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RESEARCH ARTICLE

Reverse Engineering Approach for Enhancing Product Circularity Under Consideration of Ecological and Economic Aspects

Sebastian Zürn[1*], Torsten Müller[1], Frank Henning[1,2]

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Abstract

Achieving a circular economy (CE) is a key sustainability objective, but solutions and methods to guide users towards implementation at the product level are lacking. Generic guidelines such as Design for X (DfX) and purely quantitative assessment methods, such as Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and circularity assessment via the Life Cycle Gap Analysis (LCGA), confront practitioners with the challenge of translating them into actionable measures. To close this gap, this study proposes a four-step reverse engineering (RE) approach that traces back circularity weaknesses along the product life cycle and derives possible changes in product design, production steps, and materials based on DfX. The approach incorporates quantitative assessment via LCA, LCGA, and LCC to ensure ecological and economic improvement based on the changes derived at product level, without burden shifting towards another life cycle phase. This approach embeds within CE frameworks, bridging qualitative and quantitative methods.

Keywords Reverse Engineering · Circular Economy · Life Cycle Assessment · Life Cycle Costing · Life Cycle Gap Assessment · Design for Sustainability

1. Introduction

Today's understanding of sustainability still includes the fundamental principle of not consuming more resources than regenerated naturally. Satisfying the resource demand of an increasing world population and the increasing material wealth per person (e.g. 7.2t in 1970 to 11.8t in 2017) remains a persistent challenge (Lindner, 2023). This determines not only increasing waste mass but also the level of greenhouse gas emissions (GHG-Emissions) causing an increase in average global temperature by approximately 0.2 °C, due to the higher concentration of GHG in the atmosphere, preventing the radiation of sunlight back into space (European Commission, 2024). To limit further temperature increases, the Paris Climate Agreement was ratified, aiming to limit global warming well below 2 °C, pursuing efforts in limiting the increase to 1.5 °C (United Nations, 2015). While greenhouse gas emissions are the most prominent impact category, additional categories such as acidification, eutrophication, resource depletion, and human toxicity are also considered. A key success factor is the transformation of the prevailing economic model, away from the linear economy (LE), which is characterized the "take-make-waste" principle where raw materials are extracted, products manufactured and then discarded as waste, towards a circular economy (CE), in which resources are conserved and kept in high-quality use as long as possible (Neves & Marques, 2022). While the theoretical foundations of circularity

* Corresponding author: sebastian.zuern@ict.fraunhofer.de
[1] Fraunhofer Institute for Chemical Technology (ICT), Department of Applied Electrochemistry, Joseph-von-Fraunhofer-Str. 7, 76327 Pfinztal, Germany
[2] Karlsruhe Institute of Technology (KIT), Institute of Vehicle System Technology, Rintheimer Querallee 2, 76131 Karlsruhe, Germany

provide a general vision and target state, the implementation at product level requires a nuanced ecological and economic assessment, since each product entails specific requirements, challenges and value potentials. Consequently, every phase of the product life cycle must be examined to identify its potential for contributions to achieving CE, and corresponding measures must be derived. The linear product life cycle must be transformed into a circular system, where a product's end of life (EoL) becomes the starting point of a new product, which is referred to as cradle-to-cradle (C2C). Implementing a CE in sectors of mobility, food, electronics, and textiles could cut GHG emissions by 22-44% in Europe, India, and China by 2050 (Ellen MacArthur Foundation, 2021). Despite its widespread use, the CE lacks a universally agreed-upon definition. A review of 114 definitions conducted by Kirchherr et al. (2017) reveals that CE is most commonly framed around the core strategies of reduce, reuse, and recycle. This study follows the CE definition of Kirchherr et al., (2017), which is "an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering […]". Reike et al. (2018) identifies 38 distinct R-Strategies. More concise sets of strategies, such as the 3R framework (Reduce, Reuse, Recycle) (Liu et al., 2017), are reflected, for example, in the waste strategy of the European Waste Framework (Directive 2008/98/EG, 2008). The latter defines a waste hierarchy, that can be interpreted as a 4R approach: waste prevention (corresponding to Refuse), preparation for reuse (Reuse), recycling, and recovery (including energy recovery, backfilling and, in some interpretations, final disposal, all subsumed under Recover). In the context of this research and the proposed approach, the emphasis lies on product-related aspects for which the 9R framework from Buchberger et al. (2019) is suitable. The R-strategies (R0–R9 as illustrated in Figure 1) constitute the core principles and the practical 'how-to' of the CE according to Kirchherr et al. (2017). Their implementation at the product level is guided by design guidelines that can be subsumed under the umbrella term DfX (Rieg & Steinhilper, 2012). Critiques of DfX methods include the required prior selection of an X-dimension, which constrains the solution space (Andreasen & Mortensen, 1997), the absence of a product-level methodology (Mesa, 2023), and the lack of quantitative evaluation (Sassanelli et al., 2020). Frameworks to evaluate alternatives when multiple, partly contradictory criteria must be considered, such as the Multi-Criteria Decision Analysis (MCDA), are not suitable for identifying the criteria. According to Cinelli et al. (2020) the wide range of philosophies and models makes it challenging for users to clearly determine which methods fit their specific context.

This study proposes an approach, supporting practitioners at the product level, to identify current CE hindering criteria and in implementing Design for Circularity (DfC) to quantitatively enhance circularity. It is operationalized through a four-step methodology that serves to identify CE improvement potential using an existing product as the reference, thereby acquiring information and knowledge from a physically existing object, which corresponds to the definition of reverse engineering (RE) according to Kumar et al. (2013). The approach combines systematic analysis of the life cycle with the quantitative evaluation of environmental and economic assessment ensuring no trade-offs are made through design changes. In addition to introducing the approach, the study examines whether the proposed approach enlarges the solution space compared to DfX and whether it provides robust quantitative decision support.

The study is organized as follows: Section 2 provides an overview of methods for quantitative environmental, circularity, and economic assessment, which form the basis for the proposed approach. Section 3 presents qualitative eco-design tools, focusing on DfX guidelines and their integration into the product life cycle and the CE. Section 4 details RE, its origin, and the use of RE-thinking, for product development. Section 5 presents the proposed RE methodology, including the RE-thinking, qualitative DfX and the quantitative assessment, for improving circularity as well as an option for visualizing the results. Section 6 concludes the study with a summary and an outlook.

2. Assessment Methods to quantify the environmental and economic IMPACT

The foundation for carrying out environmental and economic assessment is based on LCA and LCC. While DIN EN ISO 14044 (German Institute for Standardization, 2006) is the common methodology for LCA, there is no single common methodology for LCC, rather than multiple standards and guides (Miah et al., 2017). They generally account for the costs of products, materials, technologies, or systems over various financial life-cycle stages, including investment, operation, maintenance, and demolition/disposal. For conducting an LCA this study refers to the principles and framework defined in DIN EN ISO 14044, which are not detailed, as this is described extensively in the standard and literature (Mohan & J., 2024). For the LCC the principles and framework, referred to in this study, is defined in the standard (DIN EN 60300-3-3).

Although LCA and LCC evaluate different dimensions using distinct units, their underlying methodological principles are closely related. Therefore, both methods are presented jointly in the following chapter 2.1. The assessment of circularity is introduced separately in Section 2.2, while the integrated application of all methods within the overarching RE framework is subsequently detailed in Section 4.

2.1. LCA and LCC

The environmental impact E(I) associated with the raw material acquisition (RMA), the production (P), the use phase (Use), EoL and the credits for material or energetic utilization/recovery (c) – i.e. the complete product life cycle – is quantified by an LCA. Besides the most common impact category, Climate Change - which assesses GHG emissions in [kgCO_2eq.] - other categories such as Ozone Depletion, Eutrophication, Acidification, as well as Human toxicology and Ecotoxicity, can also be evaluated with the standard. According to van Doorsselaer & Koopmans (2021) 80% of a product's environmental impacts are determined during the design phase, highlighting the importance of ecological considerations in product design for achieving the CE. For a product to succeed on the market, it must be economically viable above all as the ecological perspective alone is not enough. The economic assessment includes all costs associated with RMA, P, Use, EoL, credits (c). Mathematically, the ecological (I) and economic (C) impact (E) of a product (or product system) X_0, characterized by its material and energy flows x0, can be calculated as follows by Equation 1.

Equation 1. Environmental and economic assessment of a product X_0, (Dieterle, 2023)

$$E(I;C)_{total}(X_0) = E(I;C)_{RMA}(x_0) + E(I;C)_P(X_0) + E(I;C)_{EoL}(X_0;x_0) - E(I;C)_c(X_0;x_0)$$

Each of the summands can contribute to improving the impact. However, only a comprehensive consideration of the entire life cycle can prevent trade-offs, whereas an improvement in one summand comes at the expense of another and may worsen the overall balance. If the product is modified (X_{new}), changes in the individual summand should not increase the total sum, as defined in the following Equation 2.

Equation 2. Condition for the economic and ecological evaluation to ensure that the overall balance does not deteriorate

$$\Delta E(I;C)_{total} = \sum_i \Delta E(I;C)_i \leq 0$$

$$with\ i \in \{RMA, P, EoL, c\}$$

While LCA and LCC are well suited to quantify environmental and economic impacts, often aggregating results into a single number (E(I;C)), they primarily serve as evaluation tools. As such, they provide limited guidance on how the assessed product system should be modified to improve the LCA and LCC. Although these methods can identify life cycle stages or processes with comparatively high contributions to overall impacts, they do not indicate which specific design decisions, material choices, or process characteristics are responsible for these impacts, nor how they could be altered in a systematic and design-oriented manner. As an illustrative example, LCA and LCC can indicate that incineration at the EoL is the main contributor to the environmental or economic assessment, yet it does not reveal whether this outcome is driven by material selection, joining techniques, or other processing steps that inhibit disassembly or recycling.

The consideration of LCA and LCC does not allow for any direct conclusions regarding circularity and may, in some cases, lead to the result that circularity has no significant influence on the overall assessment. This outcome is contrary to the objectives of a circular economy. An illustrative example is the assessment of a water tap that, due to its use phase and very long service life, results in high cumulative water consumption. Consequently, the RMA and production phases represent only a small fraction of the overall life cycle impacts, such that improvements in circularity at the EoL have no significant effect on the total LCA results. Therefore, the assessment of circularity as a dedicated and independent metric is indispensable.

2.2. Life Cycle Gap Analysis

To address this challenge, the LCGA proposed by Dieterle (2023) provides a complementary perspective to conventional LCA and LCC by explicitly focusing on the preservation of invested efforts through circular EoL strategies. Instead of evaluating total life cycle impacts, LCGA quantifies the gap between the efforts initially invested in manufacturing, defined as RMA and P, and the credits recovered at the end of life. The assessment is not tied to a specific R-strategy, as the value retained through circular use is reflected in the magnitude of the c. The outcome of the LCGA is a single indicator that represents the loss of the originally invested efforts, calculated as stated in Equation 3:

Equation 3. Calculating the life cycle gap, (Dieterle, 2023)

$$E(I;C)_{LCG}(X_0) = E(I;C)_{RMA}(x_0) + E(I;C)_P(X_0) - E(I;C)_c(X_0;x_0)$$

The LCGA can be understood as an alternative perspective on the life cycle, with a focus on circularity, and thus as a measure of achieving a CE. By relating the LCG value to the initially deployed efforts from RMA+P, a relative assessment of the gap is obtained as stated in Equation 4:

Equation 4. Calculating the relative lifecycle gap, (Dieterle, 2023)

$$\%LCG = \frac{LCG}{M}$$

From a CE perspective, the LCG represents the share of environmental and economic efforts that are irreversibly lost at the EoL. A smaller gap indicates a higher degree of value retention and, consequently, a more circular product system. By normalizing the LCG with respect to the initially invested manufacturing efforts (RMA+P), the relative LCG enables practitioners to compare circularity performance across different product systems, design variants, or EoL scenarios, independent of absolute impact magnitudes.

The Material Circularity Indicator (MCI) is one of the most widely used metrics for assessing circularity at product level. It evaluates circularity primarily based on material flows, considering the mass material inputs, the mass of unrecoverable waste at the end of life, and the intensity of product use. As such, the MCI provides a material-focused measure of how effectively materials are recirculated within a product system. In contrast to material circularity indicators (MCI), the LCGA considers the full life cycle to avoid trade-offs (see Equation 2). The assessment of MCIs restricts the indicator to material recirculation and leaves other R-strategies largely unaddressed (Jannik & Ryszko, 2017).

Through assessing circularity, the MCIs but also the LCA, LCGA and LCC do not provide product-specific improvements and confront practitioners with the challenge of translating their results into actionable measures. For improvements on product level, the current state of the art (SotA), design guidelines, providing design strategies on product level, are presented below.

3. Design guidelines

Guidelines for environmental product development are commonly referred to as Eco-design in Europe and Design for Environment (DfE) in the United States (Baumann et al., 2002). In the context of circular product development, various strategies have been proposed, including approaches that begin with a vision of a desired future state and work backward to the present. This principle, termed back-casting, reverse scenarios, or reverse engineering, focuses on identifying the necessary steps to achieve predefined sustainability objectives (van Doorsselaer & Koopmans, 2021).

Numerous classifications of eco-design tools and strategies are reported in the literature (Aqeel et al., 2023; Chikofsky & Cross, 1990; Eilam, 2005; Messler, 2014; Wang, 2011). Baumann et al. (2002) distinguish six categories: frameworks; checklists and guidelines; ratings and rankings; analytical tools; software and expert systems; and organizing methods. Devanathan et al. (2010) propose a more compact classification comprising LCA-based tools, checklist-based tools, and tools based on quality function deployment. Within these classifications, Design for X (DfX) methods can be regarded as a specific subset of eco-design tools, primarily belonging to checklist-based tools and design guidelines.

DfX methods translate sustainability and circularity objectives into prescriptive design rules and recommendations that can be applied during early product development stages. Rather than providing analytical quantification, they support practitioners by specifying design features intended to achieve particular product attributes, such as circularity or durability (Huang, 1996). The "X" represents a specific property or life-cycle phase for which the product is to be designed (Andreasen & Mortensen, 1997). Common examples include Design for Recycling (DfR), Design for Reuse and Repurposing (DfRR), and Design for Disassembly (DfD) (Schüle, 2026). As the term implies, DfX follows the conventional forward engineering (FE) paradigm, progressing from functional requirements and design variables to physical solutions and final products (Aqeel et al., 2023). The R-strategies are structured from R9 to R0 according to their potential contribution to circularity (Potting et al., 2017). Depending on the strategy pursued, value is reintegrated into different life-cycle phases, as illustrated in Figure 1, for instance, reuse (R3) re-enters the use phase, whereas refurbishment (R5) reconnects at the assembly stage (Buchberger et al., 2019).

The application of DfX methods requires the selection of a specific design objective, which inherently limits the solution space. DfX guidelines are intentionally generic and globally applicable. For example, DfD recommends limiting joint types, using standardized connection techniques, enabling easy disassembly, ensuring accessible interfaces, and reducing the number of fastening points (van Doorsselaer & Koopmans, 2021). Similarly, DfR focuses on recyclability-related aspects such as material traceability, separability, and the reduction of material combinations, providing general recommendations rather than system-specific solutions.

While DfX tools are widely applied and strongly recommended in literature (Benabdellah et al., 2019; Chiu & Kremer, 2011; Sassanelli et al., 2020), they are also criticized for lacking clear application pathways (Mesa, 2023) and for the complexity arising from the multitude of possible objectives and interdependencies within product development (Rieg & Steinhilper, 2012). Most importantly, DfX methods do not provide quantitative feedback on how design changes affect life-cycle environmental impacts or costs. As a result, trade-offs between life-cycle stages cannot be systematically evaluated, and the risk of burden shifting remains unaddressed. Consequently, DfX methods serve as overarching, prescriptive design guidelines but lack a direct linkage to the specific product system, a structured identification of existing weaknesses, and a quantitative evaluation of alternative design variants. To address these limitations and incorporate a systematic analytical perspective into the design process, the following section introduces the proposed reverse engineering (RE) approach.

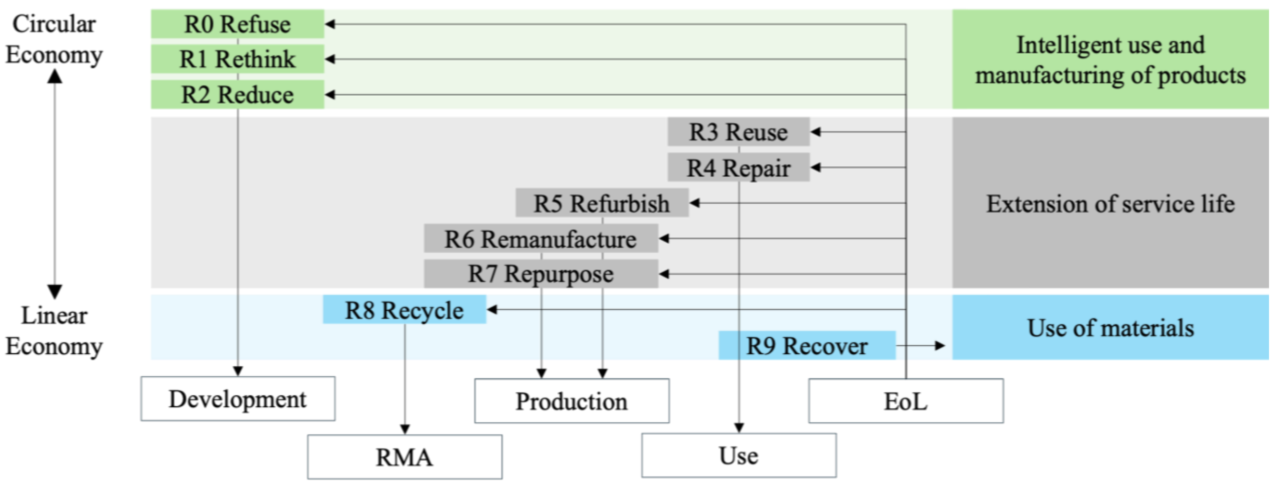

Figure 1. Mapping of the 9R strategies (R0–R9) to the product life cycle, illustrating where circular loops re-enter the life cycle and how strategies differ in value retention, own graphic based on (Buchberger et al., 2019; Kirchherr et al., 2017; Potting et al., 2017).

4. Reverse Engineering

The term RE refers to the reversal of the conventional engineering chain of FE, as described previously, but also as backward problem solving (Messler, 2014). The exact temporal origin of RE cannot be determined, as there is no consensus in literature. According to Chikofsky & Cross (1990) and Rekoff, (1985), its roots lie in the analysis of hardware and the deciphering of designs from finished products. An early documented application, dates back to 1900 in the field of aviation, where the Wright brothers built an aircraft based on RE a bird (Aqeel et al., 2023). According to Aqeel et al. (2023) RE can be generally understood as learning process and implementation, how an object works. A definition of Rekoff (1985) describes RE as a process of examination, and not changing or replicating, but to analyze and identify components and their interrelationship. The motivation for RE can be divided in two goals: to create a clone, which is an exact copy or a surrogate performing the same function as the original, but employs an alternative method of operation and may differ in its outward design from the original (Rekoff, 1985). There is no uniform approach for the steps of RE. According to Wang (2011), the methodologies applied across various fields can differ greatly, but often involve steps such as data collection, analysis, modelling, prototyping, performance evaluation, and regulatory compliance; however, the underlying principles and fundamental limitations remain largely consistent across most industries. Numerous examples of RE applications and approaches for creating clones and replacement parts can be found in literature (Engel & Al-Maeeni, 2019; Gameros et al., 2015; Kyaw et al., 2023; Li et al., 2017; Qie et al., 2021; Yanamandra et al., 2020; Zivkovic et al., 2018), while applications of RE for sustainable product development remain comparatively rare. RE applications involving sustainability (e.g. Saiga et al., 2021) aim at making the process of cloning products less dependent on devices and computation. Blumenthal et al. (2025) presents a sensory RE framework to optimize formulations for sustainable food. Elashwah et al. (2025) developed a programming model for the optimization of locations for collection points to promote reuse or disposal. Within the applications, RE is used to reproduce missing or broken product components (Engel & Al-Maeeni, 2019; Gameros et al., 2015; Kyaw et al., 2023; Li et al., 2017; Qie et al., 2021; Yanamandra et al., 2020; Zivkovic et al., 2018), thereby extending the use and lifespan of a product to contribute to an improved LCA by reducing the consumption of RMA. However, their primary motivation is typically attributed to a shortage of replacement parts rather than environmental considerations. Therefore, these applications are not regarded as RE for improving sustainability, as understood in this work. In previous work, a RE approach is presented, though it lacks the integration of quantitative economic and environmental assessment aspects (Zürn and Dieterle 2024). The approach follows the idea of RE as a surrogate, starting with an existing product and analyzing its structure. Thereby a learning process is initiated to understand the changes made to material and product, referred to as process characteristics, throughout the life cycle. In line with the RE-Thinking, the proposed method adopts the DfE throught "Starting from Behind" (van Doorsselaer & Koopmans, 2021), meaning starting from the current EoL of a product and its current process chain of production, as the analytical starting point. The proposed methodology provides a comprehensive tool for sustainable product development. The objective of the proposed approach is to contribute to the vision of a CE and to enhance product circularity without compromising costs or environmental performance.

From a CE perspective, RE offers a suitable methodological foundation by focusing on existing product systems rather than idealized new designs. To date, no methodology or framework exists for applying reverse engineering to improve product circularity. Many products currently in use were not originally designed for circularity and therefore exhibit structural, material, or process-related barriers that limit higher-value circular end-of-life options. Conventional circular design approaches, such as DfX guidelines, mainly support high level design decisions and provide limited support for systematically analysing current designs and identifying barriers in existing products.

Despite the widespread availability of both quantitative assessment methods (e.g., LCA, LCGA, LCC) and qualitative circular design frameworks (e.g., R-strategies, Re-thinking, MCI), a fundamental research gap persists: the lack of a systematic and operational link between environmental impact quantification and actionable, product-specific circular design improvements. Existing qualitative tools provide generic, prescriptive guidance for circular economy (CE) implementation, but remain largely detached from the actual environmental performance of a concrete product. Conversely, quantitative assessment tools robustly quantify environmental and economic impacts along the life cycle, yet fail to indicate where, how, and why specific design modifications should be implemented to improve circularity at the product level.

As a result, decision-makers lack an integrated methodology that translates quantified life-cycle impacts into targeted, product-specific circular design actions.

Furthermore, RE-thinking, as a learning process and implementation of how an object works, has not yet been operationalized within a structured methodology for identifying CE potentials at the product level. As a result, practitioners lack a practical, design-oriented method that begins with an existing product and explicitly links CE principles to the introduced changes along the life cycle, while simultaneously accounting for environmental and economic impacts to ensure that no trade-offs are made. Addressing this gap is essential to enable targeted, evidence-based design interventions that support circular product development without unintended burden shifting.

5. Methodology of the Reverse Engineering approach

The proposed approach, illustrated in Figure 2, is structured into four phases with corresponding steps. The first phase focuses on documenting the initial system and conducting its quantitative assessment. The second phase is dedicated to identify a new EoL, thereby defining a target state. The third phase aims to identify the specific process step within the current product life cycle that hinders or prevents the achievement of the defined CE objective. The fourth phase comprises the final quantification of the modified product system to ensure that no environmental or economic trade-offs have been introduced.

The following section is structured according to the four phases and elaborates the phases as well as the included steps. In doing so, the product life cycle and the changes introduced along it are analyzed in detail, and a graphical representation is developed, which is progressively extended from Figure 2 to Figure 6 by adding further elements. Finally, this chapter presents a diagram that illustrates for both product systems, the baseline system and the circularity-enhanced system, the results of LCA, LCGA, and LCC, thereby enabling a straightforward relative comparison of the corresponding metrics.

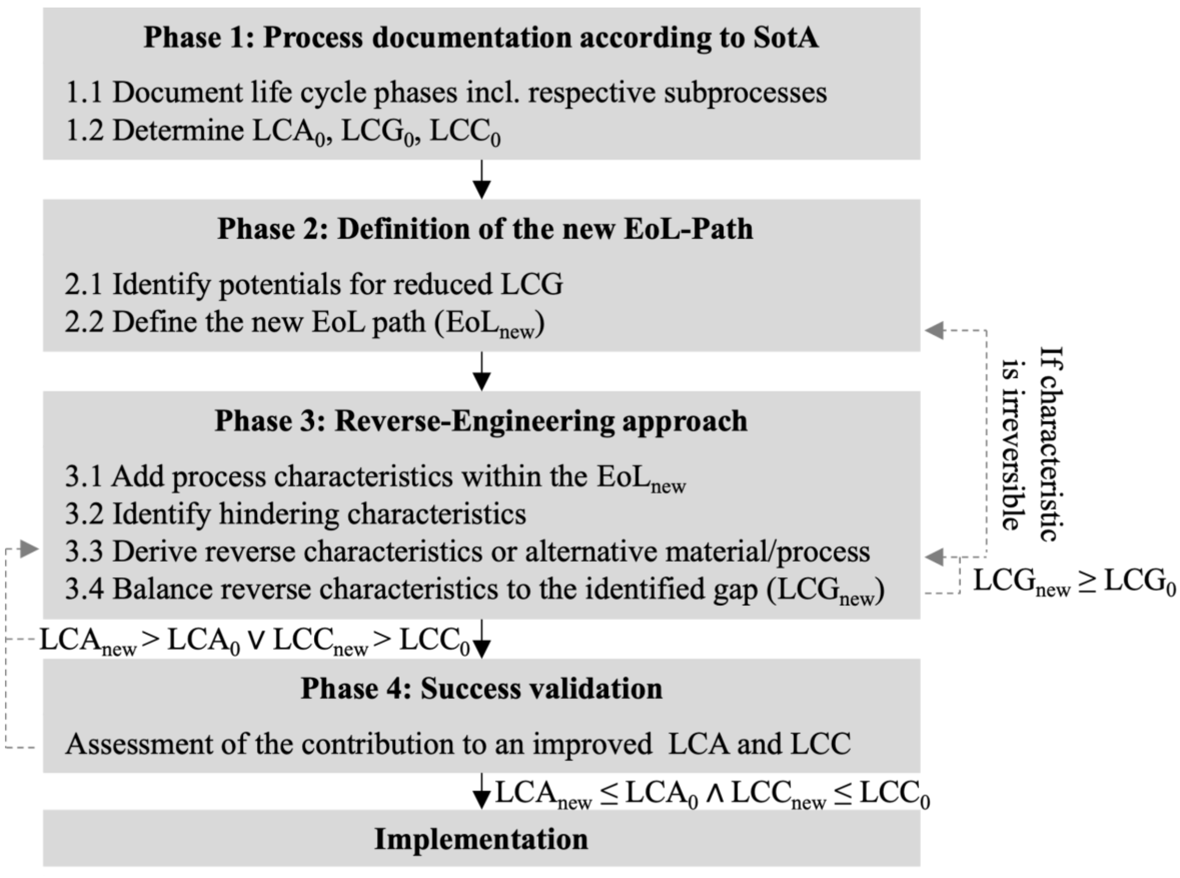

Figure 2. Flowchart of the RE methodology, including decision points for circularity improvement and environmental and economic trade-off prevention.

5.1. Phase 1: Process documentation according to SotA

The goal of this phase is to document the current life cycle and the transformations that the raw material undergoes from its original form to the finished product, as well as the changes that subsequently occur to the product during the use phase. In step 1.1, as illustrated in Figure 3, the product's full life cycle from Research and Development (R&D) to the EoL is mapped and the production chain, is decomposed into its individual steps (P1, P2), based on DIN 8580 (German Institute for Standardization, 2022). This incorporates the definition of RE to analyze interrelationships and to understand how an object functions according to Rekoff (1985). In the second step 1.2, the quantitative assessment of the current (baseline) product, utilizing the methods outlined in Section 2, by evaluating the LCA_0, $LCGA_0$, and LCC_0 is conducted. With this step, the initial product is assessed in terms of both economic and ecological aspects.

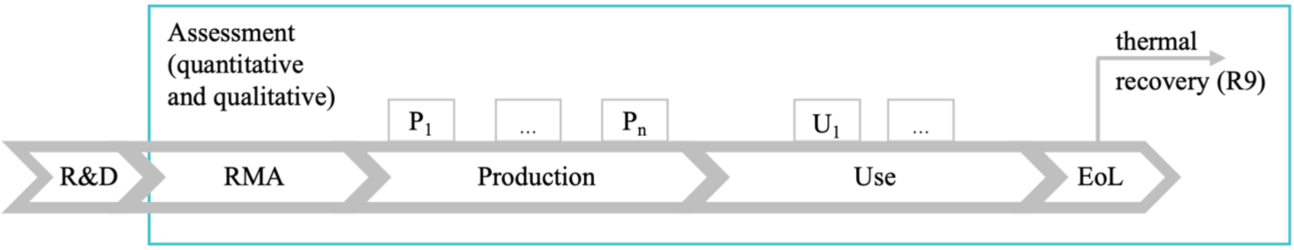

Figure 3. Graphical documentation of the life cycle phases from R&D to EoL and the subsequent steps P_1–P_n during production and the use phase U_1 according to step 1.1.

5.2. Phase 2: Definition of the new EoL-Path

The goal of this phase is to identify a new EoL with an increased circularity compared to the current EoL. To facilitate this in step 2.1, potential options for reducing the LCG, through an improved EoL are examined. For instance, if the current EoL route is thermal recovery (R9), the next higher contribution towards the CE, following the R0-R9 framework, as shown in Figure 1, is material recycling (R8). It should be noted that the EoL is not only determined by the technical framework conditions, but also by legal and social boundary conditions. Such boundaries represent regulatory and societal requirements, such as laws restricting material selection e.g. EU Directive 1907 (2006) or set design restrictions for children's toys e.g. EU Directive 48/EG (2009), that cannot be altered and lead to restrictions for recirculation. As illustrated in Equation 5 the intersection of all framework conditions with the assessment defines all possible product EoL scenarios. This is not a mathematical equation, but rather a representation of the solution space.

Equation 5. Intersection of all framework conditions with the assessment defining all possible EoL scenarios

$$Possible\ EoL = framework\ Conditions \cap assessment\ (quant.\ +\ qual.)$$

After defining a new targeted EoL, the following step 2.2 graphically adds, the new targeted EoL-Route, starting from the EoL-Stage reintegrating into the RMA-Stage, as shown in Figure 4 by the orange arrow.

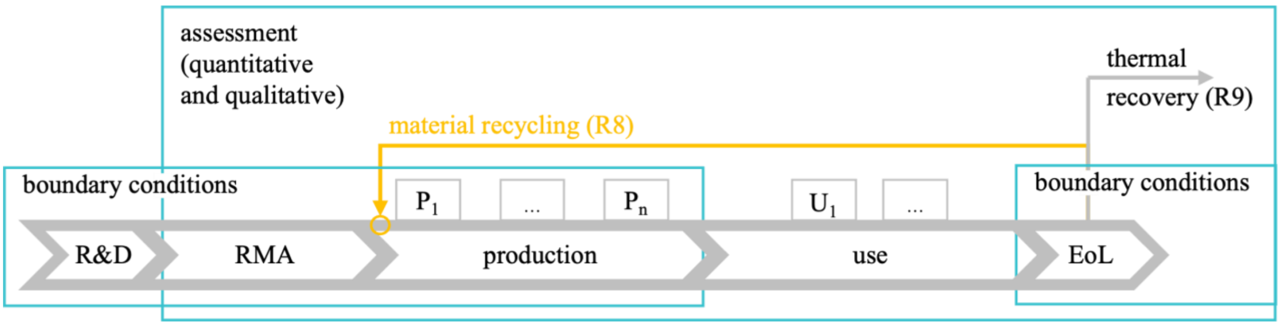

Figure 4. The Product life cycle, including the targeted new EoL material recycling (R8) pathway, highlighted in orange, along with the reintegration point into the life cycle at the beginning of the production phase.

5.3. Phase 3: Reverse-Engineering approach

The third phase's goal is to identifying the current life cycle step that prevents higher-value circular routing at the product's EoL and deriving alternatives to achieve the more circular EoL defined in the previous phase. It follows the idea: If the changes introduced are analyzed and subsequently reversed, the product returns to its initial state. In the present example, the objective is, to recycle the material and therefore revert to the point at which the material is in its RMA-Stage. Consequently, only those changes that have been implemented since this point in the life cycle must be considered. These correspond to all changes that are represented graphically beneath the orange arrow route in Figure 5.

The changes introduced along the product life cycle are referred to as process characteristics. A process characteristic is defined as a change in the product's physical, chemical, or functional properties that is induced by a specific life cycle stage, including production steps (e.g. P_1) as well as the use phase (e.g. U_1). Typical process characteristics during the production phase include cutting, shaping and bonding. Typical process characteristics during the use phase include wear, contamination, ageing, material degradation, or the consumption of auxiliary materials.

Step 3.2 aims to identify the specific process characteristic that determines the current EoL pathway of the product (e.g. thermal recovery). Process characteristics that constrain circularity include, for example, the cohesive bonding of two dissimilar materials, which renders thermal recovery the only feasible EoL option. Another example is a forming process that does not alter the material composition but changes the orientation of polymer chains, thereby reducing shredding performance and again limiting the EoL to thermal recovery.

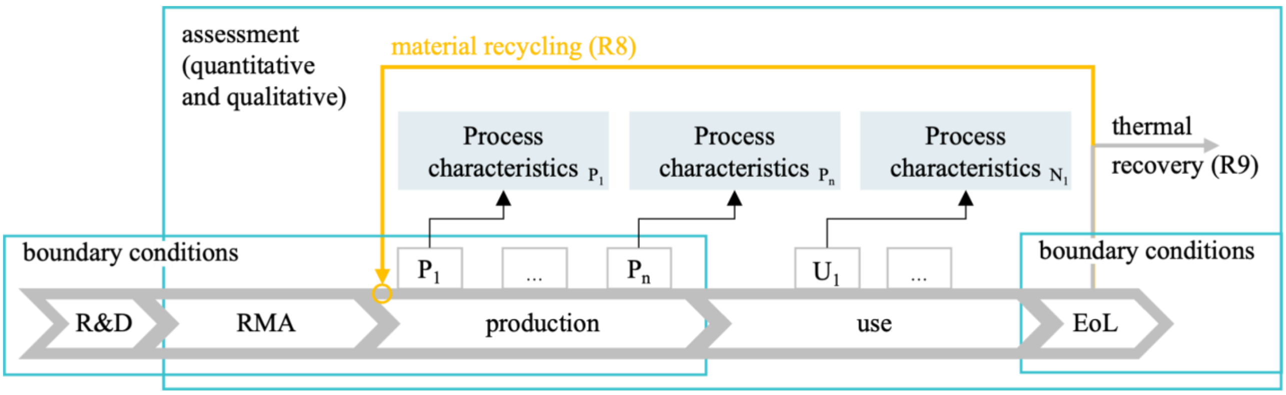

Figure 5. Graphical representation of the product life cycle extended by the process characteristics of the individual process steps P_1-P_n as well as U_1, which describe the changes introduced along the life cycle.

In Step 3.3, so-called reverse characteristics are derived and added to the graphic as shown in Figure 6. A reverse characteristic is defined as a process or intervention that counteracts or reverses a previously introduced process characteristic and enables a backward movement along the process chain. While some process characteristics, such as the cohesive bonding of dissimilar materials, may not be reversible, others can be mitigated. For instance, the orientation of polymer chains may be reduced through a thermal tempering step, thereby improving material processability and enabling alternative circular EoL routes.

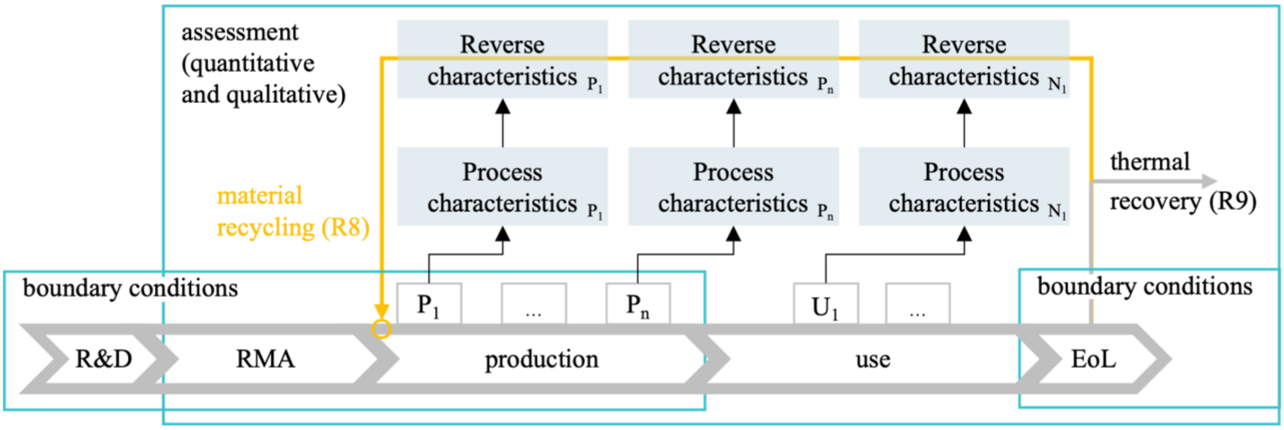

Figure 6. Graphical representation of the product life cycle extended by the reverse characteristics, which represent the countermeasures to the process characteristics, i.e., the opposing process from a process-engineering perspective.

If no reverse characteristics can be derived, alternative materials or production processes for manufacturing the product may be considered, e.g. using the same materials for cohesive bonding or using a screwed connection instead of adhesives. If this is also not feasible or does not lead to improvement (evaluated in step 3.4), the iterative methodology directs the user back to step 2.2 to select an alternative EoL_{new} and to proceed with step 3.1.

Step 3.4 verifies that the identified reverse characteristics (e.g. joining two parts by screwing instead of cohesive bonding) of the newly selected materials and/or processes enhance circularity and do not cause adverse to the LCG. Figure 7 qualitatively illustrates the relationship between the value potential of material, product recycling and the associated value potential, as well as the time, energy, and cost requirements.

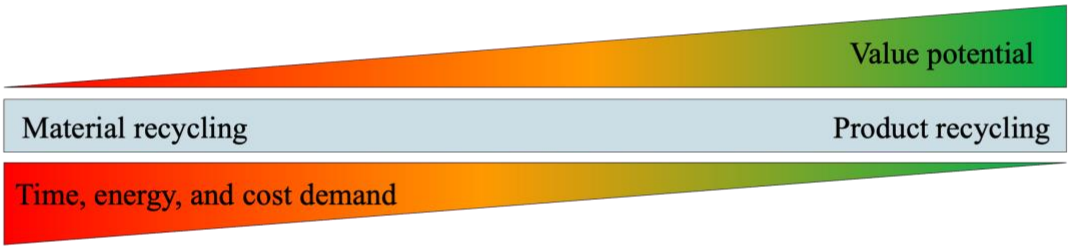

Figure 7. Value potential of material, product recycling vs. time, energy, and cost requirements.

If the condition of step 3.4 for an increased gap, rather than a reduction, is met, the methodology guides the user back to step 3.3. The condition is stated in the following Equation 6:

Equation 6. Condition to ensure improved circularity of the new product X_{new}

$$LCG_{new} > LCG_0$$

Before the final implementation (phase 4) as for the baseline product, a complete reassessment of the new product by LCA_{new}, $LCGA_{new}$, LCC_{new} is required.

5.4. Phase 4: Success validation

The goal of the fourth phase is to ensure an overall environmental improvement compared to the baseline system, while also achieving improvements in circularity and economic performance, and ensuring that no trade-offs arise from the introduced changes. If the conditions (as defined in step 4, Figure 2) are met, implementation can proceed. The conditions are stated in the following Equation 7:

Equation 7. Condition to ensure improved LCA and LCC of the new product X_{new}

$$LCA_{new} \leq LCA_0 v\, LCC_{new} \leq LCC_0$$

It is noteworthy that the proposed approach does not primarily aim at substantial LCC or LCA reductions, rather it establishes the boundary condition that neither LCC nor LCA may deteriorate as LCG decreases, meaning an increase in circularity.

For displaying the quantified results of $E(I;C)_{total}(X_0)$, $E(I;C)_{LCG}(X_0)$ and $E(I;C)_{total}(X_{new})$, $E(I;C)_{LCG}(X_{new})$ an XY-Diagram, schematically shown in Figure 8, adopted from (Dieterle, 2023), is proposed. In this graph, the environmental assessment e.g. the impact category of carbon footprint in [kgCO_2eq./Unit], is plotted on the Y-axis, while the economic assessment in [€/Unit] is plotted on the X-axis. The enclosed area can be interpreted as a techno-economic assessment. The change along the Y-axis represents the ecological improvement, while the change along the X-axis represents the economic improvement. Connecting the corners of the respective squares illustrates the techno-economic improvement, quantifying the relative reduction of the area. If a further impact category, e.g. ozone depletion, is of interest, this can be added as a third axis to the diagram and the resulting cubic volume can be assessed for the relative comparison of X_0 and X_{new}.

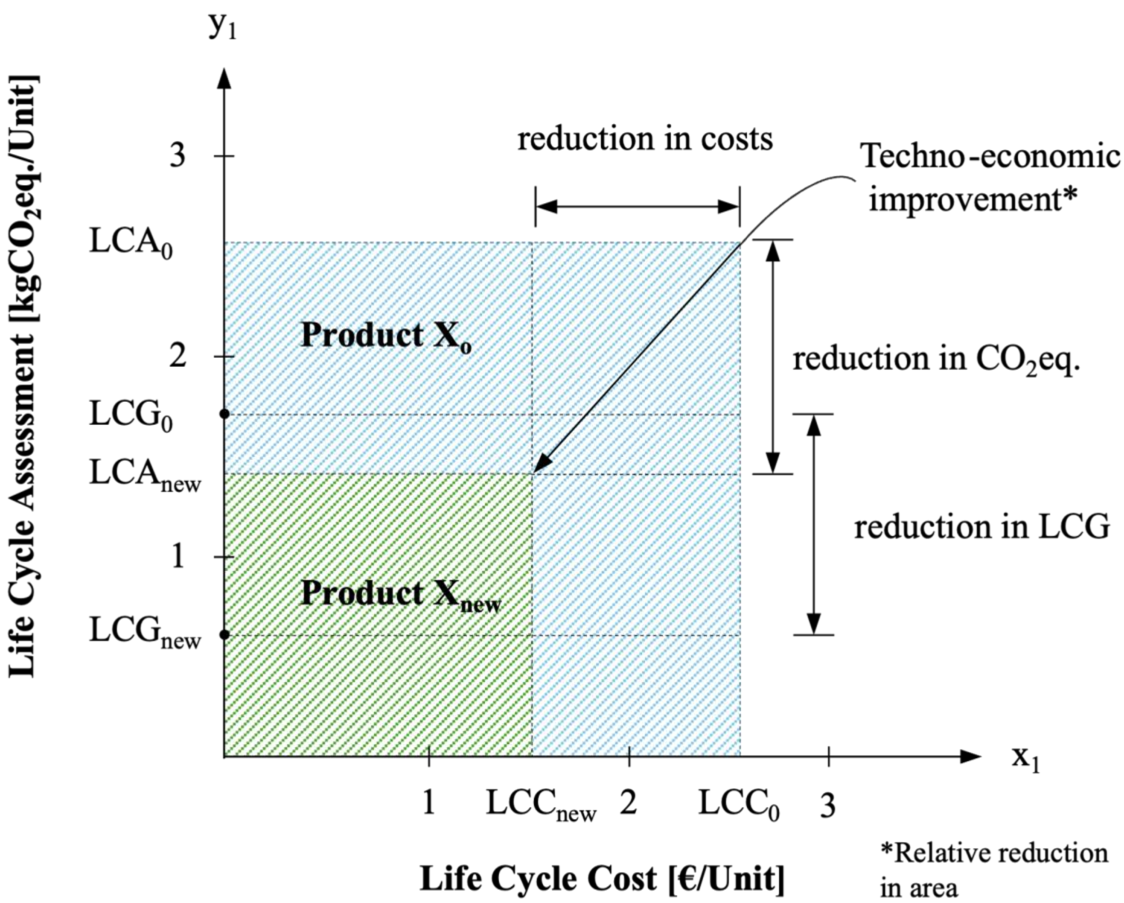

Figure 8. Proposed diagram for visualizing the changes in LCA, LCG and LCC adopted from (Dieterle, 2023).

6. Conclusion and Outlook

The proposed approach is based on RE-thinking, applied to achieve a CE, a topic of high societal and political relevance. It constitutes the first application of RE explicitly aimed at improving the circularity of products. In summary, the main contribution of this work lies in operationalising RE for the explicit improvement of product circularity, the integrating LCA, LCC and LCGA into a single, trade-off-sensitive decision framework, and providing a reproducible, product-level procedure that can be applied across industries. Together, these elements offer practitioners a clear pathway from identifying circularity bottlenecks to deriving and evaluating design changes.

Beyond the methodological contribution, a key insight gained from developing this approach is that circular design decisions at early life-cycle stages must be informed by EoL feasibility constraints of existing products and processes. The proposed RE perspective makes these constraints explicit by tracing circularity bottlenecks back to specific process characteristics that originate in material selection, joining, and manufacturing decisions. This matters for early-stage product development because it supports designers in prioritizing design choices that keep higher-value circular routes technically achievable, while simultaneously safeguarding environmental and economic performance.

The proposed reverse-engineering-based method closes the research gap between generic DfX guidelines and purely quantitative assessment tools by providing an operational, product-specific and quantitatively validated procedure to improve circularity without compromising environmental or economic assessment. The approach is explicitly directed at achieving a CE by increasing circularity, subject to the constraint that neither the LCA nor the LCC performance is adversely affected. It combines established LCA and LCC with the circularity assessment of the LCGA and a process analysis of the manufacturing chain to identify specific changes in the manufacturing process determining the current EoL of the product. The applicability is not restricted to a single impact category. By deriving reversal measures or alternative processes, the method aims at closing circularity directly at product level. Starting from the existing product and tracing induced CE vulnerable characteristics back from the current EoL, the approach uncovers CE-vulnerable changes and allows multiple circular pathways to be explored. If a given step or condition cannot be achieved, the approach directs the user back to the selection of an alternative R-strategy. The approach, divided into four iterative phases, can be situated within the CE framework. It enables an open solution space and is not tied to any specific product or industry. Despite its strengths, the proposed approach is subject to several limitations.

First, the approach is strongly technical in orientation, with the aim of improving sustainability; however, the social dimension of sustainability is not directly addressed.

Second, it relies on the availability of sufficiently detailed life cycle inventory data and process knowledge.

Third, the quality of the results depends on the underlying LCA and LCC models and their inherent uncertainties.

The combined quantitative decision support, through $\Delta E(I;C)_{total}$ and $E(I;C)_{LCG}$, enables trade-off checks and evidence-based selection among design alternatives. The approach's graphical representation provides a universally applicable and clear visualisation that combines two (or more) independent variables of economy and ecology into a single diagram. In this way, the proposed approach again bridges the gap between generic Design for Sustainability guidelines and purely quantitative assessment methods and provides a structured, evidence-based route from identification to solution and to the evaluation of the point in question.

In further research, the proposed approach should be applied and systematically tested on a broader range of products and manufacturing processes. In particular, future studies should investigate products with varying levels of technical complexity and different production technologies by explicitly implementing the proposed methodology on concrete components, representative use cases, and real-world process chains, in order to assess the robustness of the method and its practical applicability. Such case studies would allow for a systematic evaluation of the method's usability, transparency, and reliability when applied under diverse industrial conditions.

Another promising research direction is the integration of the approach into digital design tools that already support LCA and LCC, thereby enabling a software-based implementation within the product development process. In addition, incorporating sensitivity analysis into the reverse engineering framework represents a valuable extension, as it would allow for a more systematic examination of uncertainties and parameter dependencies within the assessment results.

While the present work focuses on environmental and economic performance, an important avenue for future research is the extension of the approach to include the social dimension of sustainability. Combining the reverse engineering steps with social life cycle assessment could help to identify potential trade-offs between circularity measures and social criteria along the value chain, thereby supporting more holistic sustainability-oriented decision-making.

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Declarations

Competing Interests The authors declare no competing interests.

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Abbreviation List

c	Credits for material or energy use at EoL
C2C	Cradle to Cradle
CE	Circular economy
DfC	Design for Circularity
DfD	Design for Disassembly
DfE	Design for Environment
DfRR	Design for Reuse and Repurposing
DfX	Design for X
E(C)	Total economic impact
E(I)	Total environmental impact
EoL	End of Life
FE	Forward Engineering
GHG	Greenhouse gas
IT	Information Technology
LCA	Life cycle assessment
LCC	Life cycle costing
LCG	Life cycle gap
LCGA	Life cycle gap assessment
LE	Linear economy
M	Manufacturing (RMA + P)
MCDA	Multi-Criteria Decision Analysis
MCI	Material circularity indicators
P	Production
R&D	Research and Development
RE	Reverse Engineering
RMA	Raw Material Acquisition
SotA	State of the Art
Use	Use phase of the product or product system
X_0	Product or product system
x_0	Energy and material flows of X_0
X_{new}	Modified product or product system
x_{new}	Energy and material flows of X_{new}