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Novel Methodology for Assessing Second Life Potentials of Industrial Products

Günther Schuh

RWTH Aachen University, Laboratory for Machine Tools and Production Engineering (WZL), Steinbachstr. 19, 52074 Aachen, Germany.
E-mail: g.schuh@wzl.rwth-aachen.de

Marc Nicolas Schauss*

Fraunhofer Institute for Production Technology IPT, Steinbachstr. 17, 52074 Aachen, Germany.
E-mail: marc.schauss@ipt.fraunhofer.de

Miguel Mikosch

Fraunhofer Institute for Production Technology IPT, Steinbachstr. 17, 52074 Aachen, Germany.
E-mail: miguel.mikosch@ipt.fraunhofer.de

* Corresponding author

Abstract: In their transition towards a circular economy, companies encounter considerable challenges in harvesting the inherent value of industrial products. To overcome this challenge, it is reasonable to systematically determine second-life options in the early product design phases. The present paper introduces a methodology that promotes a value-based prioritization of (sub-)components and materials regarding their second-life potential. To achieve this, each level of a product architecture is assessed against sustainability and circularity criteria in the areas of technology, business, ecology, and legislation. The individual scores of (sub-)components and materials enable a value-based prioritization with three distinct levels of second-life potential. Moreover, a comparative evaluation of different product architectures regarding their sustainability and circularity can be conducted by determining an overall score. The development of the methodology is supported by a comprehensive literature review and expert interviews.

Keywords: Circular Economy; Sustainability; Circular Product Design; Sustainable Design; Second Life Options; Reuse; Recovery.

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1 Introduction

In recent decades, the need for a transition from a linear to a circular economy (CE) has become increasingly apparent. The growing pressure on natural resources, increasing environmental pollution and the finite nature of raw materials are leading to global challenges such as climate change, biodiversity loss and environmental pollution (BMUV 2024, 1–2). This threefold environmental crisis is largely attributable to the extraction and utilisation of raw materials. In general, the use of raw materials is responsible for around 55 % of emissions, around 40 % of air pollution and around 90 % of biodiversity loss (IRP 2024, 2). At the same time, only 7.2 % of goods produced globally are part of a CE, which represents a decrease of around 21 % from 2019 to 2024. (Fraser et al. 2024, 8)

The CE aims to extend the life cycle of products and materials in order to maintain value in the economic system (Kirchherr et al. 2017, 229). The strategies used to achieve the CE are frequently referred to as R-strategies (Stahel 2019, 29–31). By utilizing resources over a longer period, decoupling economic growth from resource consumption is made possible. At the end of their life cycle, products or materials are reintegrated into the value chain, which again initiates a new life cycle. This not only leads to ecological benefits, but also opens up economic potential (Alexander et al. 2023, 1–7). Examples from a Tier 1 automotive supplier and a water meter OEM show that remanufactured products achieve higher margins than new products since less primary raw materials need to be processed (Schuh et al. 2023, 337–341). Other projects that focus on secondary life applications, i.e., reuse or repurpose for wind turbine blades demonstrate that the lifetime can be extended up to 20 years, while reducing costs and CO_2 emissions at the same time (Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) 2024, 77).

Around 80 % of environmental impacts are determined during the design phase of products, which displays the importance of circular design (CD) in the CE (Nasr et al. 2018, 152). Thus, the central goal of the CE can only be achieved if the product design incorporates circular and resource-efficient aspects. The CD approach makes it possible to develop products that fulfil the requirements of resource-conserving design (Ellen MacArthur Foundation 2015, 55). It is therefore crucial that designers and companies integrate circular principles into the development process in order to create sustainable products that are both ecologically and economically beneficial (Bocken et al. 2016, 317). Industrial companies are increasingly addressing this potential by incorporating the principles of the CE into their product design processes and business models (GEA Group 2023; BASF SE 2023; NKWS 2024).

However, identifying and prioritizing products, (sub-)components and materials with second-life potential is a challenge due to the complexity of industrial products and the multitude of influencing factors. It is therefore necessary to develop a methodology to determine the second-life potential of industrial products to capture their inherent value within the CE.

Purpose and scope of this research paper

Derived from the situation described above, the objective of this paper is to determine the most promising second-life potentials of industrial products. Despite the existence of some successful industry examples, it is evident that the value of industrial products is not yet fully captured when the majority of them end up in landfill or are thermally recycled (Fraser et al. 2024, 22–23). A significant challenge is the absence of a systematic approach to identify the (sub-)components and materials that could and should be used beyond their original life cycle. It is therefore essential to develop a methodology, which ensures that the inherent value of industrial products is retained in a CE. Against this background, the research question "How can industrial products be assessed according to their second-life potential?" is formulated and tackled in this paper.

Structure of this research paper

Since this paper focuses on solving a practical problem observed in the industry, its structure follows Ulrich's research approach for applied sciences. According to Ulrich, a problem with a practical relevance needs to be identified at first. To address this, problem-specific theories and methodologies are to be analyzed and elaborated in the field of fundamental and formal science. Finally, the developed methodology needs to be validated in the industrial practice and refined based on the results. (Ulrich 1984, 168–199)

After detailing the practical relevance and challenges in this chapter, the theoretical fundamentals are introduced in chapter 2. With the aforementioned aspects, an emphasis is therefore put on circular economy, product life cycle and development process, circular design, product architecture as well as sustainability and circularity criteria. Chapter 3 analyses existing methodologies to understand the state of research, identify the research gap and derive requirements towards the methodology. In chapter 4, a methodology is proposed that allows for the determination of second-life potentials. Finally, chapter 5 draws a conclusion and provides an outlook to further research.

2 Fundamentals

Circular economy

The Ellen MacArthur Foundation defines a CE as an economic system in which no waste is produced, and nature regenerates itself. To preserve value, all products and materials are kept in circulation through processes such as maintenance, reuse, refurbishment, remanufacturing, recycling, and composting. The concept is based on three principles: the elimination of waste and pollution, putting products and materials into circulation, and regenerating nature (Ellen MacArthur Foundation 2024). The strategies employed to attain the CE are frequently designated as R-strategies (Stahel 2019, 29–31). POTTING ET AL. (2017, 5) divide the R-strategies into three categories: Smarter product use and manufacture, with a focus on the principles of refuse, rethink and reduce, the extension of the lifespan of products and their parts through reuse, repair, refurbish, remanufacture, repurpose, and the useful application of materials through recycling and recovery.

To identify second-life potentials for stimulating the secondary life cycle of an industrial product, it is essential to consider the most relevant R-strategies. These are the extension of the lifespan of products and their parts as well as the useful application of materials. Table ***1*** summarizes these R-strategies.

Table 1 Description of relevant R-strategies to extend the lifespan and make use of materials

Category	*R-strategies*	*Description*
Extend lifespan of product and its parts	Reuse	Reusing products without modification.
	Repair	Repairing defective products for the original function.
	Refurbish	Restoring products to make them up to date.
	Remanufacture	Repurpose components of a discontinued product in novel products.
	Repurpose	Using products for a different purpose.
Useful application of materials	Recycle	Recovery of materials for the manufacture of new products of the same (higher) or lower quality
	Recover	Incineration for energy recovery

Source: Potting et al. 2017

The transition from a linear economy to a CE necessitates not only technological advancement but also the formulation of circular business models and design methodologies to extend the lifespan of products and capture the full value of circular products (Bocken et al. 2016, 317).

Product life cycle and development process

The technical life cycle of a product can be divided into three main phases: Beginning-of-life (BOL), middle-of-life (MOL) and end-of-life (EOL). The BOL consists of product development and production. This is followed by the MOL, which consists of logistics (distribution), use, service and maintenance, and EOL incorporating reverse logistics (collection), refurbishment (e.g., disassembly, reassembly), reuse, recycling and disposal. (Jun et al. 2007, 855)

As outlined by the association of German engineers (VDI) in standard VDI 2221 (2019, 31), the product development process for the design of technical products and systems can be divided into three overarching phases: planning, conception, and design and creation. In the planning phase, specific requirements of the product are defined. In the conception phase, the functional structure, solution principles, and the module structure of the product are defined. Preliminary and overall drafts of the product are finally elaborated in the design and creation phase. According to GERICKE ET AL., the feasibility and costs of a product design are additionally pre-determined during the overall product development process (Gericke et al. 2021, 68–70).

Circular design

CD describes design and development approaches that take circular design principles into account (Ellen MacArthur Foundation 2013, 9). The objective of CD is to maintain the value of a product over several life cycles and reduce the consumption of resources (Kamp Albæk et al. 2020, 4). Since CD has a major impact on the entire life cycle, especially on the EOL scenarios, it is crucial that circularity is considered right from the start of product development (Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) 2024, 20; Rexfelt and Selvefors 2024, 9–10). As it forms the link between the current and subsequent life cycle, the EOL of products represents a strategic phase that needs to be considered carefully during the development phase. (Favi et al. 2017, 136)

In order to achieve the goals of the CE and manage the EOL, product designers and developers have various approaches at their disposal (Pruhs et al. 2024, 5). These strategies are summarized under the term "Design for X" (DfX) (Ijomah et al. 2007, 716). A selection of different DfX strategies is presented in Table 2. The closure of resource loops represents a significant objective within the context of CD (Geissdoerfer et al. 2017, 766).

Table 2 Design for X (DfX) strategies

Design focus	*DfX method*
Design for reliability and durability	Design on demand or on availability
	Design the appropriate lifespan of products/components
Design for product attachment and trust	Create timeless aesthetics
	Design for pleasurable experiences
	Meaningful design
Design for extending product life	Design for repair/refurbishment
	Design for easy maintenance, reuse and repair
	Design for upgradability and flexibility
Design for dematerialising products	Design for product-service systems
	Design for swapping, renting, and sharing.
Design for resource recovery	Design for easy end-of-life cleaning, collection, and transportation of recovered material/resources
	Design for cascade use
	Design for remanufacturing or dis- and reassembly
	Design for upcycling or recycling

Source: Charnley et al. 2016, 7

Product architecture

The product architecture allows for the description of complex products. A distinction is drawn between the functional structure and the product structure (Schuh and Riesener 2017). In this context, it is sufficient to provide a description of the product structure according to SCHUH ET AL., which is enhanced by the level of the materials employed. An overview of a simplified product structure is provided with Figure 1. The individual elements of the product structure are referred to as product structure elements.

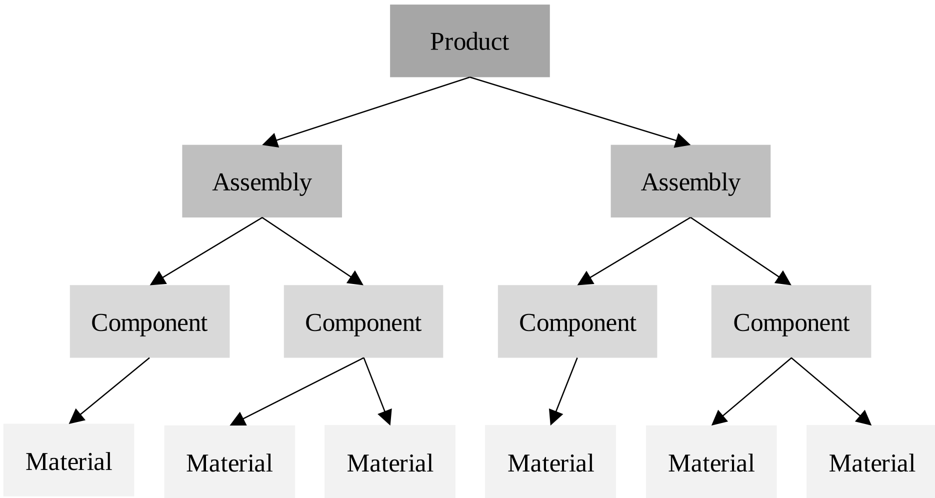

Figure 1 Product structure based on SCHUH AND RIESENER (2017)

The proposed product structure according to SCHUH ET AL. can also be used to describe value retention in conjunction with the Value Hill Model (Kurilova-Palisaitiene et al. 2023, 4). The Value Hill Model describes the value creation across the life cycle stages from raw material extraction to product utilization and shows that value is generated in both the linear economy and the CE. In the linear economy, value is destroyed after use through downcycling or disposal. In the CE, the value produced is not reduced at all or is reduced gradually (Achterberg et al. 2016, 4). The Value Hill Model highlights that the value of a product is at its highest on the top level of the product structure, i.e., the product itself, while it is at its lowest on the material level.

Sustainability and circularity assessment

The CE can be divided into micro (companies and products), meso (industrial parks) and macro (cities, regions, countries) levels to ensure a targeted sustainability and circularity assessment (Kirchherr et al. 2017, 229). Most assessments focus on the macro and meso levels (Baratsas et al. 2022, 4). This paper puts emphasis on the micro level.

At the final stage of the product life cycle, it is essential to identify the optimal EOL scenario (Alamerew et al. 2020, 2). As OLIVEIRA ET AL. (2021) and OLIVEIRA AND OLIVEIRA (2023) show, there are already several circularity indicators that can be used to determine EOL scenarios. In the area of product evaluation, there is still a lack of standardised methodologies and approaches (Sassanelli et al. 2019). SAIDANI ET AL. (2019) came to a similar conclusion in their analysis of 55 circularity indicators.

A variety of different approaches for evaluating sustainability and CE have been introduced in research differing primarily in the specific assessment, indicators, and scope of consideration. One method of evaluating a substantial number of indicators and criteria is the multi-criteria decision-making (MCDM) approach. This method allows for the incorporation of qualitative and quantitative factors as well as of diverse criteria such as environmental, economic, social, legal, and technological criteria (Bufardi et al. 2004, 3140–3141; Alamerew et al. 2020, 15).

The selection of target-oriented criteria is of decisive importance for the effectiveness of the evaluation system. It is necessary to integrate relevant stakeholders into the selection process in order to ensure the completeness and contextualisation of the criteria (Lindfors et al. 2019, 13). Overall, it can be observed that economic indicators are most frequently used for the evaluation of products, followed by environmental indicators (Kristensen and Mosgaard 2020, 14; Mesa et al. 2018, 1431).

3 Analysis of existing sustainability and circularity methodologies

Against the background of the objective to develop a methodology, which ensures that the inherent value of industrial products is retained in a CE, existing methodologies in research will be analyzed in more detail. Thus, the methodology that is proposed in this paper can incorporate the strengths and close the identified research gaps. This chapter therefore provides an overview of suitable methodologies to evaluate the circularity or sustainability of products and provides an overview of the advantages and disadvantages in Table 3. The chapter is closed by the derivation of research gaps.

Environmental and circularity indicator – MCDA (ECI-MCDA) (Barrak et al. 2024): The ECI-MCDA method for the assessment of product circularity and environmental performance is comprised of six steps. The initial stage of the process entails the development of a life cycle model, which is followed by the calculation of environmental impact indicators (LCIA) as well as the selection and calculation of the circularity indicators (C-indicators). Subsequently, MCDA is conducted to generate a ranking. The results from the LCIA and the C-indicators are considered to enable an integrated assessment of product performance. Subsequently, a robustness analysis is conducted to guarantee the dependability of the outcomes. The iterative design of the method permits the flexible adjustment of the data to enhance the accuracy and relevance of the analysis.

Circular life cycle sustainability assessment (C-LCSA) (Luthin et al. 2024): The C-LCSA framework method incorporates circularity into the life cycle assessment (LCSA) to guarantee a comprehensive evaluation of products and services. The focus of this methodology lies on C-indicators and the examination of materials, processes, and product design within the context of the CE. The methodology is structured into four phases. The initial step is to define the objective and scope of the assessment. Subsequently, a life cycle inventory is compiled, which records all relevant data pertaining to the product life cycles. In the subsequent phase, the environmental impacts and circular aspects are evaluated. Ultimately, the results are interpreted. This approach is particularly advantageous during the concept development phase for the CE, as it enables the identification of hotspots and trade-offs. Consequently, design, material selection and manufacturing processes can be optimized at an early stage, which is often more challenging in the later production phase.

Life cycle assessment – MCDM (LCA-MCDM) (Torkayesh et al. 2022): The objective of this methodology is to develop a structured approach for decision-making in waste management. This entails a systematic identification of waste management issues, the selection of appropriate technologies, and the evaluation of treatment scenarios and locations for waste management facilities. The methodological approach comprises a series of structured steps, commencing with the definition of the study objectives to identify specific waste problems. Subsequently, the temporal and geographical scope, as well as the relevant life cycle phases, are determined. The third phase entails the selection of sub-criteria that integrate environmental, economic, and social aspects. Subsequently, relevant data must be gathered, after which an impact analysis can be conducted, thereby enabling iterative adjustments to be made to the objectives. To evaluate the various waste management alternatives, a MCDM is developed, which incorporates the weighting of the criteria by experts. Ultimately, the alternatives are ranked to establish a robust foundation for decision-making.

A comprehensive multi-level circular economy assessment framework (Ahmed et al. 2022): The methodology is centred on the development of a comprehensive CE assessment framework that is both flexible and user-friendly, and which provides guidance on the selection of optimal processes or products. The evaluation process is divided into four distinct phases. In the initial phase, three categories of indicators are collated: macro, meso and micro indicators; sector-specific indicators; and indicators specific to CE practices. In the second phase, fuzzy logic[1] is employed to transform both qualitative and quantitative indicators into quantifiable scores. The third phase comprises the weighting of the indicators, which may be accomplished through either subjective approach, such as the Analytic Hierarchy Process (AHP), or objective methods, such as the entropy method. In the final phase, a variety of MCDM techniques are employed to normalize, evaluate, and aggregate the generated scores, thereby producing the final scores and ranking of alternatives.

Sustainable Design Optimization (SDO) (Ameli et al. 2019): The methodology is designed to achieve the greatest possible benefit for economic, environmental, and social indicators. In accordance with this strategy, the objective is to achieve the greatest overall profit, the least environmental impact, and the largest social impact of a product family. A primary objective is to ensure compliance with recycling and recovery rates in accordance with the principles of the CE. To facilitate the attainment of these objectives, a model is designed for the purpose of evaluating the efficacy of alternative strategies pertaining to the CE. The model is based on input-production-resource theory and addresses the challenges of selecting design alternatives and determining EOL options. The model accounts for a range of potential uncertainties, including quality status, return times and the cost-benefit ratios associated with EOL treatment. Simulation-based optimization is employed to ascertain Pareto-optimal solutions, thereby facilitating a systematic examination of the multiple influencing factors.

End-of-Use Product Value Recovery (EPVR) (Cong et al. 2019): The objective of this methodology is to enhance the economic viability of EOL product recovery by optimizing product design in terms of component reusability and recyclability. This contributes to the development of a CE by facilitating the transfer of materials and components into new life cycles. The methodology commences with the delineation of EOL scenarios, which ascertain the viability of module groups for reuse, recycling, or disposal. Subsequently, bottlenecks and potential for improvement are identified, and a selection of suitable connection types is made using the AHP. Concurrently, material compatibility is evaluated to minimize the potential for recycling issues. To assess the recyclability of the modules, a value-based recycling indicator is developed to quantify design proposals. In the final

[1] Fuzzy logic aims to process human thinking or ambiguous information in formal methods for problem-solving and decision making (Noll 2009, 25).

phase, valuable modules are selected for redesign to ensure their accessibility and dismantlability. The methodology is illustrated by a case study on the redesign of a hard drive, which demonstrates the improvements achieved in terms of recovery and recyclability.

Product Recovery Multi-Criteria Decision Tool (PR-MCDT) (Alamerew and Brissaud 2019): The methodology for analyzing economic, environmental, and social indicators is designed to facilitate an integrated approach to end-of-life selection. The simultaneous consideration of environmental, technical, economic, and social criteria enables decision-makers to integrate a range of relevant factors into the decision-making process. More specifically, factors include legal requirements, technological developments, market requirements and user preferences. The PR-MCDT comprises a structured process comprising six successive phases. The initial stage of the methodology entails the identification of potential end-of-life strategies, which are then subjected to a narrowing-down process to select the most relevant options. In the subsequent step, suitable indicators are defined and employed for the evaluation of the strategies. This is followed by a comprehensive analysis aimed at identifying the strengths and weaknesses of the strategies. In the final phase, the strategies are refined and subjected to a final evaluation, thereby enabling well-founded decisions to be made.

End-Of-Life Decision Making (EOL-DM) (Favi et al. 2017): The methodology to promote reuse, remanufacturing and recycling aims to recover materials at the end of their life cycle (EOL) and, where appropriate, to recycle energy through incineration. As part of this methodology, indices are employed for the assessment of product recovery efficiency. These indices are employed for the analysis of end-of-life EOL performance of disparate components, with a view to identifying the most suitable EOL scenarios. A central tenet of the methodology is the reduction of components with open life cycles, thereby enhancing sustainability. If the defined targets are not met, a product design process is initiated that necessitates either significant or minor modifications to optimize EOL performance from both an environmental and economic standpoint. The methodology empowers designers to assess the sustainability of products and augment the proportion of closed life cycle components, which ultimately contributes to improving overall resource utilization.

End-of-Life Index (EOLI) (Lee et al. 2014): The methodology employed in this study is designed to enhance the EOL performance of products by incorporating EOL indices as well as dismantling and disposal indicators. The objective is to encourage the reuse and recycling of materials, while simultaneously identifying areas for enhancement. The model serves as a tool for designers and stakeholders in the EOL sector, facilitating the exchange of information and optimizing EOL planning and product design. The model facilitates rapid and effective evaluation of design modifications, thereby aiding decision-making processes. The EOL index model provides the capability to assess the EOL performance of a product by entering a range of indicator values. This enables the identification of deficiencies in the areas of disassembly, disposal, and recovery, and provides a comprehensive analysis of the sub-indices. The capacity to estimate EOL performance with minimal data input is a significant benefit for designers, as it encourages the consideration of EOL aspects in the early stages of product development.

Table 3 Advantages and disadvantages of existing evaluation methodologies

Methodology	*Advantages*	*Disadvantages*
ECI-MCDA (Barrak et al. 2024)	- Holistic evaluation of product circularity - Flexibility and accuracy through iterative design	- Complexity of the method can lead to misunderstandings - High data requirements
C-LCSA (Luthin et al. 2024)	- Applicable in the development phase of a product	- Possibly limited applicability for very specific products or processes
LCA-MCDM (Torkayesh et al. 2022)	- Comprehensive consideration of environmental, economic and social aspects - Solid basis for decision-making	- Time-consuming and resource-intensive data collection - Focus is on waste management
A comprehensive multi-level circular economy assessment framework (Ahmed et al. 2022)	- Flexible and easy to handle - Comprehensive evaluation of processes and products	- Subjectivity in the weighting of the indicators can influence the results - Comprehensive consideration of macro, meso and micro level
SDO (Ameli et al. 2019)	- Maximising profit and social impact as well as minimizing environmental impact - Consideration of uncertainties	- Complexity of modelling and high data quality requirements
EPVR (Cong et al. 2019)	- Increasing economic profitability through targeted design adjustments - Improving recyclability by selecting suitable materials and compounds	- Requires extensive data analysis and expert knowledge - Complexity of the method can act as a deterrent
PR-MCDT (Alamerew and Brissaud 2019)	- Holistic view of EOL strategies - Consideration of legal requirements	- Possible challenges when integrating data from different sources
EOL-DM (Favi et al. 2017)	- Promotion of reuse and recycling - Support for product redesign	- Risk of over-complexity in the analysis of EOL scenarios
EOLI (Lee et al. 2014)	- Fast and effective evaluation of design changes - Identification of improvement levers	- Can be superficial, without deeper analysis of the EOL processes

Source: Lee et al. 2014; Favi et al. 2017; Alamerew and Brissaud 2019; Ameli et al. 2019; Cong et al. 2019; Ahmed et al. 2022; Torkayesh et al. 2022; Luthin et al. 2024; Barrak et al. 2024

The existing methodologies for assessing the circularity of products and their EOL options, such as ECI-MCDA, C-LCSA, and LCA-MCDM, offer structured approaches for decision-making. These methodologies integrate multiple indicators with MCDM, emphasizing the identification of environmental, economic, and social aspects of EOL options. They enable a comprehensive assessment of product design, materials, and processes in the context of the CE and are characterized by their iterative adaptability, allowing for flexible data integration.

In terms of indicators, the presented methodologies take different aspects into account. While the LCA-MCDM considers environmental, economic, and social criteria for assessment, the PR-MCDT supplements these with regulatory requirements. C-indicators, such as in C-LCSA, assess the life cycle of materials, while EOLI focuses on EOL-specific indicators.

As for the specific methodological focus, ECI-MCDA evaluates product performance, while SDO aims to maximize the efficiency of economic, environmental, and social indicators. LCA-MCDM enables systematic solutions, and EPVR emphasizes material compatibility. The effort required for implementation varies. While models like EOLI allow quick assessments with minimal data input, methodologies like PR-MCDT necessitate detailed data collection. C-LCSA is particularly helpful in the concept phase, whereas SDO and EPVR employ simulation-based optimizations. Special attention is given to identifying hotspots, trade-offs, and optimizing design and material selection to minimize resource use and increase efficiency.

Research gaps and requirements towards a methodology

Although the existing methodologies show several significant strengths, there are still certain challenges as indicated in Table 3. One major challenge is the inclusion of relevant stakeholders in the assessment process. Models such as ECI-MCDA and PR-MCDT enable a certain degree of involvement through criteria weighting, while many other approaches do not. Stakeholder participation is particularly beneficial in the selection of indicators and criteria since a lack of involvement can lead to limited contextualisation and completeness of the assessment.

When selecting indicators, the focus is strongly on ecological and economic criteria. Technological and legal indicators are only considered in isolated cases. The existing methodologies focus primarily on life cycle analyses, carbon footprint, resource use, energy efficiency and recyclability of materials. However, these analyses require detailed data sets and are thus subject to adjustments to allow an evaluation in early design phases. Some iterative methodologies, such as ECI-MCDA and C-LCSA, are designed for long-term adaptability to new requirements but show a lack regarding the end-to-end flexibility. Methodologies such as EOLI, which allow for evaluations with minimal data requirements appear to be exceptions. Many approaches require detailed data sets at an early stage, which limits the applicability.

The aforementioned aspects indicate that there are critical gaps for assessing the product circularity potential in the early product design phases. Despite various approaches and methods, there is still no uniform standard for measuring product circularity (Shevchenko et al. 2024, 17), which makes it difficult to compare and generally accept the evaluation results (Kusumo et al. 2022, 15). According to expert interviews, standardised and adaptable assessments that integrate relevant company stakeholders and a broader range of indicators are critical. Regarding the latter, especially technological, market and legal indicators need to be considered. Moreover, a methodology that is able to process qualitative and quantitative data is necessary to promote comparability and wider acceptance of CE assessments. Especially the latter is supported by interviews with industry partners, which emphasised the need for pragmatism in decision-making.

To close the identified research gaps, four specific requirements towards the methodology can be derived. First, the methodology should comprehensively incorporate economic (incl. market demand), environmental, technological, and legal criteria. Second, the methodology should be able to process qualitative and quantitative information according to the MCDM. Thirdly, the methodology should enable a consistent assessment of industrial products in the design and creation phase of the product development process according to VDI2221. Finally, the methodology should support the decision-making process with limited data availability.

4 Methodology for assessing second-life potential of industrial products

The following chapter proposes a methodology that addresses the aforementioned research gaps and derived requirements. Therefore, the analysis approach as well as the identified evaluation criteria and indicators will be introduced in detail. An explanation for utilizing the developed methodology closes this chapter.

Approach

For the identification of relevant evaluation indicators and the development of a respective methodology, a comprehensive literature review and semi-structured expert interviews were conducted.

The search for suitable literature was based on the keywords CE, sustainability assessment, circularity assessment, EOL decision making and MCDM. Relevant literature was shortlisted based on titles and abstracts. A forward and backward snowball search was also carried out on the papers identified as relevant (Wohlin et al. 2022, 4).

To gain further insights into the industrial practice, semi-structured expert interviews were conducted. Besides the identification of indicators used in or required by the industry, a dedicated focus was also put on the industry's needs regarding the utilization of evaluation methodologies during the product development process. In order to capture a comprehensive view, experts from manufacturing companies, research, and sustainability consultancies were interviewed. Each interview was transcribed and similar content between different interviews was clustered. In addition, relevant aspects were specifically documented with the relevant contextual information.

The results of the expert interviews revealed that three overarching steps are required to assess the second-life potential of products. First, the product structure and its respective elements (product structure elements) need to be determined. In the second step, the indicators relevant to the product and company should be selected from the longlist of identified indicators in the ecological, economic, technological, and legal dimensions. Finally, in the third step, the evaluation of the product structure elements to identify the second-life potentials is to be conducted. By evaluating the industrial product along the product structure, individual scores and an overall score for the product structure can be determined. The latter can be used to compare product structures of, e.g., similar product variants with each other. In the following, all three steps will be presented in more detail using the example of a Wi-Fi router.

Product description

The first step of the methodology is the description of the product based on the previously described product structure, see Figure 2. Within this process step, interview partners from industry involved technical experts or product designers. The result of this step is a specific product structure with all relevant product structure elements, which can then be evaluated regarding their second-life potential.

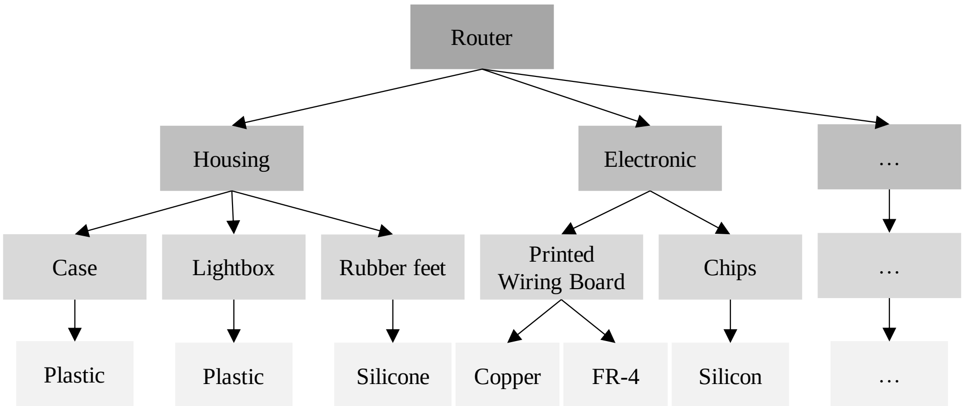

Figure 2 Product structure of a Wi-Fi router

Indicator

The literature research and expert interviews have shown that especially environmental, economic, technological, and legal criteria are particularly relevant for the assessment. Therefore, these criteria will be analyzed in more detail regarding specific indicators that are used to assess the second-life potential. Expert interviews have shown that the selection of indicators must be adapted to the product and the company-specific context.

Ecological evaluation criteria

At the micro level, the life cycle assessment (LCA) is the most reliable method of measuring the environmental impact of a product. Regarding the evaluation of products, the midpoint indicators of a LCA, such as global warming or acidification, prove to be the best available indicator (Harris et al. 2021, 180–182; European Commission 2003). Furthermore, it has been shown that the categories of a LCA are linked to the circularity of a product. This illustrates that minimising the environmental impact can promote circularity (Linder et al. 2020, 6). SCHUH ET AL. (2022) showed in an analysis of 2,112 environmental indicators that energy consumption, recycling rates and emissions are among the most frequently used indicators. These indicators are also part of most LCAs, either directly or in a slightly modified form. Another advantage of LCA is that it is widely used and known in its application, which is confirmed by the interview results, which support the usefulness of this method. However, as there is insufficient data available in the development phase, it is advisable to use LCA as a guideline when assessing environmental aspects. The assessment is facilitated by the availability of many database values (e.g. GEMIS (IINAS 2024), Ecoinvent (ecoinvent Association o.J), ProBas (UBA 2024). If there is insufficient data, the available values can be used as comparative values and orientation to approximate LCA results. The selection of indicators to be considered may vary depending on the product since not all indicators are relevant for every product. For example, toxicity may only be relevant for selected products. However, certain indicators should always be included in the assessment. These include, e.g., emissions caused or saved as well as the energy and overall resource consumption. These indicators are common and included in most LCAs.

As ecological indicators are highly dependent on the context of the company and the product, a list of indicators is provided from which relevant indicators can be selected. Accordingly, Table 4 presents a list of 40 indicators, identified through literature review and expert interviews. Similar indicators were grouped into a sub-category. In total eight sub-categories were derived.

Table 4 Ecological evaluation criteria

Sub-category	*Indicator*
Material consumption	Material extraction, Material input, Share of reused/recycled material, Recyclability of materials
Energy consumption	Energy consumption, Energy efficiency, Renewable energy rate, Renewable energy used, Fossil fuel consumption
Waste management	Hazardous waste generated, Solid waste, Waste volume, Kilograms of persistent, Landfill volume, Wastewater, Liquid waste generation, Recycling rate
Emissions	CO_{2e} emissions, Fine dust emissions, NOx emissions, SOx emissions, VOC emissions, Noise emissions
Ecosystem impact	Human health (HH), Ecosystem quality (EQ), Toxicity, Biodegradability, Eutrophication, Acidification potential, Ozone depletion, Global warming potential
Water consumption	Water consumption, Freshwater consumption, Share of treated/recycled water,
Health and safety	Hazardous substances, Material safety, Heavy metal concentration
Land use	Land use, Land occupancy, Soil production

Source: Veleva and Ellenbecker 2001; Jawahir et al. 2006; Kim et al. 2014; Lee et al. 2014; Ma and Kremer 2016; Alamerew and Brissaud 2019; Kravchenko et al. 2019; OECD 2020; Schuh et al. 2022; Barrak et al. 2024; Interviews

Economic evaluation criteria

The analysis of economic viability relies on both revenue and cost-relevant indicators, allowing for a thorough examination of these options. According to BOYACI ET AL., one important aspect to consider is diversification. In more detail, companies are increasingly willing to invest in the reusability of products if it enables them to diversify their market segments (Boyaci et al. 2016, 32). This willingness to invest highlights the growing recognition of the economic benefits associated with second-life potentials of products. The selection of economic indicators is carefully tailored to provide clear insights into the expected costs and revenues of various alternatives. For instance, sales-related indicators such as resell value and market demand offer valuable information about potential revenue streams. On the other hand, cost-relevant indicators, including production, transportation, and maintenance costs, are essential for evaluating the overall economic viability of secondary life applications. A comprehensive list of these indicators is provided in Table 5. In total 23 indicators were identified and clustered in six sub-categories.

Table 5 Economic evaluation criteria

Sub-category	*Indicator*
Costs	Material cost, Labour cost, Production cost, Packaging cost, Energy cost, Transportation cost, Maintenance cost, Repair cost, Recycling cost, Disassembly cost, Disposal cost, Remanufacturing cost, Operational cost, Emission costs (CO2eq), Cost saving potential
Monetization	Resell potential
Market demand	Customer demand (Market demand), Competitive pressure
Quality	Quality of the recovered parts, Product quality, Degree of damage
Investment and infrastructure	Cost of technology, Cost on infrastructure setup

Source: Veleva and Ellenbecker 2001; Jawahir et al. 2006; Kim et al. 2014; Lee et al. 2014; Ma and Kremer 2016; Alamerew and Brissaud 2019; Kravchenko et al. 2019; OECD 2020; Barrak et al. 2024; Interviews

Technological evaluation criteria

With technological indicators, the circularity of a product and specific technological EOL requirements are to be assessed. A complex technological product can make the identification of secondary life applications more challenging, but opens up new possibilities if the relevant CD principles, see chapter 2, are taken into consideration (Boyaci et al. 2016, 4). BUCHMÜLLER therefore proposes to take modularity aspects into account, which provides information about the ability to adapt the industrial product (Buchmüller 2019, 225–233). Possible adaptations include upgrades and replacement of individual components or materials. Literature and expert interviews indicate that the ability to adapt to changing requirements by replacing or upgrading components promotes flexibility and potentially product longevity. Another aspect is the compatibility, which assesses the extent to which existing technologies, assemblies and materials can be used in secondary applications with different or improved performance. It indicates whether the company can use the evaluated alternatives in other products, i.e., repurposed without major adaptations or whether they can be reused for the same product. (Egenhoefer 2017, 508)

The expert interviews also revealed other indicators that should be considered such as the R-strategy potential, e.g., reuse, repurpose or recycling potential, the separability of materials or the strategic fit with the company. Especially the separability of materials is a relevant indicator on the material level as it allows for a differentiation between composite and pure materials. The repairability indicator describes the possibility to repair the product, assemblies or (sub)components. The 13 indicators identified during literature review and expert interviews are listed in Table 6.

Table 6 Technological evaluation criteria

Sub-category	*Indicator*
Product design characteristics	Modularity, (Technological) compatibility
Production characteristics	Separability, Repairability
Strategic fit	Risk of supply bottlenecks, degree of circular innovation, corporate strategy fit, internal process fit
R-strategy potential	Reuse, Refurbish, Remanufacture, Repurpose, Recycle, Recover

Source: Egenhoefer 2017; Potting et al. 2017; Alamerew and Brissaud 2019; Buchmüller 2019; Interviews

Legal evaluation criteria

The increasing relevance of regulatory aspects is particularly evident in the planned legislation, which is to be extended to more companies as part of the European Green Deal (European Commission 2024). Similar to the technological indicators, the indicators in the legal dimension are to be understood as guidelines and are therefore less dependent on the specific product than for example economic or ecological indicators. Within this dimension, the legal conformity and legal adaptability are evaluated (OECD 2020, 118; Alamerew and Brissaud 2019, 177). These indicators enable the assessment of compliance with relevant legal requirements, norms, and standards. This includes compliance with existing national and EU laws, which apply to disposal, recycling, and other relevant areas. In addition, the legal adaptability indicator covers the ability to adapt to future legal changes and new legal requirements. To be able to adequately assess and fulfil future requirements, it is essential for companies to continuously monitor the relevant trends and developments in the respective legal areas.

Table 7 Legal evaluation criteria

Sub-category	*Indicator*
Legal conformity	Current legal conformity, Future legal conformity

Source: Alamerew and Brissaud 2019; OECD 2020; Interviews

In summary, the evaluation is based on four dimensions: ecological, economic, technological, and legal criteria. Ecological criteria are supported by LCA, which considers indicators such as material consumption and emissions. Economic criteria analyze both revenue and cost-relevant indicators to assess the economic viability of second-life potentials. Technological criteria focus among others on modularity, compatibility, and R-strategies, while legal criteria analyze compliance with existing and future legal requirements. In conclusion, the indicator, when considered alongside the product structure outlined in chapter 2, offers a structured methodology for advancing the CE in product development and for conducting a systematic determination of second-life potentials.

Evaluation of second-life potential

In the third step, the identified product structure elements need to be evaluated regarding selected and company-specific indicators. With the aforementioned aspects in chapter 3, this methodology incorporates a MCDM approach. For the MCDM approach, two common approaches are the weighted sum model (WSM) and the analytical hierarchy process (AHP) (Taherdoost and Madanchian 2023, 83). AHP provides a method to combine data and subjective judgments, perform cost-effective analysis, set priorities and optimize management decisions (Saaty 2013, 1103). WSM is a method for analyzing complex alternative courses of action, which aims to rank them according to the user's preferences in order to create an optimal basis for decision-making (Zangemeister 2014, 45).

In this case, the WSM is preferable to the AHP, which requires a considerable amount of time and effort due to its detailed approach, especially with a large number of options and indicators. This makes it less suitable for use in the early design phase. On the other hand, the WSM offers several advantages, including the clear structuring of complex decision-making processes through the combination of quantitative and qualitative criteria, as well as the promotion of transparency through documented decision bases (Saaty 1990, 14–18; Kühnapfel 2021, 18–19). Additionally, the individual preferences are taken into account.

The initial stage of the evaluation process is the assignment of weights to the categories. In addition to the indicators, the categories are also assigned a weighting in order to avoid the potential for bias and distortion, which can arise when a large number of indicators are employed (Kühnapfel 2021, 39–40). The following weighting is selected for this example: Environment (0.3) economy (0.4), technology (0.2), regulatory (0.1). As for the industrial practice, the weighting of the indicators should be determined by relevant stakeholders of a company.

As for the evaluation, a 10-point scale is used since it appears to be the simplest scale that can be used and allows the use of both quantitative and qualitative indicators, according to KÜHNAPFEL. Compared to a 3 or 5-point scale, it still provides sufficient differentiation to obtain a clear result. (Kühnapfel 2021, 69). In this case, 10 is the best and 1 is the worst score that can be awarded. Additionally, a score of 0 is used if the indicator to be evaluated has no relevance for the product structure element. If there are indicators for which the level of detail is lower, smaller scales can be used and then normalized to the 10-point or any other scale desired by the individual company (Kühnapfel 2021, 59).

The value for every category ($S_{p,K}$), i.e., environmental, economic, technological, and legal results from the weighting (w_K,) and the individual evaluation ($v_{j,K}$) within the respective category. Thus, for each element of the product structure, see Figure 2, a specific value can be determined.

$$S_{p,K} = \sum_{j=1}^{n} v_{j,K} * w_i$$

With the category-specific value ($S_{p,K}$), the second-life potential (S_p) of the respective product structure element can then be obtained. Therefore, the weighting (w_K) of the evaluation category and the determined category-specific value ($S_{p,K}$) are used.

$$S_p = \sum_{K=1}^{n} S_{p,K} * w_K$$

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Besides the second-life potential of the product structure elements, the overall score of a product can be determined, which allows for the comparison of different product variants. The overall score (P_g) is the result of all individual second-life potentials (S_p) that are summed up and averaged.

$$P_g = \frac{1}{n}\sum_{i=1}^{n} S_p$$

Figure 3 exemplifies a simplified evaluation of the Wi-Fi router and indicates the second-life potentials S_p as well as the overall score P_g, which equals 4.2. It should be noted that the values were anonymized and freely chosen for illustrative purposes.

		Environmental				Economic				Technological				Legal				
		Indicator 1	Indicator 2	…		Indicator 3	Indicator 4	…		Indicator 5	Indicator 6	…		Indicator 7	Indicator 8	…		
	Weighting	0,3/0,4/0,3			0,3	0,2/0,6/0,2			0,4	0,2/0,6/0,2			0,2	0,1/0,5/0,4			0,2	S_p
Product	Router	8	2	1	**3,5**	3	3	2	**2,8**	5	6	2	**5,0**	4	7	2	**4,7**	**4,3**
Assembly	Electronic	3	7	1	**5,0**	3	1	2	**1,6**	4	7	2	**5,4**	8	2	4	**3,4**	**3,6**
	Housing	4	3	2	**3,0**	6	2	4	**3,2**	3	4	1	**3,1**	5	6	1	**3,9**	**3,2**
	…																	
Component	Lightbox	2	5	1	**2,9**	3	4	1	**3,1**	5	6	2	**0,2**		…		**…**	**…**
	Case	1	7	2	**3,7**	4	7	2	**5,4**		…		**…**		…		**…**	**…**
	…																	
Material	Plastic	3	8	1	**4,4**	5	6	2	**…**		…		**…**		…		**…**	**…**
	Copper	3	6	2	**...**		…		**…**		…		**…**		…		**…**	**…**
	…																	
																		4,2

Figure 3 Evaluation assessment Wi-Fi router

5 Conclusion and outlook

Based on literature review and expert interviews, this paper introduces a general methodology to assess the second-life potential of industrial products. Therefore, the methodology leverages the product structure of an industrial product ranging from product to material level as well as ecological, economic, technological, and legal evaluation criteria. Within the four evaluation criteria, a list of common indicators from available publications and expert interviews is derived. The proposed methodology offers a resource-efficient approach for the identification of the most promising second-life potentials. It is important to note that the methodology primarily allows for a relative comparison of product alternatives regarding their second-life potential and that it cannot be used to determine the absolute circularity of an industrial product.

The methodology shows several advantages. Firstly, it encompasses a comprehensive list of indicators in relevant evaluation criteria beyond the scope of a conventional environmental and economic analysis. This enables the evaluation of a wide range of industrial products through the selection of appropriate indicators. Secondly, the methodology facilitates the evaluation process, particularly during the development phase, when only limited information is available. Therefore, an individual score for product-specific elements is determined along the product structure that allows for prioritization. Product-specific elements with a higher score, i.e., second-life potentials tend to be more suitable for the identification of second-life options in a CE. Finally, by introducing an overall score, the methodology supports the comparison of different product alternatives and the identification of the product alternative with the highest potential in a CE.

However, the methodology also presents certain challenges. For complex products, for example, it may be effortful to create an appropriate product structure. In addition, prioritizing second-life potentials with limited information availability can distort results and lead to further promising second-life options being neglected. In terms of industrial adoption, the involvement of relevant stakeholders could increase the complexity.

Since this research primarily focuses on capturing the current research and industrial landscape, more research needs to be done regarding the validation of this methodology. Thus, the proposed methodology will be validated and refined using existing industrial products that are designed for the CE in collaboration with industry partners. Additionally, the usability needs to be considered in future research to reduce complexity and ensure a widespread adoption.

References

Achterberg, Elisa/Hinfelaar, Jeroen/Bocken, Nancy (2016). Master Circular Business with the Value Hill.

Ahmed, Aser Alaa/Nazzal, Mohammad A./Darras, Basil M./Deiab, I. M. (2022). A comprehensive multi-level circular economy assessment framework. Sustainable Production and Consumption 32, 700–717. https://doi.org/10.1016/j.spc.2022.05.025.

Alamerew, Yohannes A./Brissaud, Daniel (2019). Circular economy assessment tool for end of life product recovery strategies. Journal of Remanufacturing 9 (3), 169–185. https://doi.org/10.1007/s13243-018-0064-8.

Alamerew, Yohannes A./Kambanou, Marianna Lena/Sakao, Tomohiko/Brissaud, Daniel (2020). A Multi-Criteria Evaluation Method of Product-Level Circularity Strategies. Sustainability 12 (12), 5129. https://doi.org/10.3390/su12125129.

Alexander, Allen/Pascucci, Stefano/Charnley, Fiona (Eds.) (2023). Handbook of the Circular Economy: Transitions and transformation. De Gruyter.

Ameli, Mariam/Mansour, Saeed/Ahmadi-Javid, Amir (2019). A simulation-optimization model for sustainable product design and efficient end-of-life management based on individual producer responsibility. Resources, Conservation and Recycling 140, 246–258. https://doi.org/10.1016/j.resconrec.2018.02.031.

Baratsas, S. G./Pistikopoulos, E. N./Avraamidou, S. (2022). A quantitative and holistic circular economy assessment framework at the micro level. Computers and Chemical Engineering 160. https://doi.org/10.1016/j.compchemeng.2022.107697.

Barrak, Erika/Rodrigues, Carla/Antunes, Carlos/Freire, Faustos/Dias, L. C. (2024). Applying multi-criteria decision analysis to combine life cycle assessment with circularity indicators. Journal of Cleaner Production 451. https://doi.org/10.1016/j.jclepro.2024.141872.

BASF SE (Ed.) (2023). Zusammengefasster Lagebericht. Unsere Strategie. Available online at https://bericht.basf.com/2023/de/_assets/downloads/str-strategy-basf-gb23.pdf (accessed 10/1/2024).

Bocken, Nancy/Pauw, Ingrid de/Bakker, Conny/van der Grinten, Bram (2016). Product design and business model strategies for a circular economy. Journal of Industrial and Production Engineering 33 (5), 308–320. https://doi.org/10.1080/21681015.2016.1172124.

Boyaci, Tamer/Verter, Vedat/Galbreth, Michael (2016). Design for Reusability and Product Reuse Under Radical Innovation.

Buchmüller, Melanie (2019). Nachhaltigkeit und Produktmodularisierung. Nachhaltiges Business Im Kontext Von Risiken der Globalisierung. Wiesbaden, Springer Fachmedien Wiesbaden GmbH.

Bufardi, A./Gheorghe, R./Kiritsis, D./Xirouchakis, P. (2004). Multicriteria decision-aid approach for product end-of-life alternative selection. International Journal of Production Research 42 (16), 3139–3157. https://doi.org/10.1080/00207540410001699192.

Charnley, Fiona/Moreno, Mariale/los Rios, Carolina de/Rowe, Zoe (2016). A Conceptual Framework for Circular Design. Sustainability 8 (9), 937. https://doi.org/10.3390/su8090937.

Cong, Liang/Zhao, Fu/Sutherland, John W. (2019). A Design Method to Improve End-of-Use Product Value Recovery for Circular Economy. Journal of Mechanical Design 141 (4). https://doi.org/10.1115/1.4041574.

ecoinvent Association (Hrsg.) (o.J). https://ecoinvent.org/database. (accessed 10/13/2024).

Egenhoefer, Rachel Beth (2017). Routledge Handbook of Sustainable Design. London, Taylor and Francis.

Ellen MacArthur Foundation (2013). Towards the circular economy: Economic and business rationale for an accelerated transition. Available online at https://www.werktrends.nl/app/uploads/2015/06/rapport_mckinsey-towards_a_circular_economy.pdf.

Ellen MacArthur Foundation (Ed.) (2015). Delivering the circular economy: a toolkit for policymakers.

Ellen MacArthur Foundation (Hrsg.) (2024). Circular economy introduction. Available online at https://www.ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview (accessed 8/14/2024).

European Commission (2003). Integrated Product Policy - Building on Environmental Life-Cycle Thinking.

European Commission (Hrsg.) (2024). Der europäische Grüne Deal. Available online at https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_de (accessed 10/14/2024).

Favi, Claudio/Germani, Michele/Luzi, Andrea/Mandolini, Marco/Marconi, Marco (2017). A design for EoL approach and metrics to favour closed-loop scenarios for products. International Journal of Sustainable Engineering 10 (3), 136–146. https://doi.org/10.1080/19397038.2016.1270369.

Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) (Ed.) (2024). Entwurf einer Nationalen Kreislaufwirtschaftsstrategie (NKWS).

Fraser, Matthew/Conde, Álvaro/Haigh, Laxmi (2024). The Circularity Gap Report 2024. Available online at https://circularity-gap.world/2024.

Geissdoerfer, Martin/Savaget, Paulo/Bocken, Nancy/Hultink, Erik Jan (2017). The Circular Economy - A new sustainability paradigm? Journal of Cleaner Production 143, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048.

Gericke, Kilian/Bender, Beate/Pahl, Gerhard/Beitz, Wolfgang/Feldhusen, Jörg/Grote, Karl-Heinrich (2021). Der Produktentwicklungsprozess. In: Beate Bender/Kilian Gericke (Eds.). Pahl/Beitz Konstruktionslehre. Methoden und Anwendung erfolgreicher Produktentwicklung. 9th ed. Berlin, Heidelberg, Springer Berlin Heidelberg, 57–93.

German Environment Agency (Hrsg.) (2024). Probas. Available online at https://www.probas.umweltbundesamt.de/datenbank/#/ (accessed 10/13/2024).

Harris, Steve/Martin, Michael/Diener, Derek (2021). Circularity for circularity's sake? Scoping review of assessment methods for environmental performance in the circular economy. Sustainable Production and Consumption 26, 172–186. https://doi.org/10.1016/j.spc.2020.09.018.

Ijomah, Winifred L./McMahon, Christopher A./Hammond, Geoffrey P./Newman, Stephen T. (2007). Development of design for remanufacturing guidelines to support sustainable manufacturing. Robotics and Computer-Integrated Manufacturing 23 (6), 712–719. https://doi.org/10.1016/j.rcim.2007.02.017.

International Institute for Sustainability Analysis and Strategy (Hrsg.) (2024). https://iinas.org/arbeit/gemis. Available online at https://iinas.org/arbeit/gemis/ (accessed 10/13/2024).

International Resource Panel (2024). Bend the trend. Pathways to a liveable planet as resource use spikes. Nairobi, Kenya, International Resource Panel.

Jawahir, I. S./Dillon, JR., O. W./Rouch, K. E./Joshi, Kunal J./Venkatachalam, Anand/Jaafar, Israd H. (2006). Total life-cycle considerations in product design for sustainability: A framework for comprehensive evaluation.

Jun, Hong-Bae/Kiritsis, Dimitris/Xirouchakis, Paul (2007). Research issues on closed-loop PLM. Computers in Industry 58 (8-9), 855–868. https://doi.org/10.1016/j.compind.2007.04.001.

Kamp Albæk, Julie/Shahbazi, Sasha/McAloone, Tim C./Pigosso, Daniela C. A. (2020). Circularity Evaluation of Alternative Concepts During Early Product Design and Development. Sustainability 12 (22), 9353. https://doi.org/10.3390/su12229353.

Kim, Seung Jin/Kara, Sami/Kayis, Berman (2014). Economic and environmental assessment of product life cycle design: volume and technology perspective. Journal of Cleaner Production 75, 75–85.

Kirchherr, Julian/Reike, Denise/Hekkert, Marko (2017). Conceptualizing the circular economy: An analysis of 114 definitions. Resources, Conservation and Recycling 127, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005.

Kravchenko, Mariia/Pigosso, Daniela CA./McAloone, Tim C. (2019). Towards the ex-ante sustainability screening of circular economy initiatives in manufacturing companies: Consolidation of leading sustainability-related performance indicators. Journal of Cleaner Production 241, 118318. https://doi.org/10.1016/j.jclepro.2019.118318.

Kristensen, Heidi Simone/Mosgaard, Mette Alberg (2020). A review of micro level indicators for a circular economy - moving away from the three dimensions of sustainability? Journal of Cleaner Production 243, 118531. https://doi.org/10.1016/j.jclepro.2019.118531.

Kühnapfel, Jörg B. (2021). Scoring und Nutzwertanalysen. Ein Leitfaden Für Die Praxis. Wiesbaden, Springer Fachmedien Wiesbaden GmbH.

Kurilova-Palisaitiene, Jelena/Sundin, Erik/Sakao, Tomohiko (2023). Orienting around circular strategies (Rs): How to reach the longest and highest ride on the Retained Value Hill? Journal of Cleaner Production 424, 138724. https://doi.org/10.1016/j.jclepro.2023.138724.

Kusumo, F./Mahlia, T.M.I./Pradhan, S./Ong, H. C./Silitonga, A. S./Fattah, I.M.R./Nghiem, L. D./Mofijur, M. (2022). A framework to assess indicators of the circular economy in biological systems. Environmental Technology and Innovation 28. https://doi.org/10.1016/j.eti.2022.102945.

Lee, Hui Mien/Lu, Wen Feng/Song, Bin (2014). A framework for assessing product End-Of-Life performance: reviewing the state of the art and proposing an innovative approach using an End-of-Life Index. Journal of Cleaner Production 66, 355–371. https://doi.org/10.1016/j.jclepro.2013.11.001.

Linder, Marcus/Boyer, R.H.W./Dahllöf, L./Vanacore, E./Hunka, A. (2020). Product-level inherent circularity and its relationship to environmental impact. Journal of Cleaner Production 260. https://doi.org/10.1016/j.jclepro.2020.121096.

Lindfors, Axel/Feiz, Roozbeh/Eklund, Mats/Ammenberg, Jonas (2019). Assessing the Potential, Performance and Feasibility of Urban Solutions: Methodological Considerations and Learnings from Biogas Solutions. Sustainability 11 (14), 3756. https://doi.org/10.3390/su11143756.

Luthin, Anna/Traverso, Marzia/Crawford, Robert H. (2024). Circular life cycle sustainability assessment: An integrated framework. Journal of Industrial Ecology 28 (1), 41–58. https://doi.org/10.1111/jiec.13446.

Ma, Junfeng/Kremer, Gül E. Okudan (2016). A Modular Product Design Method to Improve Product Social Sustainability Performance. In: Proceedings of the ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference - 2015: Presented at ASME 2015 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference : August 2-5, 2015, Boston, Massachusetts, USA. New York, N.Y., The American Society of Mechanical Engineers.

Mesa, Jaime/Esparragoza, Iván/Maury, Heriberto (2018). Developing a set of sustainability indicators for product families based on the circular economy model. Journal of Cleaner Production 196, 1429–1442. https://doi.org/10.1016/j.jclepro.2018.06.131.

Nasr, Nabil/Russell, Jennifer/Bringezu, Stefan/Hellweg, Stefanie/Hilton, Brian/Kreiss, Cory/von Gries, Nadia (2018). Redefining Value – The Manufacturing Revolution. Remanufacturing, refurbishment, repair and direct reuse in the circular economy. United Nations Environment Programme. Nairobi, Kenya. Available online at https://www.resourcepanel.org/reports/re-defining-value-manufacturing-revolution.

Noll, Patrick (2009). Statistisches Matching mit Fuzzy Logic. Theorie und Anwendung in Sozial- und Wirtschaftswissenschaften. Zugl.: Marburg, Philipps-Univ., Diss., 2009. Wiesbaden, Vieweg + Teubner.

OECD (2020). The circular economy in cities and regions. Synthesis report. Paris, OECD Publishing.

Oliveira, Carla Tognato de/Dantas, Thales Eduardo Tavares/Soares, Sebastião Roberto (2021). Nano and micro level circular economy indicators: Assisting decision-makers in circularity assessments. Sustainable Production and Consumption 26, 455–468. https://doi.org/10.1016/j.spc.2020.11.024.

Oliveira, Carla Tognato de/Oliveira, Giovanna Groff Andrade (2023). What Circular economy indicators really measure? An overview of circular economy principles and sustainable development goals. Resources, Conservation and Recycling 190, 106850. https://doi.org/10.1016/j.resconrec.2022.106850.

Potting, José/Hekkert, Marko/Worell, Ernst/Hanemaaijer, Aldert (2017). Circular Economy: Measuring innovation in the product chain: Policy Report.

Pruhs, Annika/Kusch, Anina/Woidasky, Jörg/Viere, Tobias (2024). Design for circularity in manufacturing industries-operationalisation and decision support. Resources, Conservation and Recycling 202. https://doi.org/10.1016/j.resconrec.2023.107376.

Rexfelt, Oskar/Selvefors, Anneli (2024). Mapping the landscape of circular design tools. Resources, Conservation and Recycling 209. https://doi.org/10.1016/j.resconrec.2024.107783.

Saaty, Thomas L. (1990). How to make a decision: The analytic hierarchy process. European Journal of Operational Research 48 (1), 9–26. https://doi.org/10.1016/0377-2217(90)90057-I.

Saaty, Thomas L. (2013). The Modern Science of Multicriteria Decision Making and Its Practical Applications: The AHP/ANP Approach. Operations Research 61 (5), 1101–1118. https://doi.org/10.1287/opre.2013.1197.

Saidani, Michael/Yannou, Bernard/Leroy, Yann/Cluzel, François/Kendall, Alissa (2019). A taxonomy of circular economy indicators. Journal of Cleaner Production 207, 542–559. https://doi.org/10.1016/j.jclepro.2018.10.014.

Sassanelli, Claudio/Rosa, Paolo/Rocca, Roberto/Terzi, Sergio (2019). Circular economy performance assessment methods: A systematic literature review. Journal of Cleaner Production 229, 440–453. https://doi.org/10.1016/j.jclepro.2019.05.019.

Schuh, Günther/Mauß, Wilhelm/Potente, Till/Schmitz, Seth/Adlon, Tobias/Maetschke, Jan/Neumann, Henning/Salzwedel, Jan/Kozielski, Stefan/Luckert, Melanie/Reuter, Christina/Schmidhuber, Matthias/Witthöft, Jörg (2022). How to measure ecological sustainability in manufacturing? -A literature review of indicator frequency and relevance. https://doi.org/10.13140/RG.2.2.27219.86560.

Schuh, Günther/Mauß, Wilhelm/Potente, Till/Schmitz, Seth/Adlon, Tobias/Maetschke, Jan/Neumann, Henning/Salzwedel, Jan/Kozielski, Stefan/Luckert, Melanie/Reuter, Christina/Schmidhuber, Matthias/Witthöft, Jörg (2023). Grüne Re-Montage Upgrade-Fabrik. https://doi.org/10.24406/publica-968.

Schuh, Günther/Riesener, Michael (2017). Produktkomplexität managen. München, Carl Hanser Verlag GmbH & Co. KG.

Shevchenko, Tetiana/Shams Esfandabadi, Zahra/Ranjbari, Meisam/Saidani, Michael/Mesa, Jaime/Shevchenko, Stanislav/Yannou, Bernard/Cluzel, François (2024). Metrics in the circular economy: An inclusive research landscape of the thematic trends and future research agenda. Ecological Indicators 165, 112182. https://doi.org/10.1016/j.ecolind.2024.112182.

Stahel, Walter R. (Ed.) (2019). The circular economy: A user's guide. London and New York, Routledge Taylor & Francis Group.

Sterley, Nadine (2023). Nachhaltigkeitsbericht 2023. GEA Group Aktiengesellschaft. Available online at https://cdn.gea.com/-/media/sustainability/sustainability-report-2023-de.pdf?rev=cd1fd6bdc86b4789b0ecd7d2d12753cd (accessed 10/1/2024).

Taherdoost, Hamed/Madanchian, Mitra (2023). Multi-Criteria Decision Making (MCDM) Methods and Concepts. Encyclopedia 3 (1), 77–87. https://doi.org/10.3390/encyclopedia3010006.

Torkayesh, Ali Ebadi/Rajaeifar, Mohammad Ali/Rostom, Madona/Malmir, Behnam/Yazdani, Morteza/Suh, Sangwon/Heidrich, Oliver (2022). Integrating life cycle assessment and multi criteria decision making for sustainable waste management: Key issues and recommendations for future studies. Renewable and Sustainable Energy Reviews 168, 112819. https://doi.org/10.1016/j.rser.2022.112819.

Ulrich, Hans (1984). Die Betriebswirtschaftslehre als anwendungsorientierte Sozialwissenschaft. In: Hans Ulrich/Thomas Dyllick/Gilbert J. B. Probst (Eds.). Management. Bern/Stuttgart, Haupt.

Veleva, Vesela/Ellenbecker, Michael (2001). Indicators of sustainable production: framework and methodology. Journal of Cleaner Production 9 (6), 519–549. https://doi.org/10.1016/S0959-6526(01)00010-5.

Verein Deutscher Ingenieure e.V (2019). VDI 2221: Entwicklung technischer Produkte und Systeme: Modell der Produktentwicklung.

Wohlin, Claes/Kalinowski, Marcos/Romero Felizardo, Katia/Mendes, Emilia (2022). Successful combination of database search and snowballing for identification of primary studies in systematic literature studies. Information and Software Technology 147, 106908. https://doi.org/10.1016/j.infsof.2022.106908.

Zangemeister, Christof (2014). Nutzwertanalyse in der Systemtechnik : eine Methodik zur multidimensionalen Bewertung und Auswahl von Projektalternativen. Norderstedt.