific application, a gripper frame must be developed as an interface between the robot's round flange and the actuators. These structures are custom-designed and typically constructed from aluminum profiles manufactured through extrusion. The profiles feature T-slots on all sides, enabling flexible connections and easy adaptation. Connectors such as angles and hinges, made of cast aluminum, are used to join the profiles and are assembled using T-slot nuts and screws. The application under consideration, depicted in Fig. 1, involves a gripper frame supporting four suction cups (Schmalz SAF 30) on the top side, two magnetic grippers (Schmalz SGM 49) on the bottom, as well as cables and hoses for power and media supply, and a pneumatic valve manifold. The handling system is used to place steel inserts into a press and to remove a thermoformed and overmolded seat shell after pressing, as shown in Fig. 1. The cycle time of the fully automated process is 86 seconds. For conducting an LCA for the baseline scenario, the state-of-the-art aluminum gripper frame, the weight of the components and gripping devices are summarized in Table 1. To determine the baseline LCC, the component prices are, based on project-specific quotation prices, summarized in Table 1.

The power demand of an articulated robot depends on the size of its motors and is therefore directly linked to its design, which in turn is based on the payload it is intended to carry. The electrical energy E_{el} required is calculated by integrating the time-dependent power $P(t)$ over time t, using the formula: $E_{\mathrm{el}} = \int P(t)\,\mathrm{d}t$. That the energy consumption of a movement is mass-dependent is well established through the formulas for kinetic energy $E_{\mathrm{kin}} = \frac{1}{2}*m*v^2$ and potential energy $E_{\mathrm{pot}} = m*g*h$. As motor size, and consequently, power consumption, increases, so does the overall energy demand. This relationship is illustrated in Fig. 2, showing the increasing power consumption with higher payloads for various robots. The energy consumption of each robot model (a–h) varies depending on the acceleration and trajectory kinematics. In the absence of detailed data per robot for this relationship, the electrical input power and the load capacity of various robot models (a–h) are linearized, as displayed in Fig. 2. Note that the x-axis is not scaled uniformly, as the payload capacities of the different robot models do not follow a linear progression. To evaluate the influence of weight on the load, a linear regression was derived $y = 0.0213x + 0.3948$ for $x \in [5, 60]$, which is subsequently used for the LCA and LCC analysis of power consumption. It should be noted that the course of the

Fig. 1 Considered robotic application

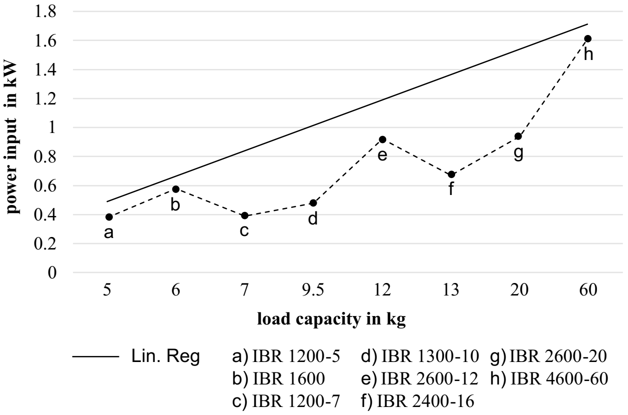

Fig. 2 Robotic power input depending on load capacity

Table 1 Component list and acquisition costs of aluminum gripper frame

Components	Quantity	Unit	Mass per unit	Price per unit	Total mass	Total price
Hinge	8	pcs	209 g	6.03 €	1672.00 g	48.20 €
Angle Joint	14	pcs	31 g	0.67 €	434.00 g	9.41 €
Aluminum profiles 40 mm	2392,55	ccm	2.68 g/ccm	0.02 €	6415.59 g	56.43 €
Screws and T-slot nuts	44	pcs	21 g	0.37 €	924.00 g	16.38 €
Total frame					9445.59 g	130.42 €
Total attachments, parts					9456.32 g	
Total frame, attachments, parts					18901.91 g	

regression curve appears above the curve due to the scaling of the x-axis.

For the ecological and economic evaluation, an LCA is conducted in accordance with ISO EN 14044/14040, using the Environmental Footprint 3.1 method. Additionally, a cost analysis covering acquisition, assembly, usage, disassembly, and disposal is performed. The circularity of the system is assessed using LCGA developed by (Dieterle 2023). In this method, the credits at the EoL, arising for example from the substitution of primary materials or from thermal recovery, are subtracted from the efforts associated with RA and the P as shown in Eq. (2). While circularity indicators often evaluate only material flows, neglecting both environmental impacts and quality degradation, the LCGA explicitly takes the environmental credits of high-quality recycling processes into account and highlights cases in which material loops are closed but only low-grade recycling is achieved, contextualizing these credits relative to the original impacts from RMA and P. The formula for calculating the absolute LCG can be found in Eq. (1), highlighting the gap, resulting from the impact of RMA (I_{RMA}), the input during production (I_P) and credits at the EoL (I_C).

$$I_{\mathrm{LCG}} = I_{\mathrm{RMA}} + I_P - I_C \tag{1}$$

The relative LCG (%LCG), as calculated in Eq. (2), relates the identified gap (I_{LGA}) to the original Input ($I_{\mathrm{RMA}} + I_P$).

$$\%\mathrm{LCG} = \frac{I_{\mathrm{LCG}}}{I_{\mathrm{RMA}} + I_P} \tag{2}$$

To determine the component costs, sales prices from online retailers were used. Electricity consumption was calculated at a price of €0.30 per kWh. The assessment considers the acquisition, operational, and disposal costs over the product life cycle, without discounting. For the calculation of the carbon footprint, the functional unit (FU) is defined as follows: one load-bearing structure for mounting grippers used to manipulate a component, with a combined mass of 9456.32 grams, over a period of 10 years, operating 12.8 h per day, 365 days per year. For the considered functional unit, this results in 46,720 h of operation. The chosen impact category is Global Warming Potential (GWP), measured in kilograms of CO_2 equivalents [$kgCO_2eq$]. The associated normalization factor, which puts the calculated environmental impacts in relation to a reference value, such as the annual environmental footprint of an average person, is 7.550 $kgCO_2eq$ per year per person.

2.2 Environmental and economic assessment of the state-of-the-art gripper frame

The objective of the LCA is to quantify the environmental footprint in order to identify impactful improvement measures at the product level. The aim of the LCC is to quantify the associated costs. To carry out the process described in Sect. 2.1 using the aluminum-frame structure, a robot with a payload capacity of 18.9 kg is required. To ensure comparability across payloads, the linear regression model, displayed in Fig. 2, serves as the foundation for calculating the power consumption in the LCC and LCA assessments. In the specific case considered, a robot with a power demand of 0.797 kW is required. The assembly costs, including the cutting of aluminum profiles, are estimated at 30% of the acquisition cost, due to the labor-intensive and small-scale manual work involved. Disassembly costs are estimated at 10% of the acquisition cost. For the EoL phase, scrap purchase prices from a market participant were used as the basis for material value recovery. For the environmental assessment, an EoL dataset for aluminum recycling was used, accounting for both efforts and credits as shown in Table 3. The results in Figs. 3, 7 and 10 show the environmental impacts, expressed in $kgCO_2eq$ and plotted in blue with reference to the left y-axis.

The economic impacts, expressed in euros, are shown in grey and refer to the right y-axis. The exact values are reported in Table 3. The results highlight that the use phase dominates both LCA and LCC. For the aluminum baseline, the use phase accounts for 99.8% of the total LCA and 98.5% of the total LCC. In this context, the motivation for a lightweight design is evident, where a reduction in moving mass directly translates into lower electricity consumption and costs. An innovative lightweight solution is presented in the following section.

2.3 Component design, technology development and material selection

To reduce the mass of the gripper frame, the metallic frame is replaced by a frame made of composite materials. Hence, the redevelopment described in this work considers the frame structure of the gripping module without attachment components. However, the functional equivalence of the entire gripping frame is ensured.

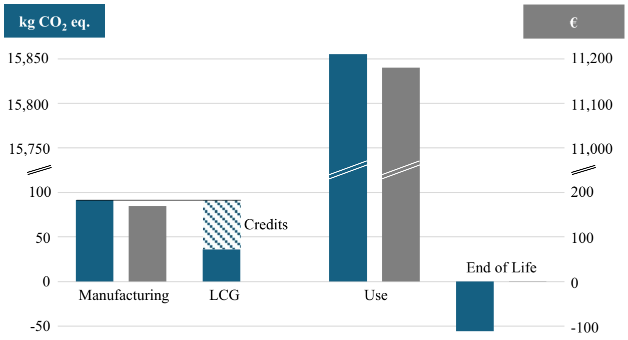

Fig. 3 LCA, LCG and LCC of aluminum gripper frame

Since the considered application benefits from the accessibility and adaptability of a modular space frame design, the composite frame is also designed as a truss structure. To limit the manufacturing costs, a standard design is used for all truss members. It is a round tube with an outer diameter of 25 mm and a wall thickness of 2.5 mm, which is produced in a filament winding process. The cross-section of a round tube offers high resistance to various load types as well as a low mass. The tubes are made from epoxy resin and carbon fibers of the type T700 produced by TORAY. Their fiber volume content is 65%. To be able to join several tubes together in order to form a truss structure, a configurable node element is developed. The base structure of this node element is a tubular structure that serves to hold an end of the filament-wound tube just described. This tubular base structure is henceforth referred to as "socket." The inner diameter of the socket matches the outer diameter of the standard tube and its wall thickness is defined as a configurable parameter. Other configuration parameters of the node element include, among others, the number of sockets, the relative angles between the sockets, and the length of each socket. Figure 4 illustrates the basic design concept of the node element, the implementation of a parameterized CAD model, and three different node configurations needed for the composite frame.

In contrast to the standardized truss members (tubes), the node elements are subject to a certain geometric variance, which requires adapted manufacturing approaches. In general, the time- and cost-efficient production of complex structures in small quantities can be achieved using additive manufacturing processes such as 3D printing. However, the widely used Fused Filament Fabrication approach (FFF) is limited in terms of the achievable mass-specific strength, and thus also regarding its lightweight potential. For this reason, an additive manufacturing chain is applied in this work: the base body of the node element is produced using the FFF process and afterwards locally wrapped with continuous fibers using the 3D Skeleton Winding technology (3DSW). The continuous fibers act as an external reinforcement skeleton that significantly increases the load-bearing capacity of the 3D-printed base body. The additive manufacturing chain enables the production of complex-shaped, thermoplastic, fiber-reinforced structures by automated processes without expensive molds, making it cost-efficient for custom-made and small series applications. By combining the FFF and the 3DSW, a combination of short and continuous-fiber reinforcement is enabled. The latter can be oriented three-dimensionally, unlike conventional continuous fiber 3D printing. Both FFF and 3DSW use thermoplastic matrices, with sufficient thermal properties of PA6, so that a consistent composite material can be used in the entire node element. In the case considered, a polyamide-carbon fiber composite is chosen. The semi-finished products used are the short-fiber reinforced filament Ultrafuse® PAHT CF15 produced by BASF 3D Printing Solutions BV (FFF) and the thermoplastic tape MCP1223 produced by Maru Hachi Corporation in a finely slit form (3DSW). Additional research focuses on achieving a material bond between the base body and the reinforcement skeleton with minimal deformation of the core. Figure 5 shows photographs from the prototype manufacturing process.

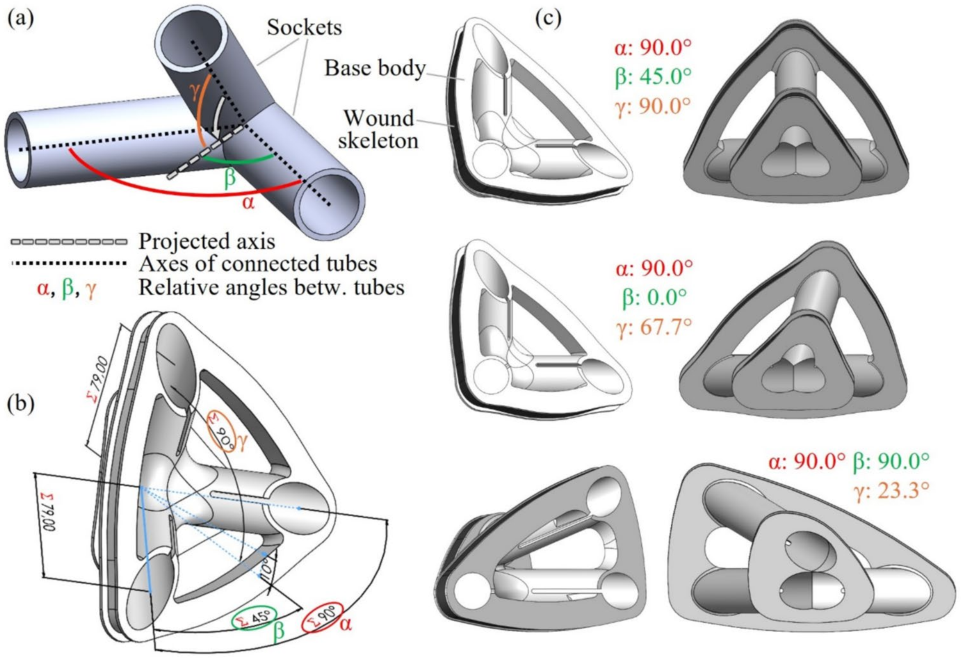

Fig. 4 Design of the configurable node element—basic design concept (**a**), parametrized CAD model with selected configuration parameters (**b**), three different node configurations (**c**) (screenshots from SOLIDWORKS 2023)

Figure 6 compares both versions of the gripping module—with a metal frame (state of the art) and with a composite frame (lightweight design).

2.4 Environmental and economic assessment of the composite gripper frame

The new development under consideration follows the LCA and LCC assumptions outlined in Sect. 2.1 and consists of the components and prices listed in Table 2. To carry out the process described in Sect. 2.1, with the lightweight gripper, a robot with a payload capacity of 12.55 kg is required, which, according to Fig. 2, has a power demand of 0.727 kW. The nodes in the lightweight design are manufactured using 3D printing on a Bambu X1 printer, which, as measured with a Fluke 1730 energy logger, consumes 0.013 kWh per gram of filament. Together with the filament cost ($0.05\frac{€}{\text{ccm}}$), the energy cost for production ($0.013\frac{\text{kWh}}{\text{g}} * 1.22\frac{\text{g}}{\text{ccm}} * 0.3\frac{€}{\text{kWh}} = 0.0047\frac{€}{\text{ccm}}$) is included in the procurement cost of the nodes, resulting in a total cost of $0.0547\frac{€}{\text{ccm}}$. Assembly of the lightweight variant is significantly less intricate than that of the aluminum structure (see Tables 1 and 2).

Therefore, assembly costs, including cutting of the carbon profiles, are estimated at 15% of the acquisition cost, while disassembly costs are assumed to be 5% of the acquisition cost. At the EoL, the nodes and clamps are subjected to mechanical recycling, while the tubes are thermally recycled. The scrap value of the PA6 CF30 nodes is estimated at 40% of the market price for virgin PA6 CF30 granulate (40% of 11 €/kg based on (Kunststoff-Rohstoffe 2025). For the thermal treatment of the tubes at EoL, a disposal cost of 400 €/kg is considered (LAGA Bund/Länder- Arbeitsgemeinschaft Abfall 2019). For the environmental assessment, an EoL dataset for recycling PA6 CF was modeled, accounting for the efforts of shredding and the credits associated with thermal recovery. The results of the LCA_0, LCG_0 and LCC_0 are shown in Fig. 7. For the calculation of the LCA and

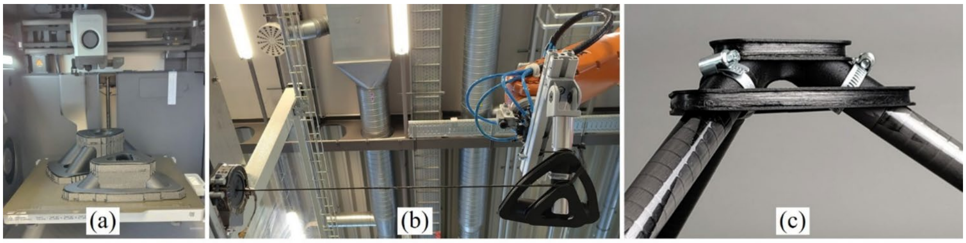

Fig. 5 Production of the configurable node element—3D printing of the base body (**a**), robot-based winding of the external reinforcement skeleton (**b**), assembly of the tubes to be connected (**c**)

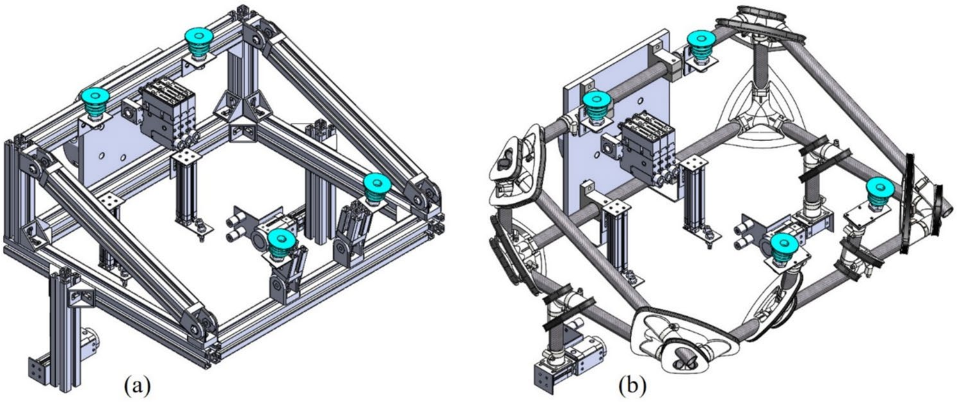

Fig. 6 CAD models of the gripping module with the metal (**a**) and the composite (**b**) frame structure (screenshots from SOLIDWORKS 2023)

Table 2 Component list and acquisition costs of composite gripper frame

Components	Quantity	Unit	Mass per unit	Price per unit	Total mass	Total price
3D-printed node	1297.68	ccm	1.12 g	0.05 €	1456.00 g	67.26 €
Carbon tubes	4.48	m	261.77 g	26.17 €	1172.72 g	117.23 €
Hose clamps	28.00	pcs	16.75 g	0.79 €	469.00 g	22.18 €
Total frame					3097.72 g	206.67 €
Total attachments, parts					9456.32 g	
Total frame, attachments, parts					12554.04 g	

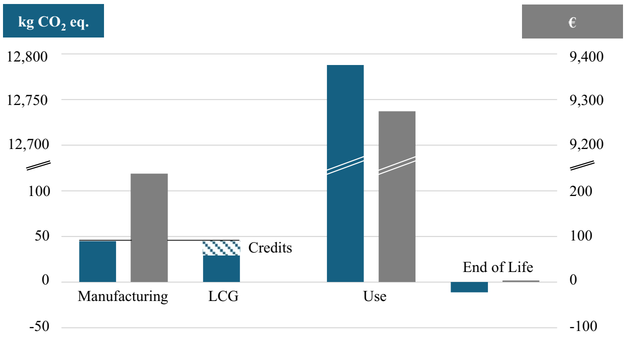

Fig. 7 LCA_0, LCG_0, and LCC_0 of thermoset composite gripper frame

LCG, the complete product life cycle was modeled in Sphera LCA for Experts. The index 0 refers to the first lightweight system, with composite tubes.

The dominant life cycle phase of the composite gripper frame remains to be the use phase. Compared with the aluminum baseline scenario (Fig. 3), however, there is a marked reduction in the carbon footprint during both use and manufacturing. As shown in Table 3, the overall carbon footprint improves by 19.43%. On the cost side, the manufacturing phase exhibits a deterioration, with an increase of 40.18%. Yet savings in the use phase offset these additional expenditures, resulting in a 16.94% improvement in LCC. The absolute LCG decreases from 35.81 $kgCO_2eq.$ to 30.99 $kgCO_2eq.$; however, this must be interpreted relative to manufacturing, such that the relative LCG, computed according to Eq. (2), worsens substantially from 39.06% to 69.23%.

Thus, while the composite gripper represents a clear improvement from an LCA and LCC perspective, this illustrates a typical trade-off where use phase optimization gains come at the expense of circularity. Accordingly, a RE approach is proposed and implemented below to enhance circularity.

2.5 Reverse engineering approach

The goal of this approach is to increase the circularity of products without worsening their LCA or LCC. In other words, it aims to prevent the emergence of trade-offs in favor of circularity. To ensure holistic success without trade-offs, the approach integrates both an LCA and an LCC analysis. The analysis of the existing system and the derivation of information, as an analytical component of RE, serve to identify potential for improving the circularity (evaluated using LCGA (Dieterle 2023)). In previous work, an approach was developed that aims to improve circularity and thus preserve value throughout the life cycle (Zürn and Dieterle 2024).

In the present research, this approach and its systematic analysis of the product life cycle have been further tested and evaluated and additionally extended to incorporate economic aspects. The method combines LCA, LCGA, and LCC. It consists of four phases and, unlike DfX, does not require a single predefined design goal. DfX approaches that target a specific R-strategy focus on only one strategy and therefore require the practitioner to make a prior selection. By contrast, the RE approach does not rely on this pre-definition and can reveal circularity improvements across different R-strategies. The sequence of steps, illustrated in Fig. 8, begins with the documentation of the state-of-the-art (SotA) process. In step 1.1, the life cycle phases and subprocesses relevant to the user are recorded in a flowchart, in line with DIN 66001. This flowchart begins with raw material acquisition (RMA), which includes raw materials or semi-finished products being acquired, followed by transport (T_p) to the production site, P itself, including subprocesses in accordance with DIN 8550, transport to the use site (T_u), use phase (Use), transport to end-of-life treatment (T_{EoL}), and the current EoL phase. The EoL includes both the required efforts, such as shredding or washing, and the credits, e.g., material substitution. Alongside environmental data, also economic life cycle data are collected, including acquisition, manufacturing, transport, usage, and disposal costs or revenues. Subsequently, an initial LCA_0 is carried out in accordance with ISO 14040 (2009) and 14044 (2006) to quantify the environmental baseline, as well as an initial LCG_0 to evaluate circularity according to Eq. (1). For the economic evaluation, all costs and revenues from RMA, T_p, P, T_u, use, T_{EoL},

Table 3 LCA, LCG and LCC results of aluminum and first composite gripper frame design

	Environmental assessment			Economic assessment		
	LCA_{AL}	LCA_0	Change	LCC_{AL}	LCC_0	Change
	$kgCO_2eq$		%	€		%
Manufacturing	91.68	44.76	– 51.18%	169.55	237.67	40.18%
Use	15860.70	12774.43	– 19.46%	11170.75	9278.59	– 16.94%
End of Life	– 55.87	– 11.37		1.08	3.40	
Total	15896.51	12807.82	– 19.43%	11341.38	9519.66	– 16.06%
Credits [$kgCO_2eq$]	– 55.87	– 13.77	– 75.35%			
LCG [$kgCO_2eq$]	35.81	30.99	– 13.46%			
LCG [%]	39.06 %	69.23 %	30.17%			

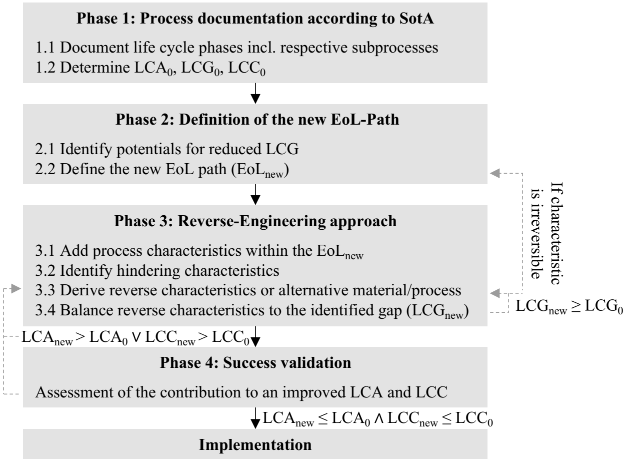

Fig. 8 Methodological reverse engineering approach, further development based on (Zürn and Dieterle 2024)

and EoL are aggregated and an LCC$_0$ is conducted. In phase 2, a new and improved target EoL pathway is defined and added to the flowchart from step 1.1 as EoL$_{new}$, with the aim of increasing circular value retention.

The R-strategies relevant to the product EoL, such as remanufacturing (technical renewal), repurposing (reusing or modifying components), recycling, and recovery (material or energy recovery), can be applied to identify a suitable circular scenario. These strategies are listed in descending order of value retention. In phase 3, the process steps that prevent or hinder EoL$_{new}$ are identified. In step 3.1, all process characteristics associated with the EoL$_{new}$ pathway are analyzed. These are graphically placed beneath the EoL$_{new}$ path and represent part of the intended circular flow. Based on DIN 8550, these characteristics are evaluated in terms of material, form, and connection modifications, focusing on their reversibility and their impact on circularity. In step 3.2, the processes that obstruct the EoL$_{new}$ scenario are identified. Consequently, reverse measures, or reverse characteristics, are developed in step 3.3. If no viable reversal measure exists for a process, a different material, alternative process, or a revised EoL target (step 2.2) must be selected, and the process returns to step 1.1.

The identification process requires expertise in recycling and process engineering. The user must assess the introduced modifications in the context of existing processes and technologies for reverse logistics and material recovery. For each reverse characteristic introduced, economic and environmental life cycle inventory (LCI) data must be collected.

In this context, non-reversible characteristics are induced changes in the product's properties that cannot be undone by a reverse process step. They permanently constrain the targeted EoL and limit circularity. An example is the cohesive bonding of dissimilar materials, where no feasible process exists to separate the materials again; as a result, higher-value EoL routes such as reuse or material recycling are excluded and thermal recovery becomes the only viable option. In step 3.4, the additional effort associated with reverse characteristics is evaluated in relation to the LCG$_0$ to ensure that these efforts do not outweigh the benefit of increased EoL credits. Finally, in phase 4, success validation, a new LCA$_{new}$ and LCC$_{new}$ are conducted. If the resulting environmental and economic assessments are equal to or better than the original system, the new process may be implemented. The precise magnitude of the reduction in values is not critical; however, the smaller the new assessments, the more favorable.

2.6 Application of reverse engineering approach

The documentation of the four life-cycle phases, RMA, P, use, EoL, as well as the subprocesses to produce parts and assembly of the composite gripper frame, are illustrated in Fig. 9 in accordance with step 1.1. The results of the initial LCA$_0$, LCG$_0$, and LCC$_0$ of the composite are also presented in Fig. 7. Beginning with RMA, the acquisition of the individual components is shown in parallel until they are assembled into the gripper structure in the final production step. After the use phase, disassembly takes place, during which the hose clamps are reused, a strategy that, according to the hierarchy of R-strategies, represents the second-best circularity approach after avoidance. The nodes, which are application-specific 3D-printed parts, can be mechanically recycled due to the use of the same fiber-matrix and polymer-fiber combination in both the filament and the wound structure. The tubes are custom-cut for the application to minimize energy consumption during the use phase and are currently disposed via incineration. In line with step 2.2, the goal is to establish a new pathway EoL$_{new}$, as shown in Fig. 9 in green, that allows for material recycling. In step 3.1, the process characteristics, which describe the changes, such as bonds, materials, and shapes, introduced at each step and assess their reversibility, are displayed above the manufacturing processes, shown in light grey in Fig. 9. The analysis, starting from the EoL phase, shows that the assembly processes are reversible. However, the cutting of the tubes as well as the winding-based production are irreversible. This is due to the use of a thermoset matrix in the tubes. Even the fiber impregnation prior to winding is irreversible, as pyrolysis of the epoxy resin leads to significant fiber degradation. According to step 3.2 of the RE approach, fiber impregnation, a hindering characteristic has been identified due to the creation of a thermoset material bond. Consequently, in step 3.3, alternative material must be selected. In the present case, the thermoplastic polymer polyamide (PA6) is suitable as a substitute for epoxy resin, as PA6 is already used in the production of the nodes and can therefore

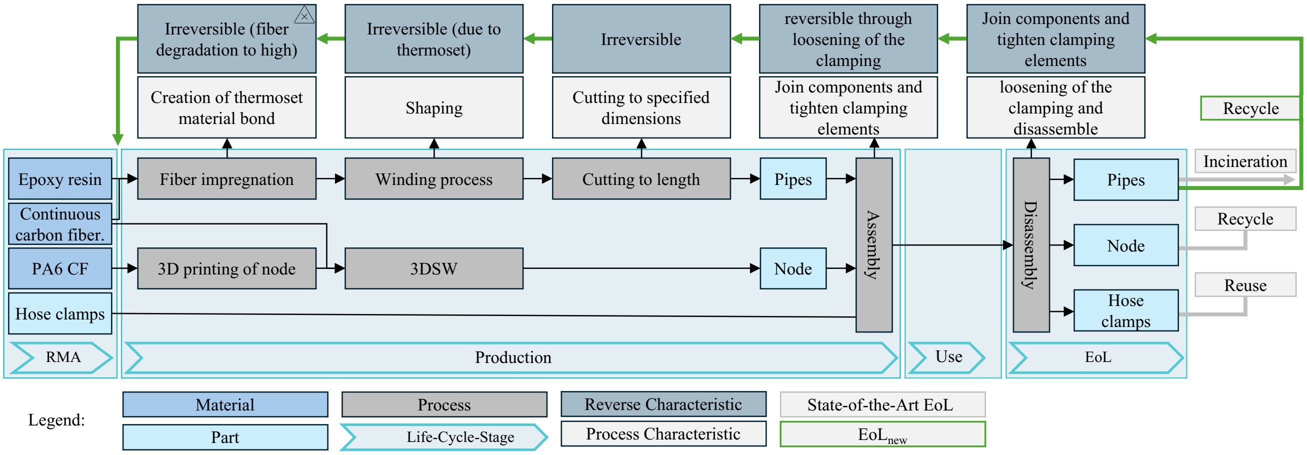

Fig. 9 RE approach of composite gripper frame

also be mechanically recycled at the EoL. In addition to the main target, to improve the circularity, the use of PA6 offers the benefit of a lower density, resulting in a slightly reduced payload weight. Tubes with a PA6 matrix weigh 2.1% less than those made with epoxy resin at the same fiber volume content. To avoid delamination, a suitable fiber was selected to match the PA6 matrix. At the EoL, the tubes and nodes are mechanically recycled (shredded, washed, and regranulated) with a substitution rate of 86% for virgin PA6 CF, which is applied in both the environmental and economic assessments. The substitution rate is used from the dataset for mechanical recycling, as recycling trials are ongoing.

Using thermoset tubes for the gripper frame, the robot requires 0.661 kW to carry a payload of 12.52 kg. For the calculation of the LCA_{new} LCG_{new} and LCC_{new}, the complete product life cycle was modeled in Sphera LCA for Experts. The results are presented in Fig. 10 in the following section. According to step 3.4, all values, both ecological and economic, of the new development show an improved balance and implementation can finally be carried out in the product system.

3 Results

By systematically applying the RE methodology, mapping out the production process of the first composite design, thermoset fiber impregnation was identified in step 3.2 as an irreversible, hindering characteristic for circularity. In step 3.3, an alternative material, a thermoplastic PA6, was selected as a substitute, enabling a mechanical recycling route for both tubes and nodes. The assessment of the improved thermoplastic composite gripper frame, indicated as *new*, is shown in Fig. 10, the exact values are provided in Table 4. The use phase remains the dominant life cycle phase, accounting for 99.8% of the LCA and 97.7% of the LCC.

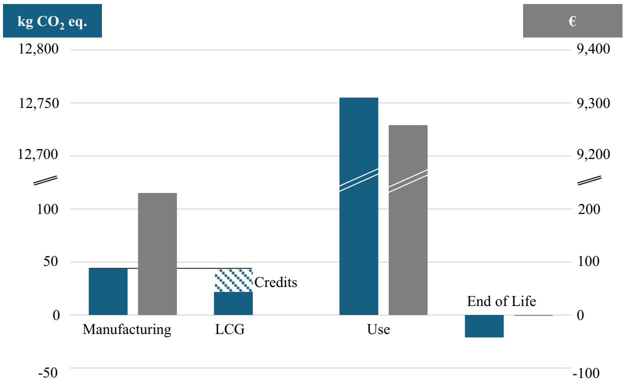

Fig. 10 LCA_{new}, LCG_{new} and LCC_{new} of the improved thermoplastic composite gripper frame

The use of PA6-based tubes reduced the mass slightly further to 12.52 kg, resulting in marginal additional improvements in the LCA of manufacturing and use phases (1.61% and 0.15%, respectively) and LCC reductions (3.09% in manufacturing and 0.25% overall).

These effects are minor in magnitude, reflecting the 2.1% weight difference between epoxy resin and PA6, but they are sufficient to satisfy the method's requirement (step 3.4) of avoiding deterioration in LCA and LCC. The main contribution to the improved circularity can be found in the credits, where closing the material cycle of the new development increases the credits by 60.54% from the original 13.77 $kgCO_2eq.$ to 22.11 $kgCO_2eq.$

Table 4 LCA, LCGA and LCC results of the composite and improved composite gripper frame

	Environmental assessment			Economic assessment		
	LCA_0	LCA_{new}	Change	LCC_0	LCC_{new}	Change
	$kgCO_2eq.$		%	€		%
Manufacturing	44.76	44.04	− 1.61%	237.67	230.34	− 3.09%
Use	12774.43	12755.02	− 0.15%	9278.59	9277.19	− 0.02%
End of Life	− 11.37	− 20.93		3.40	− 1.50	
Total	12807.82	12778.13	− 0.23%	9519.66	9496.01	− 0.25%
Credits [$kgCO_2eq$]	− 13.77	− 22.11	60.54%			
LCG [$kgCO_2eq$]	30.99	21.93	− 29.23%			
LCG [%]	69.23%	49.79%	− 19.44%			

4 Discussion

This study demonstrates how deriving information from an existing object, the core idea of RE, can effectively support the development of circular product designs. Applied to a robotic gripper frame, the approach shows how circular improvements can be achieved without causing burden shifting in environmental or economic performance. The first approach focuses on lightweight design because of the dominance of energy consumption in the use phase and illustrates a typical trade-off in which optimization gains during use come at the expense of circularity. The main methodological contribution of the approach lies in combining RE thinking with quantitative LCA, LCGA, and LCC in a structured sequence of steps that reveals product-specific circularity bottlenecks. While the changes in LCA and LCC are relatively minor and might suggest that both composite variants are almost equivalent, the assessment of circularity reveals a substantial difference.

The evaluation using LCGA provides a method for interpreting LCA results in the context of the CE, as it explicitly captures the effect of improved end-of-life scenarios. In this respect, the 19.44% reduction in the relative LCG represents a substantial achievement, whereas the absolute changes in LCA and LCC are comparatively modest but still satisfy the requirements defined in step 3.4. The findings confirm the primary aim of the approach: to improve EoL circularity without compromising the environmental and economic balance of the product system.

An important finding is that material prices and their environmental impacts have no significant influence on the LCA and LCC results because the use phase is overwhelmingly dominant. This highlights the need to assess circularity independently of conventional LCA and LCC. In all three design concepts (aluminum, thermoset and thermoplastic), the use phase dominates the life cycle, meaning that the electricity price and the environmental impact per kWh are the most influential parameters. A 50% reduction in electricity price or environmental impact per kWh would almost directly translate into a comparable reduction in LCA and LCC. In comparative assessment, a change in electricity prices would have led to a change in the share of the usage phase in the overall assessment, but the differences between systems remain relatively the same. By contrast, RMA and P together account for less than 1% of the LCA and less than 2.5% of the LCC, resulting in very low sensitivity to the environmental impacts and prices of the components considered in this study. In applications where RMA and P dominate the overall assessment and the use phase is negligible, closing material loops becomes the most effective leverage point for improving LCA and LCC. This applies, for example, to products such as bicycle helmets or to products containing resource-intensive materials like gold or copper.

The case study thus illustrates how the method can be used to make targeted, data-driven design decisions that move a product closer to CE principles while keeping tradeoffs under control. From a methodological perspective, several limitations must be acknowledged.

First, successful application of the approach requires a solid understanding of product architecture, materials, and environmental impacts, as well as technical expertise to identify feasible alternative materials, joining technologies, and EoL routes.

Second, compared with prescriptive EDT such as DfX guidelines, the proposed method is more comprehensive and therefore more time-consuming, as it requires detailed life cycle modeling and the systematic documentation of process characteristics.

Third, the quality of the results depends on the availability and accuracy of data, particularly for recycling processes and EoL scenarios. Despite these limitations, the case study indicates that the approach can provide actionable guidance where purely prescriptive or purely analytical tools fall short.

Fourth, designers are required to have certain knowledge to identify components that hinder circulation. Although the RE approach highlights irreversible characteristics, it still relies on understanding how material choices, joining technologies, and treatments affect disassembly and recycling.

Designers, therefore, need basic expertise in product architecture, materials, and available recycling routes, or support from interdisciplinary teams combining design and recycling knowledge.

The results show that the step-by-step procedure can be applied even to more complex products. The underlying workflow is generic and can be transferred to a wider range of products with different material combinations and joints. Further application of the RE approach to different product types is needed to validate its robustness and applicability in industrial practice, particularly for products that use materials with high environmental impacts in primary production and/or high material costs. Also, the implementation in computer-aided design software (CAD) represents a promising direction for future research. The proposed RE method could be implemented in CAD systems by linking geometry, material, and joint definitions with embedded LCA/LCC and circularity indicators (LCGA), allowing designers to see the circularity impact of design choices directly in the 3D model.

5 Conclusion

This study demonstrates how deriving information from an existing object, the core idea of RE, can effectively support the development of low-emission and circular product designs by identifying and addressing life cycle weaknesses. The methodological contribution and the novelty of the approach lie in combining RE with quantitative LCA, LCGA, and LCC in a structured sequence of steps that reveals product-specific EoL bottlenecks and links assessment results directly to design actions. Using a robotic gripper frame as a demonstrator, the approach was first applied to a state-of-the-art aluminum structure widely used in automation. Because continuous movement of mass dominates energy consumption, a lightweight composite frame was developed using 3D-printed polyamide nodes, carbon-fiber tubes, and clamp connectors. This design significantly reduced weight and associated use-phase emissions. However, LCGA exposed reduced circularity due to thermoset-based tubes, illustrating a typical trade-off in which improvements in use-phase performance come at the expense of EoL options. By systematically applying the RE methodology, thermoset impregnation was identified as a non-reversible, circularity-limiting process characteristic. Substituting the thermoset matrix with a thermoplastic PA6 alternative enabled mechanical recycling of both tubes and nodes, improved the EoL scenario, and achieved a 19.44% reduction in the LCG without causing burden-shifting. Although the effects on LCA and LCC were small, reflecting the dominance of the use phase, they satisfied the method's requirement of avoiding deterioration (step 3.4) and confirmed the primary aim of the RE approach, to enhance circularity without compromising environmental or economic balance.

The presented approach thus provides a practical, solution-oriented tool for product developers. It helps to determine which design changes are needed to facilitate CE at the product level.

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Author contributions SZ: Conceptualization, Methodology, Writing—Original Draft JH: Validation, Investigation, Writing—Original draft preparation. FH: Supervision, Writing—Reviewing.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interest The authors declare no competing interests.

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