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Environmental assessment of lifetime extension strategies

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Cover:
Product lifetime extension with, e.g., repair is like playing the Parcae, the three personifications of destiny in Roman mythology, with objects. The owner decides when to cut the product's thread of life. A repair is similar to investing in an additional piece of thread to be tied to a cut one. Does it reduce the impact on the environment? It depends on the product lifetime, represented by the length of the initial thread and the added piece. This thesis shows that it has not been thoroughly considered in life cycle assessments and suggests ways to do it more considerately in the future.

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Abstract

Extending product lifetimes through strategies such as reuse, repair, or remanufacturing has been suggested as a means for delaying product replacement and thus improving products' environmental performance. To identify effective lifetime extension strategies, companies or policymakers seek guidance from the assessment of environmental impact of products with, for example, circular economy (CE) indicators or life cycle assessment (LCA). The additional product lifetime duration is the reason for the improved environmental performance with lifetime extension and, therefore, a key variable in this assessment. However, little guidance exists on how to assess lifetime extension strategies. Against this background, this research aims to develop knowledge of environmental systems analysis methodology for assessing product lifetime extension. This knowledge is used to identify methodological considerations for practitioners to select suitable assessment methods and LCA methodology for product lifetime that fit their specific assessment goal.

Applying CE indicators and LCA to case studies of lifetime extension reveals that LCA provides information on the environmental impacts while CE indicators detail variations in resource use. Thus, the choice between CE indicators and LCA depends on the type of impact a practitioner aims to evaluate. Moreover, no CE indicator accounts for resource use in the use phase, although it is key in the resource use of lifetime extension for some products. Therefore, the choice of method requires practitioners to ensure sufficient coverage of the parts of the product system for the changes from lifetime extension to be accounted for.

A review of existing LCAs of lifetime extension identifies differences in LCA methodology related to product lifetime in terms of 1) the lifetime definition (e.g., whether it includes the entire technical lifetime), 2) the lifetime integration in equations with three approaches using either a single value, a no-fixed value or a distribution, and 3) the lifetime sensitivity analysis. When testing the identified approaches on cases, the results answer different typical questions. For example, using a no-fixed value informs on the range of validity of the conclusions, while using a distribution informs on the spread and average environmental impacts in a population. It emphasises the importance of selecting a lifetime modelling methodology that aligns with the assessment goal.

Given the critical role of product lifetime in the environmental performance of lifetime extension, along with the often insufficient reporting practices and limited consideration in assessment methodology discussions, this research serves as a foundational step towards guidance to practitioners and further methodological developments.

Keywords: reuse, repair, remanufacturing, durability, LCA, indicator, environmental assessment

List of publications

This dissertation is based on the work contained in the following papers, referred to by Roman numerals I-IV in the text. They are appended at the end of the dissertation.

Paper I

Jerome, A., Helander, H., Ljunggren, M., Janssen, M., 2022. Mapping and testing circular economy product-level indicators: A critical review. Resources, Conservation and Recycling 178, 106080. https://doi.org/10.1016/j.resconrec.2021.106080

Paper II

Jerome, A., Ljunggren, M., Janssen, M., 2023. Is repair of energy using products environmentally beneficial? The case of high voltage electric motors. Resources, Conservation and Recycling 196, 107038. https://doi.org/10.1016/j.resconrec.2023.107038

Paper III

Jerome, A., Ljunggren, M., 2024. Product lifetime in life cycle assessments of circular economy – a review and consolidation of methodology. (manuscript in review for a scientific journal)

Paper IV

Jerome, A., Ljunggren, M., Mathieux, F., Bobba, S., Ardente, F., 2024. Product lifetime approaches in life cycle assessments of circular economy. (manuscript in review for a scientific journal)

Contribution report

Paper I

The third author conceived the original idea for the study. All authors contributed to the study's conceptualisation and developed the methodology. The first and second authors performed the literature review, analysed the data and co-wrote the article under the primary supervision of the third author. All authors participated in multiple rounds of review and revision. The author of this dissertation primarily wrote the sections related to the testing of CE indicators and comparison to life cycle assessment results.

Paper II

All authors contributed to the conceptualisation of the study. The author of this dissertation conducted the life cycle assessment and wrote the manuscript under the primary supervision of the second author. All authors reviewed the manuscript through multiple rounds of comments.

Paper III

The author of this dissertation conceived the original idea for the study, conducted the literature review and analysis, developed the resulting framework and wrote the manuscript. The co-author contributed to the writing and development of the framework in the form of multiple rounds of reviews and comments.

Paper IV

The author of this dissertation conceived the original idea for the study, conducted the life cycle assessments, developed the analysis and conclusions, and wrote the manuscript under the supervision of the second author. All co-authors supported the study's conceptualisation and contributed to the writing with multiple rounds of reviews and comments.

Other publications

Jerome, A., Helander, H., Ljunggren, M., Janssen, M., 2021. Testing product-level indicators for a more circular economy. Paper presented at the 4th PLATE 2021 Virtual Conference. 26-28 May 2021.

Helander, H., Jerome, A., Ljunggren, M., Janssen, M., 2021. What do product-level circular economy indicators measure? Paper presented at the 4th PLATE 2021 Virtual Conference. 26-28 May 2021.

Jerome, A., Ljunggren, M., & Janssen, M., 2022. Repair for high-voltage electric motors energy efficiency vs resource use?. Abstract presented at WasteLCA_3: Life Cycle Sustainability Assessment For Waste Management And Resource Optimization. Calabria, Italy. 5-10 June 2022.

Jerome, A., Ljunggren, M., & Janssen, M., 2022. Environmental sustainability of high voltage motors: do better efficiency and repair lead to improved environmental impact?. Poster presented at the 28th annual ISDRS Conference. Stockholm, Sweden. 15-17 June 2022.

Jerome, A., 2022. Repair or replace? Guidance from indicators and life cycle assessment on circular economy strategies for energy-using products. Licentiate thesis, Chalmers University of Technology.

Jerome, A., Ljunggren, M., & Janssen, M., 2023. When is repair environmentally beneficial? The case of high-voltage electric motors. Poster presented at the 11th International Conference on Industrial Ecology. Leiden, The Netherlands. 2-5 July 2023.

Jerome, A., Ljunggren, M., & Janssen, M., 2023. Comparison of LCA and circularity indicators: what method to use for what?. Abstract presented at the 11th International Conference on Life Cycle Management. Lille, France. 6-8 Sept 2023.

Jerome, A., Ljunggren, M., 2024. Product Lifetime in Life Cycle Assessment of Circular Strategies. Abstract presented at the SETAC Europe 26th LCA symposium. Gothenburg, Sweden. 21-23 Oct 2024.

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This research would also not have been possible without the help and support of my colleagues. First and foremost, my deepest gratitude goes to my main supervisor Maria Ljunggren. You were constantly supportive of my work, thorough with your guidance, and pushed me through difficult moments. I also thank my examiner, Henrikke Baumann. I truly appreciated your guidance on remembering the bigger picture and navigating the journey to grow as a researcher. The last member of my supervision team to thank is Matty Janssen. Thank you for the advice in the early part of my work.

Arriving in a new work environment during the pandemic was rough, and I am very thankful to have shared the first part of my PhD with Harald Helander. You have been a fantastic co-author and a welcomed companion in discovering the PhD-life.

One of the most exciting parts of my PhD was the research exchange I did at the Joint Research Center from the European Commission in Ispra, Italy, to discover research for policy development. I am thankful for the financial support from the Adlerbertska Foundation and the Gunnar Engström ABB Foundation during this exchange. I would like to especially thank Fabrice Mathieux for making this exchange possible and, together with Silvia Bobba and Fulvio Ardente, for the great insights and collaboration on the work that led to my last paper. A special thought to Concetta Lodato, who made this stay brighter than I could imagine.

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To my parents and little sister, thank you for being supportive from afar and accepting the fact that I love humid and cold places to live. And Rémi, this thesis would not exist without you. Thank you for always being supportive of what I do.

Table of Contents

1 Introduction

The increasing global population and consumption fuel the growing extraction of resources (UNEP, 2017). This extraction and processing of resources is responsible for around 90% of biodiversity loss, water stress, and 50% of global climate change impact (IRP, 2019). It is thus causing a growing pressure on the environment, exceeding several of the planetary boundaries that define the limits within which humanity can safely operate (Steffen et al., 2015).

One contributing factor to the growing consumption is the decline in product lifetime (Bakker et al., 2014; Cooper, 2010; Krych and Pettersen, 2025), i.e., the duration the products are used. Products are replaced more often as product obsolescence, i.e., product falling into disuse (Cooper, 2010), is estimated to happen after shorter lifetimes. For example, reduced product durability by design, low prices of new products, the more frequent release of new products and faster changes in trends are potential factors contributing to the decline of product lifetime (Krych and Pettersen, 2025).

Concerns about the environmental implications of reduced product lifetime emerged in the 1950s from the frustration of some industrialists on the perceived degradation of product quality (Cooper, 2010). In the 1970s, the Organisation for Economic Cooperation and Development (OECD) draw attention to the environmental consequences of the development of non-repairable and single-use alternatives to durable products and recommends further research on the potential benefits of longer product lifetime (Cooper, 2010; OECD, 1982). With the growing awareness of the environmental impact caused by consumption in the 1980s, ideas about sustainable design, waste reduction and resource efficiency through resource loops, including lifetime extension, were popularised (Blomsma and Brennan, 2017; Cooper, 2010). Lifetime extension now receives a growing interest in policies and from companies as a strategy to reduce resource use and its associated environmental impacts. In Europe, lifetime extension is highlighted as a strategy to reduce the impact of waste generation (European Commission, 2008) and to improve the environmental impacts of products through design requirements (European Commission, 2024a).

Multiple lifetime extension strategies have been defined, such as reuse, repair and remanufacturing (Böckin et al., 2020; Reike et al., 2018). Lifetime extension strategies are also a group of strategies considered as part of circular economy (CE) strategies (Bocken et al., 2016; Böckin et al., 2020), which also includes strategies to recover materials and energy from waste, such as recycling or incineration with energy recovery, to use products efficiently, such as improving energy efficiency, and to reduce resource inputs in manufacturing, such as reducing losses during production (Böckin et al., 2020). Although simplified guidance for choosing strategies to be implemented has been presented in the form of rankings of preferable strategies for the CE, real-world conditions, such as low collection rates after use and losses in repair or recycling, might lead to lower environmental benefits than in ideal conditions and results in different ranking of preferable strategies (Böckin et al., 2020; Ljunggren Söderman and André, 2019). Moreover, lifetime extension does not necessarily result in environmental benefits compared to product replacement due to, e.g., additional transport or the development of more efficient product alternatives (Böckin et al., 2020). Therefore, the assessment of the benefits of lifetime extension is crucial to guide the choice and implementation of strategies in, e.g., product design and development of business strategies and public policy.

Many assessment methods have been developed for assessing environmental impacts, grouped under the denomination of environmental systems analysis methods (Finnveden and Moberg, 2005). Several have been used to assess lifetime extension (Corona et al., 2019; Walzberg et al., 2021). Each method has different potential applications, with differences in the types of impacts under study and in the scope of the study (Finnveden and Moberg, 2005; Walzberg et al., 2021). At a product level, life cycle assessment (LCA) and indicators are highlighted as promising assessment methods, the former for its broad coverage of environmental dimensions (Corona et al., 2019; Elia et al., 2017) and the latter as less time- and resource-consuming to compute for, e.g., early-stage assessments in solution development.

Recommendations for the selection of methods for assessing CE strategies have been developed by Walzberg et al. (2021). They are based on the assessment scope, temporal resolution (static or dynamic) and data availability, but the recommendations do not include indicators that have been specifically developed to assess CE. Moreover, the LCA methodology is adapted to the goal of the assessment (Baumann and Tillman, 2004), but there are no methodological recommendations for LCA when assessing lifetime extension. This lack of clarity in the choice of methods and LCA methodology may be a barrier for practitioners to carry out an assessment of the effects of lifetime extension strategies (Roos Lindgreen et al., 2022).

Therefore, this dissertation aims to develop knowledge of environmental systems analysis methodology for assessing product lifetime extension, allowing practitioners to deliver decision support that corresponds to the goal of the assessment.

2 Background

2.1 Circular economy

The concept of circular economy (CE) receives growing attention in companies, public policies and literature (Alcalde-Calonge et al., 2022). Although it has multiple definitions (Kirchherr et al., 2023), CE generally aims for sustainable development across environmental, economic, and social dimensions. A key objective is the decoupling of environmental impacts from economic growth. CE focuses on the effective and efficient use of resources, with closing, slowing, and narrowing resource loops (Bocken et al., 2016).

CE research is not a clearly defined academic discipline but emerged from various disciplines, such as waste management, environmental sciences, closed-loop supply chain management, product design and industrial ecology, to support ongoing policy-making and business consultancy (Reike et al., 2018). Studies have mainly focused on supporting decision-making with tools and methods (Merli et al., 2018) at different levels (micro or product level, meso or at the level of a company, macro or national level). Otherwise, they focused on the development of enablers of the circular economy (Kirchherr et al., 2023) with circular business models, innovative processes, effective policies and product design and development (Merli et al., 2018).

The research presented in this dissertation contributes to research on assessment methods for decision-making support at a product level for environmental sustainability. It primarily focuses on supporting decisions regarding slowing resource loops with lifetime extension.

2.2 Lifetime extension

As explained in the introduction, lifetime extension refers to a group of strategies aiming to prolong the lifetime of a product. Several lifetime extension strategies have been defined (Böckin et al., 2020; Reike et al., 2018):

- *Increased technical lifetime by design:* The product design is changed to preventively address the reasons for technical failure with, e.g., more durable materials, sturdy fastenings or components.

- *Shift to multiple uses:* Single-use products are re-designed to be used multiple times,
- *Reuse:* A product that is still functional after initial use is used again by a second user after minor, non-restorative actions such as inspection and cleaning. Examples of implemented reuse are second-hand or flea markets.
- *Maintenance:* The product is inspected, maintained and protected before a technical failure or other problems occur to prevent breakdown. Maintenance usually requires little intervention, e.g., replacing minor components. Compared to repair or remanufacturing, these interventions occur before and not after a malfunction or failure.
- *Repair:* It brings a product back to a functional state after wear, malfunction or failure. It involves extensive interventions, such as replacing broken components with new ones. Repairs can be done by professionals or the product user, with or without a change of ownership. For instance, repairing a washing machine at home is an example without a change of ownership, while a company taking back malfunctioning products for repair and resale as second-hand products involves a change of ownership.
- *Remanufacturing:* Process of restoring a product to a state as good as new or even better through disassembly, repair or exchange of components, re-assembly and quality assurance. It can also involve upgrades to the current level of function or efficiency.
- *Repurposing:* The product is reused for another function than the initial use. Examples of cases of repurposing are the use of old batteries from electric vehicles for energy storage (Bobba et al., 2018; Dunn et al., 2023; Koroma et al., 2022) or of old freight containers as housing (Dara et al., 2019).

Sharing, i.e., the shared use of one product by several users, might also be considered a lifetime extension strategy. When a product is shared, for example, with car rental or libraries, the product is used more often than a product used by one user only, so the cumulative use time is extended. However, the product also wears out more quickly with more intensive use (Böckin et al., 2020). Therefore, sharing does not automatically extend a product's total cumulative use time before its replacement. In this research, sharing is included as one of the lifetime extension strategies.

Lifetime extension is a key element of CE in European legislation. In the Waste Framework Directive (European Commission, 2008) aiming at preventing and reducing the impacts from waste generation, "preparing for reuse" is presented as a more favourable action than recycling to treat waste and preserve the environment. More recently, the Circular Economy Action Plan (European Commission, 2020) initiated the Ecodesign for Sustainable Products Regulation (European Commission, 2024a) to set ecodesign requirements on products. Such requirements have already been developed under the Ecodesign Directive for energy-using products, but the scope is now extended to all types of products. Additionally, it is specified that the new requirements will promote lifetime extension by ensuring that products are more durable, reusable, reparable, and easier to maintain and refurbish (European Commission, 2024a). Additionally, the Right to Repair Directive introduces rules to promote the repair of products by ensuring access to affordable repair services and providing consumers with information on their right to repair (European Commission, 2024b).

2.3 **Product lifetime and obsolescence**

Product lifetime and obsolescence are central to lifetime extension. In this dissertation, *product lifetime* is defined as the time period between the first use of the product and when it becomes obsolete, and *product obsolescence* is when the product "falls into disuse" (Cooper, 2010) and is used in this dissertation to refer to the reasons for ending the lifetime.

The lifetime can represent different time periods depending on the type of lifetime considered (Cooper, 2010; Diener, 2017; Murakami et al., 2010; Proske and Finkbeiner, 2020). The terminology and definition of these types of lifetime differ between studies. However, four distinctive types of lifetime can be identified: the service lifetime, technical lifetime, use time and technical use time (Table 1).

Table 1. Definition of the four types of lifetime used in this dissertation, adapted from Cooper (2010), Diener (2017) and Proske and Finkbeiner (2020).

	Includes periods of idleness, i.e., when the product is not in use	Excludes periods of idleness
Until the end of the product's use	*Service lifetime:* the period between the start and end of a product's use, including periods when the product is not in use.	*Use time:* the sum of periods during which the product is in use, excluding periods of idleness.
Until the product does not have the physical capacity to function	*Technical lifetime:* the period during which a product has the physical capacity to function, ending when the product breaks or wears out based on its durability or material construction.	*Technical use time:* the sum of periods during which the product is or would be in use until the product does not have the physical capacity to function.

Different types of lifetime might represent the same time period in some conditions (Figure 1). The service lifetime and technical lifetime are equal when the product is used until it does not have the capacity to function. However, when users decide to replace a still functional product, the service lifetime is shorter than the technical lifetime. The same is true for use time and technical use time. Moreover, the use time and service lifetime are equal when the product is continuously used. When this is not the case, the use time is obtained by subtracting periods of idleness from the service lifetime. The same is true for the technical use time and the technical lifetime. However, the technical use time is relevant for products with a physical capacity to function limited by wear and tear. In contrast, technical lifetime is relevant for products with a physical capacity limited by ageing instead of wear and tear.

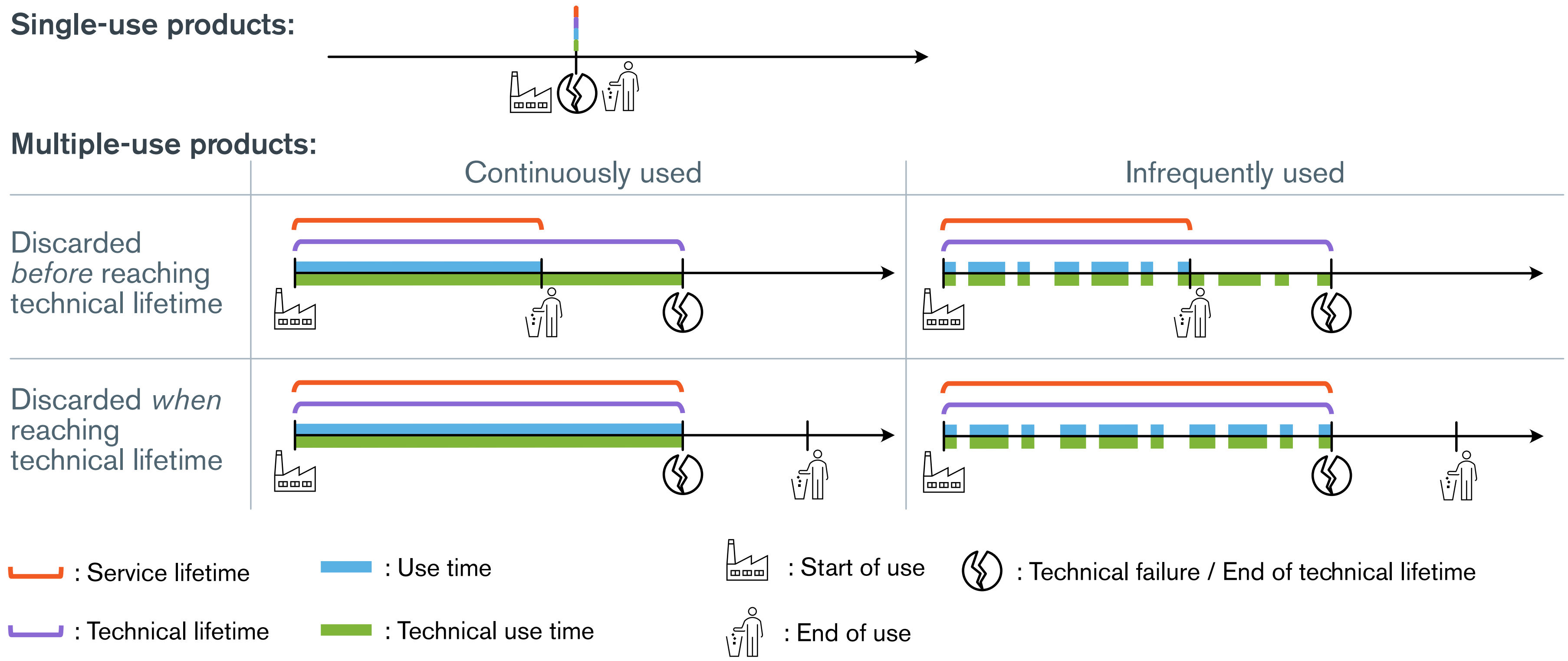

Figure 1. Visual representation of the different types of lifetime for products with different characteristics.

In addition to the distinction between the types of lifetime, the product lifetime can also be distinguished in terms of an initial and additional lifetime in cases of lifetime extension. The *initial lifetime* is the lifetime of the product without lifetime extension. The *additional lifetime* is the lifetime added to the initial lifetime after lifetime extension strategies have been applied.

There are many reasons why a product may be taken out of use, which can be categorised into different types of obsolescence (Cooper, 2010; den Hollander et al., 2017; Diener, 2017; Proske and Finkbeiner, 2020; Rivera and Lallmahomed, 2016; van den Berge et al., 2023). Two main types of obsolescence can be distinguished:

- *Absolute obsolescence:* The product's use ends when the product is not functional anymore due to, e.g., product failure.
- *Relative obsolescence:* The product's use ends when the product is still functional. There are several types of relative obsolescence:
    - *Technological obsolescence:* New technological development makes more functional and advanced products available. Consumers are then more interested in improved product performance than in keeping an older product in use,
    - *Economic obsolescence:* Costs for maintenance and ownership become higher than for product replacement,
    - *Systemic obsolescence:* The product is no longer compatible with the surrounding system or infrastructure (e.g., discontinued software updates). Related types of obsolescence are *part and knowledge obsolescence*, when replacement parts and knowledge for maintenance, respectively, are no longer available,
    - *Aesthetic obsolescence:* The product appearance is judged not "good enough", either due to wear and tear, fashion or change in the user's style,
    - *Psychological obsolescence:* The symbolic value of the product is not "good enough", either due to changed expectations (e.g., consumer lifestyle), cultural values or fashion. Related types of obsolescence are *social obsolescence*, when the product is not socially acceptable due, e.g., to a stigma, and *context-related obsolescence*, when a changed person's environment leads to different expectations (e.g., the need for a bigger car due to a changed size of the household),

- *Obligatory obsolescence:* The product is not legally authorised to be used anymore (e.g., ban for using old products),
- *Notification obsolescence:* A published or communicated end-of-use date influences the choice of replacing a functional product (e.g., best-before dates on food products).

The type of obsolescence is one of the factors deciding whether there is a difference between lifetime types. When the type of obsolescence is absolute, the service lifetime and technical lifetime, as well as the use time and technical use time, are equal. When the type of obsolescence is relative, the service lifetime and use time are shorter than the technical lifetime and technical use time, respectively.

Product lifetime and obsolescence are two key concepts for product lifetime extension. Product lifetime is a temporal characteristic of the product, namely the duration of its use phase. Distinguishing between types of lifetime is important for describing the effect of different lifetime extension strategies. For example, increased technical lifetime by design aims to extend the technical lifetime, reuse to extend the service lifetime, and sharing to extend the use time of products. Moreover, understanding the type of obsolescence is crucial for selecting an applicable lifetime extension strategy. For example, reuse is possible only for products with relative obsolescence, and increased technical lifetime by design has an effect only in cases of absolute obsolescence.

Other concepts related to product lifetime are used in different research fields. For example, *product durability* in technical engineering and product design refers to an intrinsic technical product characteristic defined as the ability of a product to perform its function over a lengthy period (Cooper, 2010). *Consumption pattern* is used in behavioural studies and behavioural economics to study product replacement motives and patterns (Polizzi di Sorrentino et al., 2016). Although lifetime extension aims at changing consumption patterns towards less frequent product replacements, a result of this change is an increase in the product lifetime value. Additionally, product lifetime is related to the product as a time period between activities in a product life cycle, while consumption patterns focus more on individual preferences and the influence of society on these preferences. As for product durability, it does not reflect eventual relative obsolescence and thus is too limited to study lifetime extension strategies targeting relative obsolescence, such as reuse.

2.4 Environmental systems analysis

Environmental systems analysis (ESA) is the analysis of how technical systems cause or contribute to environmental problems. ESA research combines studies of the actors and activities that would enable a reduction of environmental problems and the development of assessment methods to understand and communicate these problems and guide the actors in their decision-making (Baumann et al., 1999).

Different methods for assessing environmental impacts exist (Finnveden and Moberg, 2005), such as life cycle assessment (LCA), material flow analysis (MFA), life cycle costing (LCC), environmental impact assessment (EIA) or indicators. The object of analysis of these methods differs. For example, EIA assesses policies or large projects, and LCA assesses products (Finnveden and Moberg, 2005).

LCA and product-level indicators for the CE are the two ESA methods that are focused on in this research. They are further presented in sections 2.4.1 and 2.4.2. For both, lifetime extension is assessed by comparing a baseline without lifetime extension to an alternative with lifetime extension. The typical product system for both alternatives is presented in Figure 2.

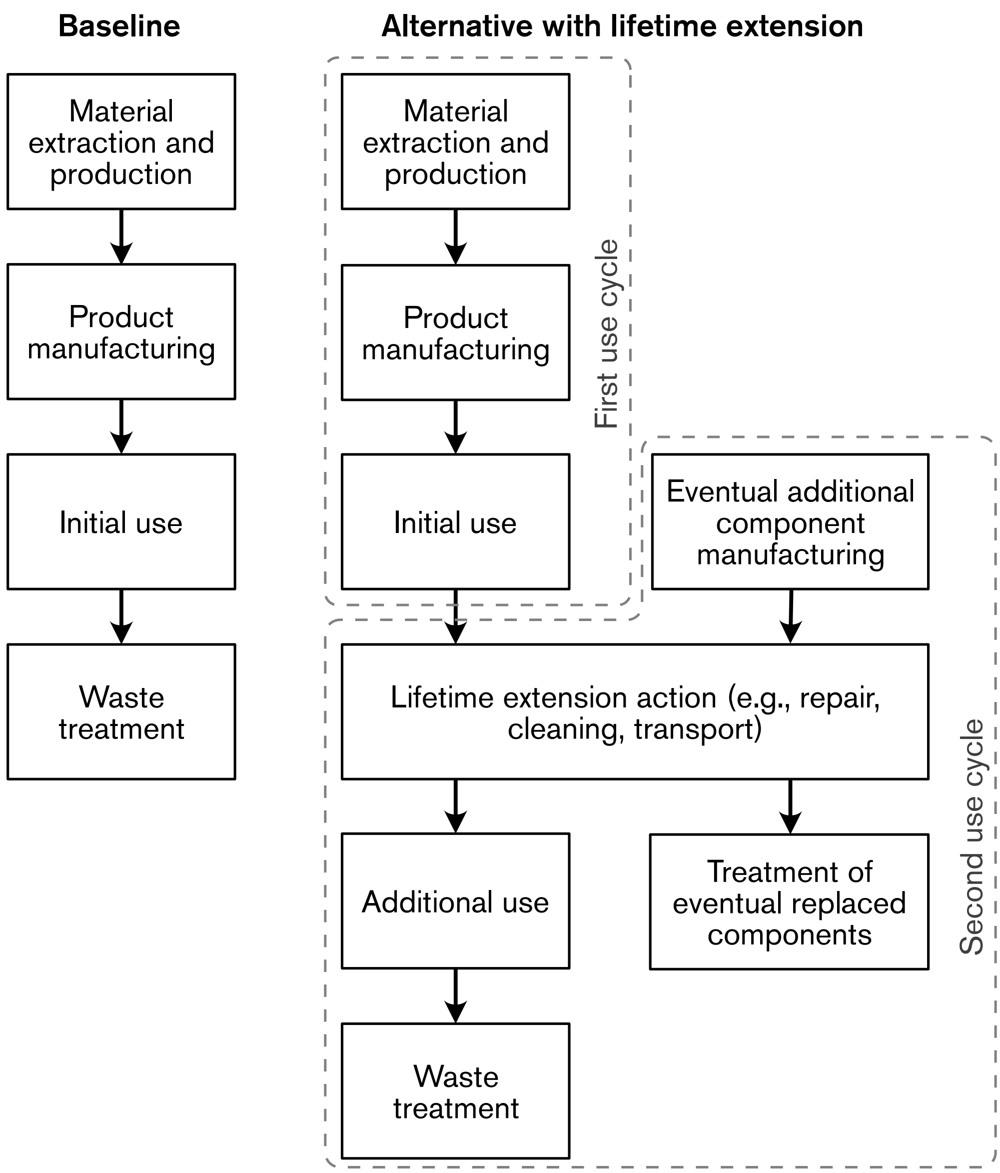

Figure 2. Flowchart of generic product systems for comparing a baseline and alternative with lifetime extension.

An assessment of lifetime extension typically answers the question: "*What is the difference in environmental impact between a baseline and an alternative with a lifetime extension?*" Lifetime extension is beneficial when the alternative with lifetime extension results in a lower environmental impact than the baseline.

2.4.1 **Life cycle assessment**

LCA is a method which provides a quantitative estimation of the potential environmental impact of a product. The scope of the assessment is the "life cycle" of a product, from raw material extraction to waste treatment. The methodology is formalised in international standards (ISO, 2006a, 2006b) and is structured into the following four steps (Baumann and Tillman, 2004; ISO, 2006a):

1. Goal and scope definition: The goal and scope of the LCA are decided. The goal expresses the reason for the assessment, the intended audience, and the intended application of the results and defines the system under study. The scope definition clarifies the modelling aspects by specifying the alternatives under study, the system boundaries, the list of environmental impact categories and the main assumptions and limitations. It also defines the functional unit, which reflects the function of the product under study (e.g., kilometres driven for a car, years of comfortable bedding for a mattress). The functional unit sets the basis for comparison between the alternatives and products with the same function: the results are expressed in relation to this unit (e.g., environmental impact per kilometre for a car, impact per year of comfortable bedding for a mattress). The scope is defined to fit the goal of the assessment.

2. Inventory analysis: Data to model the system under study are collected. Ideally, for all processes involved in the life cycle, input and output flows of material, energy, products, emissions, waste, and other physical inputs such as land use are collected. Then, these data are manipulated to obtain the amount X_i of each elementary flow i, i.e., flows between the environment and the technical system, such as emissions to soil, air or water and extracted resources, for one functional unit to be realised. In this step, data on product lifetime may be collected to quantify flows in the use phase, such as the replacement of components for maintenance or the energy used for the product to function. The lifetime may also be involved in normalising the amount for each flow to the functional unit. For example, for a functional unit of one year and a product with a lifetime L, X_i is obtained by dividing the amount x_i of each elementary flow for a system producing one product by L. In the rest of the section, the functional unit is assumed to consider the unit of the lifetime, and so a normalisation to the product lifetime is done: $X_i = x_i/L$.

3. Impact assessment: The potential contribution to environmental impacts of the alternatives is calculated. For each impact category j selected under the scope definition, the amount for each elementary flow is multiplied by its characterisation factor $CF_{i,j}$ which reflects the environmental impact of the emission or resource in relation to one equivalent stressor (e.g., CO_2 equivalent

for global warming). The environmental impact I_j is calculated as the sum of the contribution of each elementary flow:

$$I_j = \sum_i \frac{x_i}{L} . CF_{i,j} \quad (2.1)$$

4. Interpretation: The results are interpreted in relation to the goal and chosen methodology. For example, a contribution analysis can be done to identify the most impacting life cycle phases, processes or pollutants, and a sensitivity analysis can be done to estimate the variations in the results when the inputs to the model or methodological choices are changed.

The steps are not carried out sequentially but usually in an iterative way. For example, an analysis of initial results could lead to additional data quality requirements for highly contributing processes or the implementation of a sensitivity analysis for selected input variables.

Conclusions from an LCA are typically used to inform decision-making for product design and policy-making by identifying improvement possibilities and hot spots in the life cycle to prioritise actions or assess alternatives with the same product function (Baumann & Tillman, 2004).

LCA is often used to assess CE strategies in research (Corona et al., 2019; Harris et al., 2021; Sassanelli et al., 2019) and in companies (Roos Lindgreen et al., 2022). Conclusions from LCAs show that lifetime extension strategies have the potential to reduce a product's environmental impacts (Bakker et al., 2014; Böckin et al., 2020; Kaddoura et al., 2019). If nothing else in the LCA model but the lifetime value is changed, a longer lifetime reduces the number of products required to be produced to deliver the same function. For example, one product with a one-year lifetime but only 0.5 products with a two-year lifetime are required to deliver the product's function over one year. Therefore, the environmental impact per unit of function caused by resource extraction, production and waste management is reduced with a longer lifetime.

However, lifetime extension does not systematically reduce a product's environmental impact (Böckin et al., 2020; Richter et al., 2024). For example, for a product to be shared between users in a rental system, additional transport to access and return the product might offset the benefits of a lifetime extension

(Abagnato et al., 2024; Martin et al., 2021). Or the washing between uses for multiple-use products replacing single-use products might offset the benefits of shifting from single- to multiple-use alternatives (Cottafava et al., 2024).

In particular, studies have shown that the initial and the additional lifetimes are variables influencing whether lifetime extension is beneficial and the extent of its benefits:

- A minimum additional lifetime is required for lifetime extension to be beneficial. The lifetime extension action, such as repair, has a lower environmental impact than the original product as fewer resources are invested. For a repaired product to have a lower environmental impact per functional unit than the product before repair, the additional lifetime needs to be long enough to pay off the efforts to repair, with a minimum value that can be calculated, such as in Ardente and Mathieux (2014) for the repair of electrical and electronic equipment (EEE).
- Lifetime extension might not be beneficial after a long initial lifetime. For example, the repair of small household EEE is not preferred to replacement when a technical failure occurs after 3 years or more (Bovea et al., 2020). The reduction in environmental impact per year of use with a given additional lifetime (e.g., one year) decreases with the initial lifetime. It is higher for a product with a short initial lifetime (e.g., impact from production and waste management halved for an initial lifetime of one year) than a long initial lifetime (e.g., impact from production and waste management reduced by 1% for an initial lifetime of 10 years). In addition, the remaining lifetime after, e.g., repair after a long initial lifetime might not be long enough for the repair to pay off.
- For energy-using products, lifetime extension of old products might not be preferable to product replacement with a newer and more efficient product. For example, replacing old residential heating systems with more energy-efficient technologies to reduce energy use during the use phase can result in a more significant impact reduction than repairing them to avoid the production of new heating systems (Hummen and Desing, 2021).

Although many LCAs of lifetime extension have been carried out and product lifetime stands out as one key variable for the results, no concrete guidelines on how to conduct an LCA of lifetime extension and how to define and model product lifetime have yet been developed. Discussions on product lifetime in LCA are found only for LCAs of buildings. The lifetime of the building and building components greatly influence LCA results (Aktas and Bilec, 2012; Grant and Ries, 2013). Thus, methods for predicting lifetime values have been developed and compared in building LCAs (Grant and Ries, 2013; Morales et al., 2021; Silvestre et al., 2015). Moreover, Decorte et al. (2023) recommend using the same total building lifetime for a fair comparison between a building renovation and a reconstruction. However, the lifetime prediction methods and the recommendations are specific to buildings and building components and not generally applicable to other products. It highlights the following research need:

Lack of concrete guidelines for modelling product lifetime in LCA of lifetime extension.

2.4.2 **Circular economy indicators**

Indicators are variables that provide relevant information for decision-making (Gallopín, 1996; Jerome, 2022; Moraga et al., 2019). They are understood as simplified but accurate descriptions of a complex reality based on models that were developed to make sense of the world (Meadows, 1998). They provide information for comparing situations, assessing current conditions and trends, providing early warning information, and anticipating future conditions and trends (Gallopín, 1996). In contrast to a metric, an indicator's value is interpreted within the decision-making context, giving it a broader significance than its immediate meaning (Bakkes et al., 1994; Gallopín, 1996; Lundin, 2003).

The results from different environmental impact categories in LCA can be considered as a set of indicators informing on several environmental impacts (Lundqvist, 2000). However, in this research, the term "indicator" refers to measures that are less time- and resource-consuming to compute compared to data-intensive assessment methods such as LCA. Moreover, as the distinction between "metric" and "indicator" is sometimes challenging to make, all measures introduced as "indicators" in the literature are referred to the term "indicator".

Indicators for the CE were developed for various implementation levels with, for example, the European CE monitoring framework at a supra-national level (European Commission, 2023), the Circular Transition Indicators at a company level (World Business Council for Sustainable Development, 2023), and many product-level CE indicators (Elia et al., 2017; Helander et al., 2019; Moraga et al., 2019; Parchomenko et al., 2019; Saidani et al., 2019). In this dissertation, *CE indicators*, sometimes referred to only as *indicators*, refer to product-level indicators for the CE. Various CE indicators were analysed and compared based on the CE strategies (Moraga et al., 2019; Parchomenko et al., 2019; Saidani et al., 2019), sustainability aspects (Corona et al., 2019; Kristensen and Mosgaard, 2020) and life cycle phases (Helander et al., 2019) that are accounted for. Conclusions highlight that most indicators focus on one life cycle stage (Helander et al., 2019) or one CE strategy (Corona et al., 2019; Helander et al., 2019). No indicator accounts for all sustainability aspects or CE strategies at once (Corona et al., 2019; Kristensen and Mosgaard, 2020; Moraga et al., 2019; Saidani et al., 2019). Therefore, using one indicator is not sufficient to identify burden shifting in the product system. So, the use of multiple complementary CE indicators (Corona et al., 2019; Moraga et al., 2019) or other complementary indicators (Helander et al., 2019; Parchomenko et al., 2019) that remain to be identified have been suggested.

These conclusions from reviews of CE indicators are built on the analysis of the indicators' methodology description. They thus stay at a general level of CE strategies and life cycle phases and do not go into details about processes and flows included. Testing indicators is highlighted as an essential step in understanding their application and detailed abilities and in developing new assessment frameworks (Meadows, 1998). Only Saidani et al. (2017) applied a limited range of CE indicators to a case. It concludes that the three indicators tested are unable to "cover all aspects of the CE" (Saidani et al., 2017). Therefore, a clear understanding of what is explicitly quantified by CE indicators is crucial for selecting which ones to use. However, this detailed understanding of a more extensive range of CE indicators is missing, highlighting another research need:

Missing description of processes and flows included by CE indicators.

2.4.3 LCA and circular economy indicators

Reviews comparing assessment methods for CE focus either on CE indicators only (De Pascale et al., 2021; Helander et al., 2019; Kristensen and Mosgaard, 2020; Moraga et al., 2019; Parchomenko et al., 2019) or on other assessment methods except for CE indicators (Elia et al., 2017; Sassanelli et al., 2019; Walzberg et al., 2021). Corona et al. (2019) is the only review comparing LCA and CE indicators. The conclusion recommends LCA for its holistic approach to addressing the product system (Corona et al., 2019). The analysis focuses on the scope of the methods regarding the measured dimensions of sustainable development (environmental, economic, social), but the types of results and the differences in scope at the level of the product system are not analysed. Three studies present the methodology for three novel CE indicators, and they apply both the indicator and LCA on cases to test the indicator results against LCA results (Bracquené et al., 2020; Linder et al., 2020; Lonca et al., 2018). Differences in the types of results between the two methods are observed, with LCA providing information on environmental impacts and the tested indicators on changes in material flows (Bracquené et al., 2020; Lonca et al., 2018) but the range of tested indicators is limited.

Some studies apply both LCA and CE indicators to assess CE strategies. Niero and Kalbar (2019) combine results from LCA and two CE indicators, the Material Circularity Indicator (MCI) (Ellen MacArthur Foundation, 2019) and the Material Reutilisation Score (Cradle to Cradle Products Innovation Institute, 2016), with multi-criteria decision analysis. Walker et al. (2018) compare the LCA results to those from the MCI and three other indicators on a case. Luthin et al. (2024) compare the results from LCA, life cycle costing, social life cycle assessment and the MCI on a case. All three studies point to differences in the preferred CE strategy for a product between results from LCA or CE indicators. However, the range of tested CE indicators is limited, and differences in the types of results and scope of the studied system between LCA and CE indicators are not analysed.

Overall, testing and comparison to LCA of a large range of CE indicators to identify differences in the types of results and scope of the studied system are missing. These differences are essential for understanding the appropriateness of the methods for different situations (Finnveden and Moberg, 2005), hence the following research need to be addressed:

Lack of comparison between CE indicators and LCA in terms of types of results and scope of the studied system.

3 Aim and research questions

The overall aim of this research is to develop knowledge of environmental systems analysis methodology for assessing product lifetime extension, allowing practitioners to deliver decision support that corresponds to the goal of the assessment. “Methodology” refers to the selection of both 1) the method, i.e., a particular assessment procedure or approach, and 2) methodological choices, i.e., the more specific choices of procedure, modelling and calculation for conducting the assessment. For example, LCA is an assessment method, and the choice of system boundaries or the functional unit is a methodological choice to be made when conducting the assessment. “Practitioners” refer to any user of ESA for assessing lifetime extension, regardless of whether they are from academia, companies, or policy-making entities.

Under this general aim, the research needs identified in section 2 are addressed through the following two research questions. The first research question focuses on the selection of the assessment method for lifetime extension and, therefore, the differences between CE indicators and LCA in the types of results and scope of the studied system for assessing lifetime extension:

RQ1: How do CE indicators and LCA differ in the types of results and scope of the modelled product system when assessing lifetime extension?

To answer this research question, a detailed understanding of CE indicators in terms of the product system’s flows and processes included in the assessment is necessary to address both research needs related to CE indicators identified in section 2.

The second research question focuses on LCA methodology for lifetime extension, especially the lack of concrete guidelines for modelling product lifetime as a crucial variable for the outcome of lifetime extension assessments:

RQ2: In LCAs of product lifetime extension, how can product lifetime be modelled and lifetime modelling approaches be selected to correspond to the assessment goal?

The results from both research questions are used to identify methodological considerations for assessing lifetime extension.

4 Research design and methods

4.1 Research design

The research design has been developed from a need to make sense of existing knowledge and practices. Thus, the work presented in this dissertation departed from what exists and analysed it to develop new knowledge by structuring and finding relationships between existing information, thereby uncovering patterns and insights on the topic.

The research uses a mixed-method approach (Creswell, 2018). It combines two main research methods (Figure 3). Literature reviews provide an overview and qualitative analysis of existing practices, and case studies provide quantitative analysis. These research methods were selected for their relevance to addressing the research questions stated in section 3.

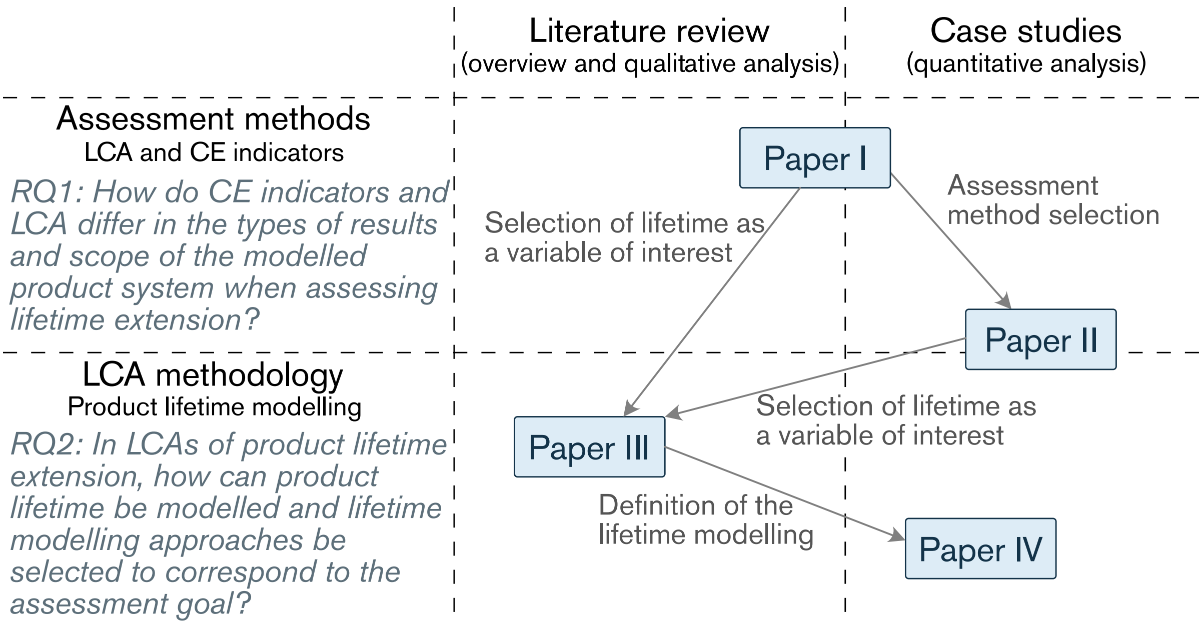

Figure 3. Relationship between the four papers, the research methods and the research questions. The arrows represent the information taken from the conclusions of one paper that influenced the design of another but do not map all conclusions from the papers.

The research was structured in four studies, each reported in a scientific article (Papers I, II, III and IV). The two research questions are addressed in Papers I and II, and Papers II, III and IV, respectively (Figure 3). The design of the studies evolved as the research proceeded: the conclusions of one study informed the content of the next ones (Figure 3).

In particular, the research started with a broad scope, encompassing the two assessment methods and a broad range of CE strategies in the choice of cases. The focus of the research was refined from CE strategies to lifetime extension strategies after identifying the limited attention to these strategies when studying CE indicators in Paper I.

Paper I addresses RQ1 and was designed to build on three steps. First, existing CE indicators were identified. A systematic literature review was used to derive a list of product-level and resource-based CE indicators. Second, the CE indicators were tested and analysed. The testing was done on seven case studies, including, but not limited to, cases of lifetime extension with reuse and shifting from single-use to multiple-use products. The analysis was done to the level of the included product system's flows and processes, supported by a mapping of included flows and processes on a generic product-system flowchart. Third, the CE indicators' results were compared with LCA results on the same cases to identify differences in how lifetime extension is assessed by each assessment method.

Paper I highlighted that CE indicators provide different types of results than environmental impacts as in LCA, and, as this work primarily focuses on assessing environmental impacts, it guided the research towards LCA as the assessment method in the subsequent studies.

The learnings about RQ 1 are subsequently developed through Paper II. This study is an LCA case study of lifetime extension, used to highlight variables that are crucial for the results of assessments of lifetime extension. The paper presents an LCA for the case of repair of high-voltage (HV) electric motors. HV motors are big stationary motors used in the industry and typically have long lifetimes. The influence of energy efficiency and lifetime extension on the product's environmental performance was studied by comparing two motor designs with different energy efficiency and their repair. In this dissertation, whether crucial variables are accounted for by CE indicators is analysed by comparing the crucial variables for LCA results highlighted in Paper II to the analysis of CE indicators in Paper I. It is used to develop the identification of differences in the scope of the modelled product system between CE indicators and LCA.

Paper II acts as a bridge between RQ1 related to LCA of lifetime extension in general by the conclusions drawn from the case study and RQ2 with more detailed considerations for product lifetime modelling in LCA (Figure 3). Additionally, the conclusions from Papers I and II highlighted product lifetime as a key variable in LCA, hence the focus on product lifetime in LCA methodology in this research.

For RQ2 on LCA methodology, the research was conducted in two steps. First, the current lifetime reporting practices and the description of lifetime modelling practices were evaluated. It is addressed in Paper III with a literature review of LCAs of lifetime extension, including Paper II in the list of reviewed articles, in order to derive conclusions that are generally applicable to LCA of lifetime extension. The analysis focused on the product lifetime modelling as reported by the reviewed studies. The results were used to analyse the attention to product lifetime in the reporting of the studies and identify the elements by which lifetime is modelled. The modelling elements were then defined and structured into a framework that followed the LCA methodological steps.

The second step for addressing RQ2 was designed to be an identification of differences in the information provided by the LCA results with different lifetime modelling for addressing different assessment goals. This step focused on one element of this modelling framework: the integration of product lifetime into LCA equations. Three approaches for such integration were identified through the literature review in Paper III. In Paper IV, they were applied to two case studies. The cases were selected to encompass a broad range of products to derive guidance that is generally applicable to LCA of lifetime extension. The results obtained were analysed to formulate typical questions answered with each approach, which were then the basis for guidelines to practitioners on suitable approaches with respect to specific LCA goals.

4.2 **Methods**

4.2.1 **Literature reviews**

Two literature reviews were conducted with different aims and so with different methodologies.

For the first review, presented in Paper I, the aim is to identify *all* existing product-level resource-based CE indicators existing at the time of the study. Therefore, a systematic literature review was conducted (Grant and Booth, 2009) with a literature search design to encompass an exhaustive list of existing CE indicators.

For the second review, presented in Paper III, the aim is to collect LCAs of lifetime extension to find existing approaches with which to model product lifetime. As an extensive number of LCAs of lifetime extension have been published, a scoping review (Arksey and O'Malley, 2005; Grant and Booth, 2009) was conducted. This type of review does not aim to be exhaustive in the list of relevant entries but instead uses a literature search designed to focus on the most relevant entries. It allows for keeping the invested time at a reasonable level compared to a systematic review and still identifying a range of existing practices (Arksey and O'Malley, 2005). In Paper III, to reduce the sample of entries to be screened and analysed during the review process, only LCAs of lifetime extension mentioning the concept of product lifetime in their title, keywords and abstract were selected.

For both literature reviews, the list of entries selected with the literature search was screened based on the title, abstract and content to select the studies to be analysed further. The selection process and analysis of the selected entries are described in detail in Papers I and III.

4.2.2 Case studies

Case studies are in-depth analyses of a case where detailed information is collected (Creswell, 2018). They allow an in-depth appreciation of an issue (Crowe et al., 2011). While case studies often focus on existing or potentially existing cases to provide detailed data, they can also incorporate hypothetical data to explore potential scenarios (Crowe et al., 2011) (e.g., hypothetical lifetime extension of an existing product).

In this work, the purpose of the case studies was to test and compare assessment methods, explore a specific case of lifetime extension, and compare methodological choices. For the testing and comparison of CE indicators to LCA in Paper I, the coverage of various types of products and CE strategies was necessary for general observations on LCA and CE indicators. Therefore, multiple cases were selected, including single-use (incontinence products) and multiple-use (laptop and truck engine) products and various CE strategies (see Table 2). Paper II aims to explore a specific case of lifetime extension to identify crucial variables for the assessment results. The cases of HV motors with different energy efficiency and repaired HV motors were chosen as they offered changes in different variables, such as the product lifetime, product design and energy efficiency, and insights on the lifetime extension of long-lived and energy-intensive products. Finally, in Paper IV, the comparison of lifetime modelling approaches in LCAs of lifetime extension aims to provide general conclusions on LCA methodology for lifetime extension. Two cases of lifetime extension were selected to cover products with use phases of different characteristics: the remanufacturing of mattresses, which do not require resources to function, and the repair of HV motors, which require energy.

Depending on the role of the case study in the research, attention to primary data collection differs: primary data were collected to explore specific cases, and data from previously published cases were used to test and compare methods or methodological choices, where the case in itself is less important than the application of the assessment method. In Paper I, LCA models from previous studies were reused and modified for the LCA calculations, while inventory data were used to calculate CE indicators.

The different cases are briefly presented in Table 2. More details are available in the Papers I, II and IV.

Table 2. Overview of case studies used in the research. The CE strategy in focus is indicated using the terminology from Böckin et al. (2020).

Case	CE strategy in focus	The main data source	Used in Paper
Recycled production waste for incontinence products	Reducing losses in production	Published data and LCA model from Willskytt and Tillman (2019)	Paper I
Change to bio-based material in incontinence products	Changing material in the product		
Multiple use of incontinence products	Shift from single-use to multiple-use		

Effective use of incontinence products	Use effectively (size tailored to users' needs)		
Reused laptop	Reuse	Published data and LCA model from André et al. (2019)	
3D-printed truck engine	Reduce material quantity in product and reduce the use of auxiliary material and energy during use (fuel consumption)	Published data and LCA model from Böckin and Tillman (2019)	
Advanced 3D-printed truck engine	Reduce material quantity in product (with advanced technology) & reduce the use of auxiliary material and energy during use (fuel consumption)		
Different energy efficiency of high-voltage (HV) electric motors	Reduce the use of energy during use	Primary data from the HV motor manufacturer, background data from the ecoinvent database (Wernet et al., 2016)	Paper II
Repair of HV electric motors	Repair		Paper II Paper IV
Mattress remanufacturing	Remanufacturing	Published data from Glew et al. (2012) and Lanoë et al. (2013), background data from the ecoinvent database (Wernet et al., 2016)	Paper IV

4.2.3 **Software for calculations in LCA studies**

LCA calculations were carried out with the help of LCA software. In Paper I, the original LCA modelling on OpenLCA from the authors of the studies presented in Table 2 (third column) was used for the cases. The analysis of the results from the software to generate the relevant figures and analysis for Paper I required copy-pasting of the results from OpenLCA to Excel (Figure 4). In Papers II and IV, the data collection, LCA calculations, analysis and visualisation were instead carried out with the programming language Python with the help of the Python package Brightway (Mutel, 2017) and its user interface, the Activity Browser (Steubing et al., 2020) (Figure 4).

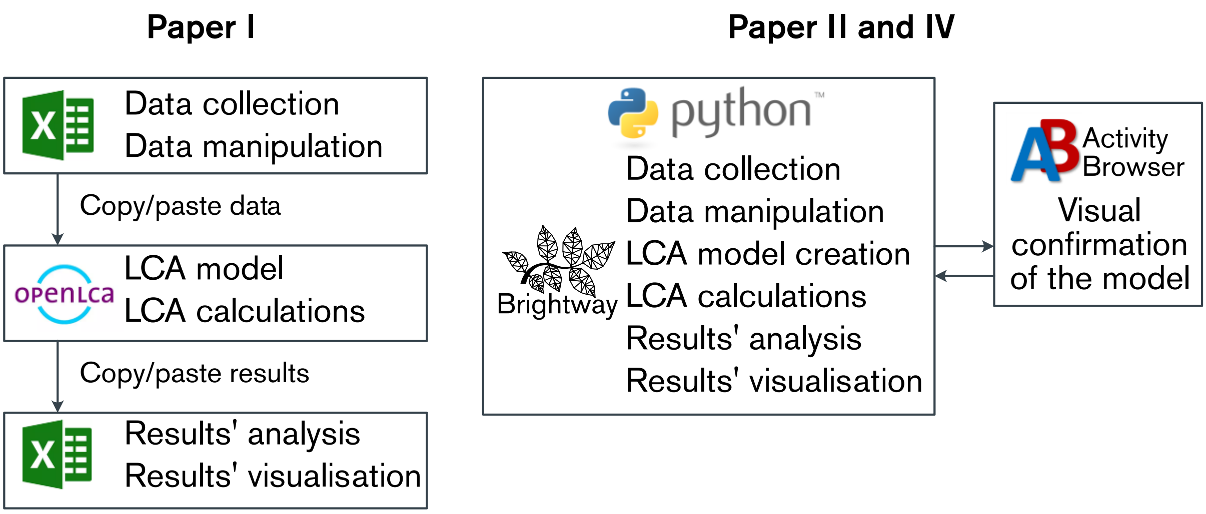

Figure 4. Workflow and software used to carry out the LCAs in Papers I, II and IV.

As LCA typically involve the manipulation of large amounts of data, using LCA software is common practice (Speck et al., 2016). In this work, the choice of LCA software has influenced the research design in Papers II and IV. Using a programming language made possible the rapid implementation of methodological choices that require uncommon input data formats and more calculations than what is done in classic LCA software. For example, generating a random data sample using a discrete probability distribution, presenting results on a histogram and analysing complex results such as parametric calculations and break-even analysis were carried out. These elements are central to the product lifetime modelling implemented in Paper II and tested in Paper IV. The possibility of having access to a time-effective and reliable way to implement this lifetime modelling enabled a focus on lifetime modelling in LCA without strong practical barriers to implementation.

5 Results and analysis

This chapter presents the results and analysis addressing each of the two research questions defined in section 3.

5.1 CE indicators and LCA for assessing lifetime extension

5.1.1 Lifetime extension in CE indicators

In total, 36 CE indicators were identified in the review and analysed based on the product system's flows and processes they account for and the CE strategies their methodology has in focus (Paper I).

Nine indicators out of 36 have at least one lifetime extension strategy in focus. Out of these nine indicators, two have only lifetime extension strategies in focus: the reusability rate (Ardente and Mathieux, 2014) and the potential reuse index (Mesa et al., 2018). Both are expressed as a mass fraction of the product that can be reused. They thus account for flows of reused products and components (Figure 5a) and have the strategies of reuse (product reuse) and remanufacturing (component reuse) in focus. However, the reusability rate accounts only for commercial reuse, while the potential reuse index also accounts for non-commercial reuse. The seven other indicators have, in addition to lifetime extension strategies (i.e., reuse, remanufacturing and increased technical lifetime by design), other CE strategies in focus, such as recycling, energy recovery or production loss reduction (see, for example, the resource net loss (RNL) by Ljunggren Söderman and André (2019) in Figure 5b). Lifetime extension is in focus in the indicator methodology by accounting for either the value of the extended lifetime (Figge et al., 2018; Ljunggren Söderman and André, 2019; Winzer et al., 2016) or the mass fraction of the product coming from reused components and the fraction that can be reused at end-of-life (Bracquené et al., 2020; Ellen MacArthur Foundation, 2019; Razza et al., 2020).

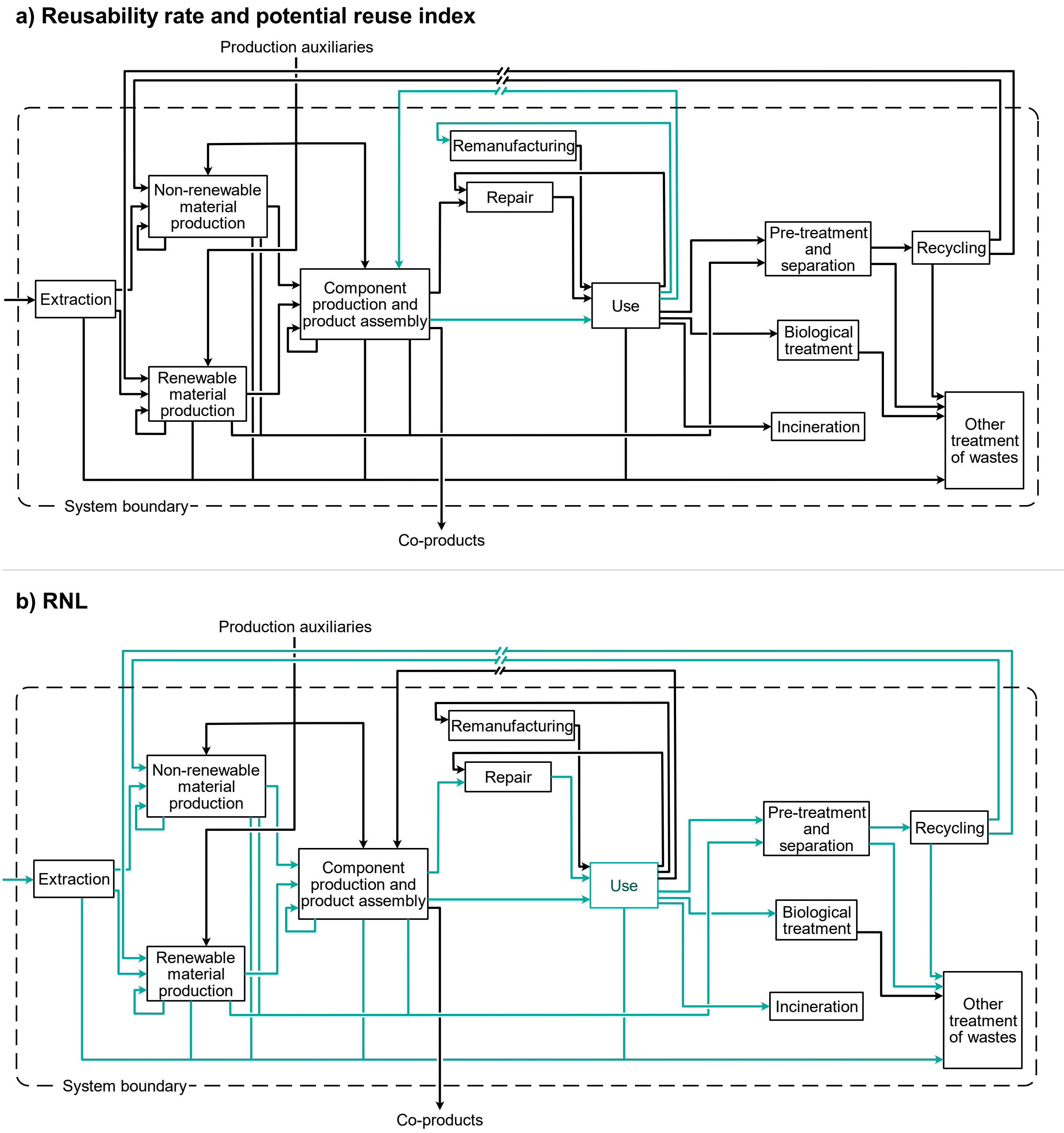

Figure 5. Flowchart mapping of a) the reusability rate (Ardente and Mathieux, 2014) and the potential reuse index (Mesa et al., 2018) and b) the resource net loss (RNL) (Ljunggren Söderman and André, 2019) as examples of indicators focusing on lifetime extension strategies (Paper I).

Six of these nine indicators use time and/or product function data in their calculations. The longevity indicator (Figge et al., 2018) is expressed in units of time and considers the time a unit of material resource is maintained in a product system based on the product lifetime and its expansion with remanufacturing and recycling. In the specific energy and resource indicator (Winzer et al., 2016) specifically addressing lighting systems, lighting performance and product lifetime are used to calculate the indicator. The RNL (Ljunggren Söderman and

André, 2019) is expressed per product function (represented by the highlighted use process in Figure 5b) accounting for product lifetime. Finally, three indicators (Bracquené et al., 2020; Ellen MacArthur Foundation, 2019; Razza et al., 2020) use a benchmark of the product function, accounting for product lifetime, to an industry average in their calculations. For all these indicators using time and/or product function data, an extended lifetime with all other variables unchanged results in an improvement in the indicator value.

Mapping the flows and processes accounted for by the reviewed indicators (Paper I) shows two processes for lifetime extension strategies that are not accounted for by any indicator: maintenance and repurposing (Figure 6). The changes in flows related to these strategies would be undetected with an assessment using only indicators from the list of reviewed CE indicators.

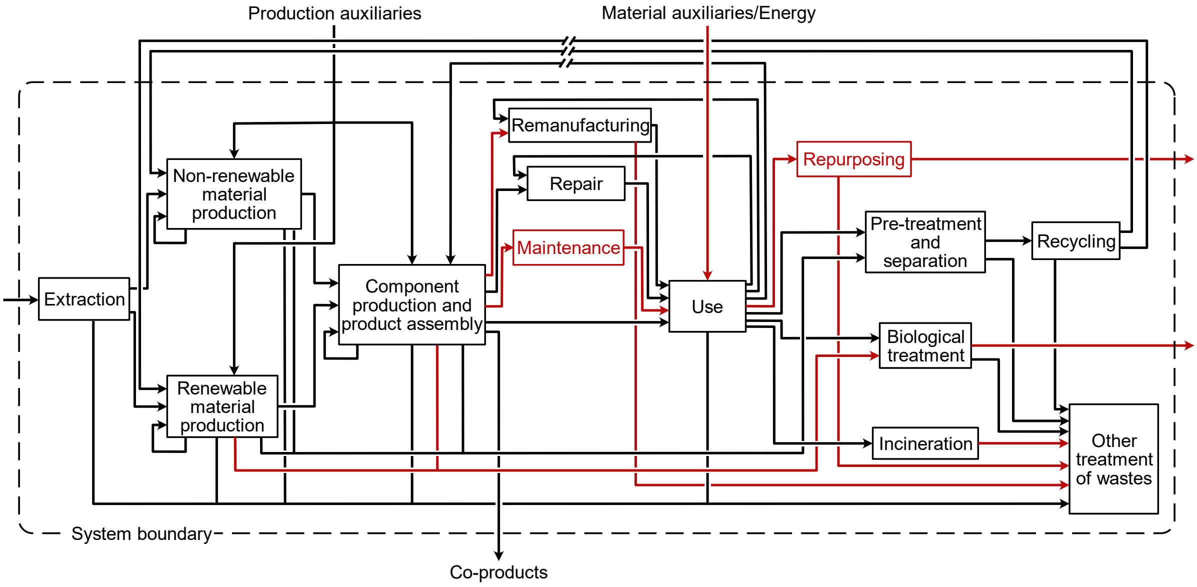

Figure 6. Flowchart of a generic product system with flows and processes captured by the reviewed CE indicators in black and flows and processes not captured in red (Paper I).

Overall, nine CE indicators have been found to focus on some of the lifetime extension strategies, primarily reuse, remanufacturing and increased technical lifetime by design. These indicators reward lifetime extension either by considering the increase in product lifetime value or product mass fraction that is possible to reuse or comes from reused components. However, since maintenance and repurposing are not accounted for, the reviewed CE indicators do not account for all lifetime extension strategies if the original indicator definitions are strictly followed. This leaves room for further elaboration on CE indicators.

5.1.2 Major differences between CE indicators and LCA for lifetime extension

Several differences were identified between CE indicators and LCA for assessing lifetime extension when applying the two methods to cases (Paper I).

First, there is a difference in the choice of system boundaries when collecting necessary data for the calculations. The practitioner in LCA decides the system boundaries, while the definition of each CE indicator decides them. In cases of lifetime extension, such as the reused laptop (Paper I), the product system can be divided into two use cycles (see the generic flowchart in Figure 2 in section 2.4). The first use cycle includes the laptop's production and initial use. The second consists of the reuse activity and second use. In most CE indicators and the LCAs presented in Paper I, the system boundaries consider a product system that includes the two use cycles. However, for seven CE indicators out of 36, the system under study focuses on one use cycle only with the reuse activity and second use. The flows related to laptop production and first use and the flow of laptops unfit for reuse are excluded from the assessment. This choice of system boundaries limits the inclusion of all activities that allow lifetime extension to happen, such as product design and collection systems fostering reuse and optimising the ratio of products that are fit for reuse. This difference is important to highlight when estimating whether the goal and scope of the assessment require the inclusion of these activities or not.

A second difference noticed in the data collection and analysis of results for the two assessment methods is the accounting of material and energy use in the use phase. In LCA, the practitioner decides whether to include these flows within the system boundaries. Results from LCAs show that the environmental performance of products using energy or materials during their use phase, such as washing machines (Ardente and Mathieux, 2014) or HV electric motors (Paper II), is significantly influenced by material and energy use in the use phase. Moreover, energy and material flows in the use phase are essential for accounting for differences in product use phase efficiency. For example, for HV motors (Paper II), variations in energy efficiency are key to the product's environmental performance and the benefits of lifetime extension with repair. The motor design with better energy efficiency results in lower environmental impacts than the motor design with lower energy efficiency with an extended lifetime with repair. Moreover, a small decrease in efficiency after repair results in the repair not being beneficial compared to replacement with a motor as efficient. For example, for motors running on low-carbon electricity from the Swedish electricity mix, a 0.04-0.05% efficiency reduction is sufficient for the repair of HV motors not to be beneficial in terms of global warming impacts (Paper II). In the reviewed CE indicators, the definition of their methodology is such that material or energy use in the use phase is not accounted for (Figure 6). Therefore, an assessment using exclusively CE indicators listed in Paper I would not reflect the overall resource performance of energy-using products and changes in energy efficiency with, e.g., lifetime extension or different product designs.

Differences between LCA and indicators were also identified when interpreting the assessment results (Paper I). First, the two methods inform on different types of impacts. CE indicators capture changes in specified materials and, in some cases, energy resource flows, while LCA provides information on environmental impacts. For example, in the case of the 3D-printed truck engine compared to a conventional truck engine (Paper I), CE indicators provide information on a lower recycled content and recovery rate due to changes in the material content and increased energy use in manufacturing with 3D printing. LCA, on the other hand, provides information on reductions in global warming and fossil resource depletion impacts due to decreased fossil energy requirements during use with the lighter engine that is enabled by 3D printing. This difference is explained by the type of flows accounted for. Both methods account for material and energy flows, but LCA also accounts for emissions. Additionally, LCA requires differentiating between various energy sources and materials for calculating environmental impacts, which are distinctions that CE indicators do not require in their calculations.

Finally, the assessment results are presented using different bases for comparison. In LCA, the basis for comparison is the functional unit. As for the system boundaries, the functional unit is decided by the practitioner. According to the international standards for LCA, the functional unit is a "quantified performance of a product system" (ISO, 2006a) depending on the goal and scope of the assessment. For example, in the case of multiple-used incontinence products (Paper I), the functional unit is chosen as one use of an absorbent product with a medium absorption capacity and size. For CE indicators, the basis for comparison is decided by their definition. Except for the RNL indicator (Ljunggren Söderman and André, 2019) expressed per product function, CE indicators are expressed per product. This difference compared to LCA explains differences in assessment results for cases with changes in product mass. For example, the multiple-used incontinence product (Paper I) is made of one reusable pair of pants and one single-use absorbing pad sold separately. Thus, more cardboard packaging is required than for the single-use alternative. This increased material requirement per functional unit leads to lower performances in results from LCA and the RNL but better performance for indicators that reward renewable material content and recycling at end-of-life, as the packaging has a high renewable content and recycling rate compared to the rest of the product. However, rewarding heavier packaging for a product that provides the same function is questionable. It shows the importance of identifying changes in the product’s mass and considering the product function as a basis for comparison.

Overall, CE indicators and LCA provide different types of information on changes in resource flows and environmental impacts, respectively, expressed per product for CE indicators except the RNL and per functional unit for LCA and the RNL. In terms of scope, assessment practitioners have more freedom to include one or several use cycles and resource flows during use in LCA, while the choice is set by definition for CE indicators.

5.2 **Product lifetime in LCAs of lifetime extension**

5.2.1 **Importance of the lifetime for the results**

Even though the importance of product lifetime is visible from previous studies (section 2.4.1), conclusions from the papers appended to this dissertation add evidence to the influence of lifetime on LCA results of lifetime extension. In particular, from the LCA results of cases of lifetime extension in Papers II, III and IV, it is possible to identify that product lifetime is important for LCAs of lifetime extension in two ways: as an essential part of the functional unit and as a variable to which LCA results are highly sensitive.

The lifetime value differs between alternatives with and without a lifetime extension. When the environmental impacts are expressed per product, the difference in lifetime value does not influence the results. For example, the LCA results of the remanufactured mattress case (Paper IV) expressed per product are the same for mattresses with different lifetimes (Figure 7a). It would not be appropriate to compare the different alternatives with different lifetime values with the impact expressed per product. With a functional unit including the unit of the lifetime (e.g., year of mattress use), the value of the lifetime influences the results. The longer the lifetime, the lower the environmental impact per year of use (Figure 7b). This demonstrates the importance of having the unit of the lifetime in the functional unit when assessing lifetime extension. With this choice of functional unit, the LCA results are necessarily influenced by the product lifetime value.

Looking at the results of the reviewed LCAs in Paper III, the benefits of lifetime extension vary greatly with the product lifetime value. These variations are especially highlighted by sensitivity analyses of results. For example, in Bressanelli et al. (2022), the environmental benefits of washing-machine remanufacturing compared to replacement vary between -10 and +40% depending on the user profile and, thus, the extent of the lifetime extension. In De Saxce et al. (2012), the LCA results comparing bedsheets with designs to increase the technical lifetimes vary by 14% and 26% with two lifetime calculation methods compared to the method chosen as the baseline.

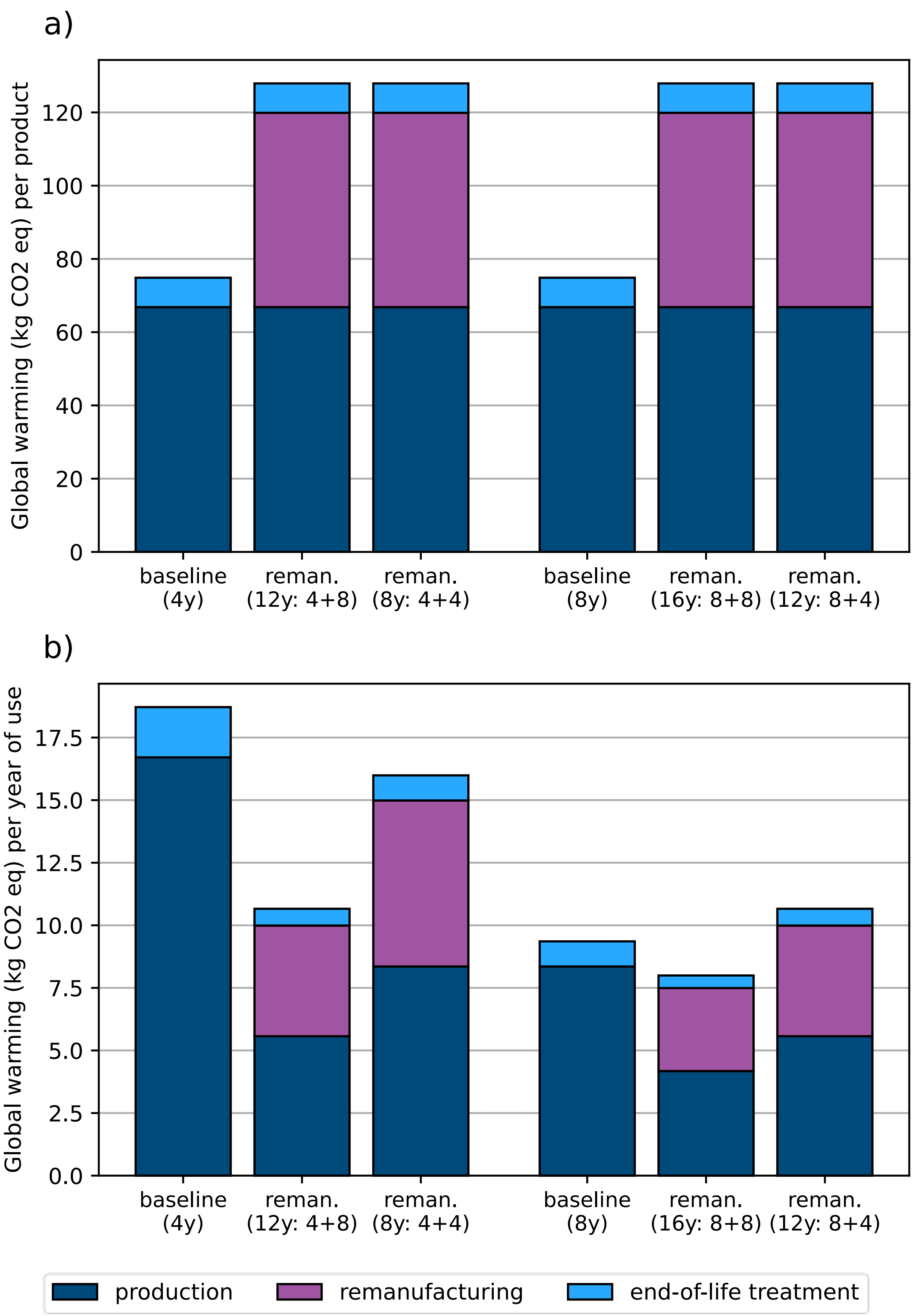

Figure 7. Global warming impact for the remanufactured mattress case (Paper IV) a) per mattress and b) per year of mattress use for different values of the mattress lifetime (initial + additional). Abbreviations: reman: remanufacturing, y: years.

Another example is the case of the repaired HV motor (Paper II). A repaired motor results in a lower environmental impact than a motor without repair only after a minimum additional lifetime. Indeed, the repair results in additional impacts from producing a new component and treating the replaced one. So, shortly after the repair, the environmental impact per year of use of the repaired motor is higher than that of the motor without repair. As explained above, a longer additional lifetime reduces the impact per year of use until this impact is lower than the impact of the product without repair. A similar situation can be observed for the remanufactured mattress case (Paper IV): the environmental impact of a remanufactured mattress with an initial lifetime of 8 years and an additional lifetime of 4 years (bar "reman. (12y: 8+4)" in Figure 7b) is higher than the one for the baseline (8 years) but is lower than the baseline with the additional lifetime increased to 8 years ("reman. (16y: 8+8)" in Figure 7b). It demonstrates the existence of a range of lifetime values for which lifetime extension is beneficial and another range for which it is not.

All of these examples show the crucial role of product lifetime in assessing lifetime extension, especially as an essential part of the functional unit and a key variable in the results. It highlights the importance of carefully considering this variable and its modelling in LCAs of lifetime extension.

5.2.2 **Lifetime reporting practices**

Reviewing LCAs of lifetime extension revealed imprecision in product lifetime definitions and incompleteness in the reporting of data sources and lifetime integration in LCA equations (Paper III). In 21 cases out of the 64 reviewed cases, several terms are used synonymously in the same study. It shows a lack of precision and attention to potential differences in the definition of different types of lifetime presented in section 2.

The description of the product lifetime does not contain enough information to clearly identify the chosen type of lifetime in 67% of the reviewed cases. More specifically, unclear descriptions make it impossible to understand if the defined lifetime accounts for periods of idleness and full technical lifetime or not in 11 and 24 out of 64 cases, respectively. Additionally, interpretation with the help of, e.g., calculations in the inventory, had to be made when analysing the type of lifetime used in 14 cases out of 64. This hinders the interpretation of the potential of lifetime extension, for example extending the service lifetime to the full technical lifetime, and the choices made in the product system of the LCA, for example, whether a frequency of use is assumed.

The studies also seldom report the reasons for obsolescence, found in 22 out of 64 cases in the review. However, this information is required for understanding if the reported lifetime accounts for the full technical lifetime and has been identified as central for evaluating the suitability of lifetime extension strategies to improve the environmental performance of products (Böckin et al., 2020).

Finally, the reporting of lifetime data sources and how the lifetime is integrated into LCA equations is not complete in all studies. The former is not reported in 27% of the reviewed cases, and the latter cannot be identified in one case. This information is crucial for ensuring a transparent LCA methodology. Reporting data sources is necessary for communicating the uncertainty and validity of results. For example, measured data may be more certain while an assumption might be highly uncertain, but the validity of measured data can be lower than assumed data if the assumed data is more valid for the goal and scope of the study.

A precise and complete reporting of lifetime modelling is therefore crucial for interpreting the LCA results of lifetime extension, but current practices show a lack of attention to reporting as well as awareness regarding the necessary elements to be reported.

5.2.3 **Product lifetime modelling**

The review of LCAs of lifetime extension considered product lifetime in all four steps of LCA methodology. A number of elements that describe how the lifetime is modelled were identified (Paper III). It was found that the elements are handled differently in the reviewed studies, and several generic options could be identified for each element. By structuring these elements and their respective options according to the four steps in LCA methodology, it was possible to design a framework for lifetime modelling that describes existing modelling practices. A technical element of this framework is the integration of product lifetime in LCA equations and is described in detail after a general presentation of the modelling framework.

Modelling framework

The elements that describe how product lifetime is modelled in LCAs of lifetime extension were identified both before and while analysing the reviewed studies (Paper III). For example, the types of lifetime and obsolescence were identified and defined based on the literature on product lifetime before the literature review (see section 2.3). In contrast, the integration of lifetime in equations and the lifetime data sources were identified while reading the studies and their different options were defined by grouping similar observations under the same entry.

The lifetime modelling framework is designed to follow the LCA methodological steps (Table 3):

1. The lifetime definition, developed in the goal and scope definition,
2. The integration of lifetime in equations, done in the inventory and impact assessment,
3. The sensitivity analysis, in the interpretation of the results.

The *lifetime definition* encompasses the description of the time period that the lifetime covers and the reasons for ending the lifetime. For the former, it is especially important to clarify whether periods of idleness and the whole technical lifetime are included in the lifetime, for example, by referring to the types of lifetime defined in section 2.1. For the latter, the types of obsolescence defined in section 2.1 introduce useful terminology, especially the distinction between absolute (i.e., the product is used until failure) and relative (i.e., the product falls into disuse before reaching its technical lifetime) obsolescence. In the context of lifetime extension, relative obsolescence indicates the possibility of extending the service lifetime to the full technical lifetime.

The lifetime definition also describes how the lifetime is expressed. This includes the choice of unit, such as in years, number of uses or number of use cycles, and whether lifetime is partitioned into an initial and additional lifetime or considered as a total lifetime only.

Table 3. Product lifetime modelling framework for LCAs of lifetime extension developed in Paper III.

<table>
<tr><th>Steps</th><th>Elements</th><th>Options</th></tr>
<tr><td rowspan="4">1. Lifetime definition</td><td>Type of lifetime</td><td>- Service lifetime
- Technical lifetime
- Use time
- Technical use time</td></tr>
<tr><td>Unit for the lifetime</td><td>- Time (e.g., years)
- Representing the function provided (e.g., number of uses)</td></tr>
<tr><td>Type of obsolescence</td><td>- Absolute
- Relative</td></tr>
<tr><td>Lifetime partitioning</td><td>- Partitioning of initial/additional lifetime
- No partitioning (total lifetime only)</td></tr>
<tr><td rowspan="2">2. Lifetime integration in equations</td><td>Lifetime representation in equations</td><td>- Single value
- No fixed value
- Distribution</td></tr>
<tr><td>Lifetime data source</td><td>- Assumption
- Literature
- Manufacturing company
- Calculated based on technical parameters or statistical data
- Expert judgement
- Measured data
- Product warranties
- Standard
- Survey to users</td></tr>
<tr><td>3. Sensitivity analysis</td><td>Sensitivity analysis method</td><td>- Testing of different values
- Comparison with other variables
- Break-even analysis
- Probabilistic simulation</td></tr>
</table>

The *lifetime integration in equations* is the description of how lifetime is represented in equations to calculate environmental impacts and the data sources used to supply the equations with lifetime values. Three main approaches have been identified from the reviewed LCAs, sorted from the most to the least used (Paper III): using a single lifetime value, a no-fixed value by leaving the lifetime variable in the calculations, and a distribution of the lifetime over a population. The approaches differ in their level of data requirements. The no-fixed value approach does not require any specific lifetime value, while the distribution approach is the most data-intensive and requires, e.g., results from a user survey or market data. For the reviewed cases using a single-value approach, various data sources have been used, listed in Table 3. The three approaches and their implementation in LCA are further described in section 5.3.2.

The last step is the *sensitivity analysis,* which aims to estimate the sensitivity of the LCA results to lifetime values. Many methods for sensitivity analysis in LCA have been identified (Björklund, 2002; Igos et al., 2019), but only four of them have been used in the reviewed LCAs (Paper III). For cases using a single-value approach, sensitivity analysis is done either by testing different lifetime values, comparing the variation in LCA results with different lifetime values to the influence of other variables, or doing a break-even analysis. The latter calculates the lifetime value for which the ranking of the compared alternatives changes and thus provides information on threshold values for which conclusions hold. For cases using a no-fixed value, sensitivity analysis is done with a break-even analysis. Finally, the only reviewed case using a distribution approach propagates the lifetime distribution to the LCA results using the values from a user survey as a sample (Bressanelli et al., 2022). Therefore, the distribution approach can be considered a sensitivity analysis method by probabilistic simulation in itself.

The framework provides a structured way to model product lifetime in LCAs, guiding practitioners to consider a comprehensive list of elements and an overview of options that can be used based on current literature.

Description of the three approaches to integrate lifetime in equations

The product lifetime representation in equations is perhaps the most technical element presented in the modelling framework. This section describes the implementation of the three identified approaches and their typical LCA results based on the example of the repaired HV motor from Paper IV. In this example, the baseline is a motor produced, used and recycled (Figure 8). The alternative with lifetime extension is a motor that undergoes repair after an initial lifetime by replacing a component and is used for an additional lifetime before recycling (Figure 8).

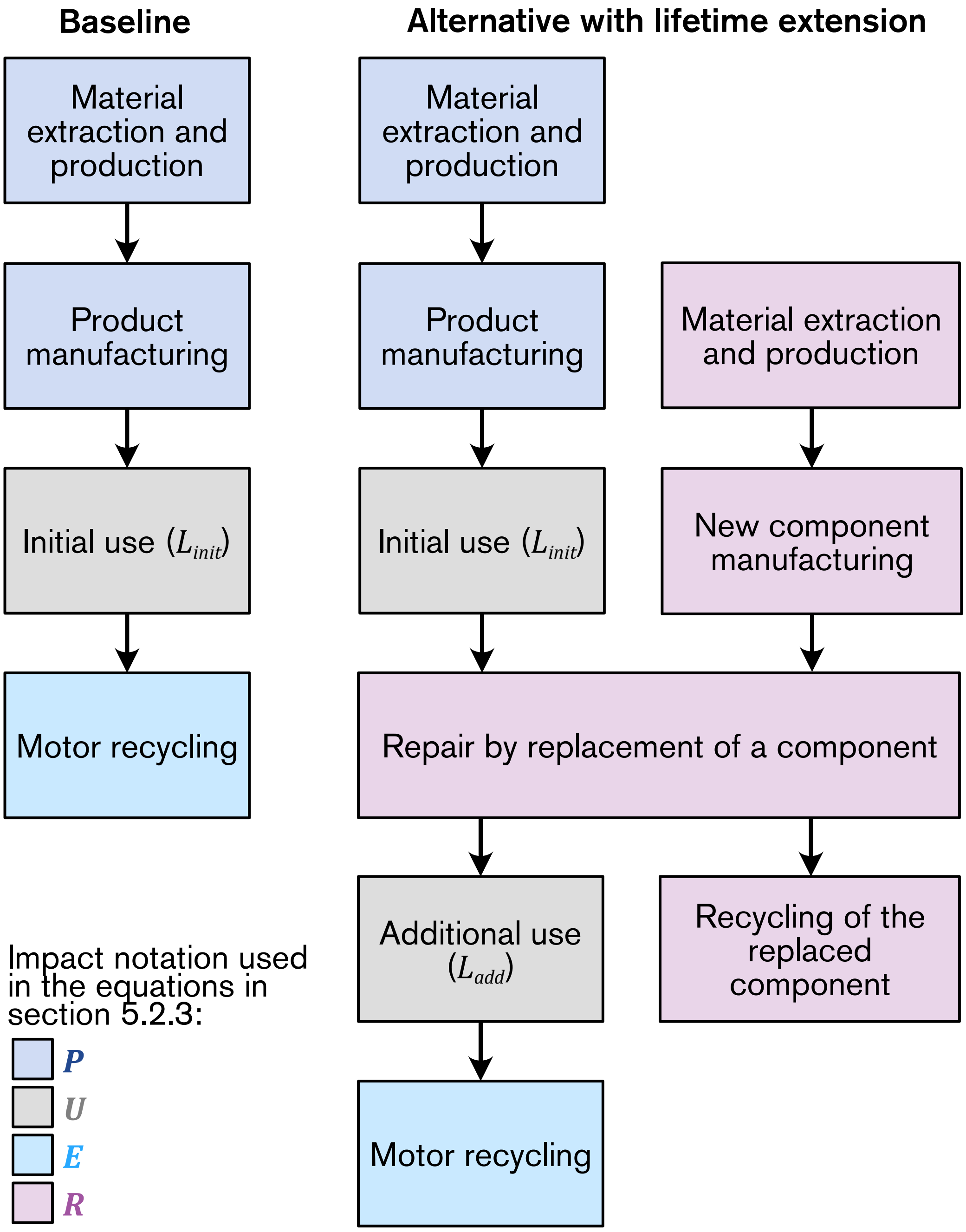

Figure 8. Flowchart of the repaired HV motor case with the notation used in the section.

Single value

One lifetime value is required for the single-value approach. If the lifetime is partitioned into an initial lifetime and an additional lifetime, a value for each is required, noted as L_{init} and L_{add} respectively. As an example, for the case of the repaired HV motor, the initial lifetime is assumed to be 20 years, as stated by the manufacturer, which is the typical minimum lifetime before a technical failure. Little information is available on the lifetime of repaired motors, so an additional lifetime of 20 years is assumed to be a reasonable additional lifetime value as the state of a repaired motor is assumed to be as good as new.

The environmental impact is calculated based on equation (2.1) (section 2.4.1) for the baseline (I_{base}) and the alternative with a lifetime extension (I_{LE}):

$$I_{base} = \frac{P + U.L_{init} + E}{L_{init}} \quad \text{and} \quad I_{LE} = \frac{P + U.L_{init} + R + U_{add}.L_{add} + E}{L_{init} + L_{add}} \quad (5.1)$$

with:

- P the impact of material extraction and production and initial product manufacturing,
- U and U_{add} the impact of the use phase per unit of lifetime during the initial and the additional lifetime, respectively,
- E the impact of the product's end-of-life treatment at the end of the lifetime,
- R the impact of the lifetime extension activity, including the production of eventual new components and treatment of old ones.

The environmental impact results are obtained as one value for the baseline and another value for the alternative with lifetime extension. These values can be subdivided into contributions of different life cycle phases. For example, the contribution from the end-of-life treatment for the baseline is E/L_{init}.

For a sensitivity analysis of how the lifetime value affects the results, alternative lifetime values are required. For the example of the HV motor, since little information is available on typical lifetime values, a low lifetime value of 1 year and a high lifetime value of 40 years are assumed for both the initial and additional lifetime. Calculations for the sensitivity analysis are using equation (5.1) with the chosen lifetime values.

The results are presented as a bar chart (example in Figure 9), each bar representing an alternative with chosen lifetime values, for an easy comparison of the environmental impact of each alternative and the contribution of different life cycle phases. Thus, several typical questions are suitable to be answered by the single-value approach:

- *What is the difference in environmental impact between a baseline and an alternative with lifetime extension for a specific lifetime value?*
- *What is the contribution of different processes or life cycle phases to the environmental impact?*
- *For which assessed lifetime values does lifetime extension reduce the environmental impact of a product?* For example, the environmental impact of a repaired motor with an initial lifetime of 20 years and an additional lifetime of 1 year (bar “repair (20+1 y.)” in Figure 9) is higher than the baseline (bar “baseline (20 y.)”). In contrast, a repaired motor with an additional lifetime of 20 years (bar “repair (20+20 y.)”) results in a lower impact than the baseline. Therefore, the results indicate that repair extending the lifetime by 1 year is not beneficial, whereas a repair extending the lifetime by 20 years is beneficial after an initial lifetime of 20 years.

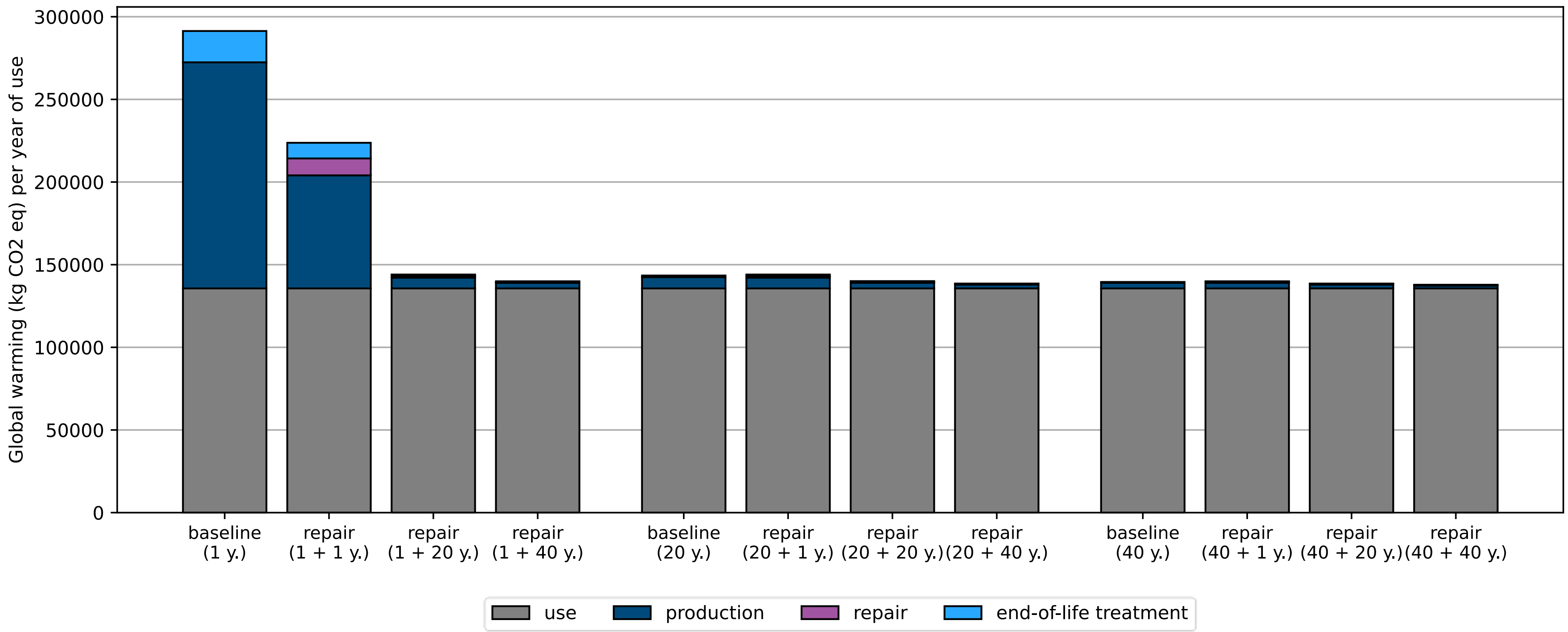

Figure 9. LCA results with the single-value approach and results from the sensitivity analysis by testing different scenarios for the repaired motor case (Paper III).

No-fixed value

No specific lifetime value is required for the no-fixed value approach. Instead, the initial and additional lifetimes are left variable. The environmental impact of each alternative is expressed as a function of the lifetime. Departing from equation (5.1) and assuming that the impact of the use phase per year of use is the same before and after repair for the HV motor, these functions are as follows:

$$I_{base}(L) = \frac{P + U.L + E}{L} \quad \text{and} \quad I_{LE}(L) = \frac{P + U.L + R + E}{L} \tag{5.2}$$

With L the total lifetime of the product, i.e., $L = L_{init}$ for the baseline and $L = L_{init} + L_{add}$ for the alternative with lifetime extension.

These LCA results expressed as functions of the lifetime can also be subdivided into contributions of the different life cycle phases. For example, the function E/L is the contribution of the end-of-life treatment for the baseline and alternative with lifetime extension.

A sensitivity analysis with a break-even analysis estimates the minimum additional lifetime value L_{break} after an initial lifetime L_{init} for which $I_{base}(L_{init}) = I_{LE}(L_{init} + L_{break})$. The latter can be simplified into (Paper IV):

$$\frac{L_{break}}{L_{init}} = \frac{R}{P + E} \tag{5.3}$$

The environmental impact and break-even value can be presented by plotting the different functions obtained in equations (5.2) and (5.3) (Figure 10). For the former, the plot presents the product lifetime on the x-axis and the environmental impact per unit of lifetime on the y-axis (Figure 10a). The range of lifetime values on the plot is first selected to be very broad, for example, between 0 and 100 years, and then refined to zoom in on the plot. For example, a range of lifetime between 0 and 40 years is sufficient for the repaired HV motor. For the break-even analysis, the plot presents the break-even value as a straight line with the initial lifetime on the x-axis and the additional lifetime on the y-axis (Figure 10b). The break-even value of the lifetime can also be identified in the figure with the evolution of the impact with the lifetime. Taking the example of the repaired HV motor after an initial lifetime of 20 years, the environmental impact for the baseline is 14 tons CO_2-eq per year of use. The same value of environmental impact for the alternative with repair corresponds to a total lifetime of 22.6 years. The break-even value for the additional lifetime is thus 2.6 years for an initial lifetime of 20 years.

Therefore, with a no-fixed approach, the following several typical questions can be answered:

- *How does the environmental impact vary with product lifetime?*
- *What is the range of lifetime values for lifetime extension to be beneficial?*
- *What is the break-even lifetime value for lifetime extension to be beneficial?*
- And if the contributions are also calculated: *What is the contribution of different activities or life cycle phases to the environmental impacts?*

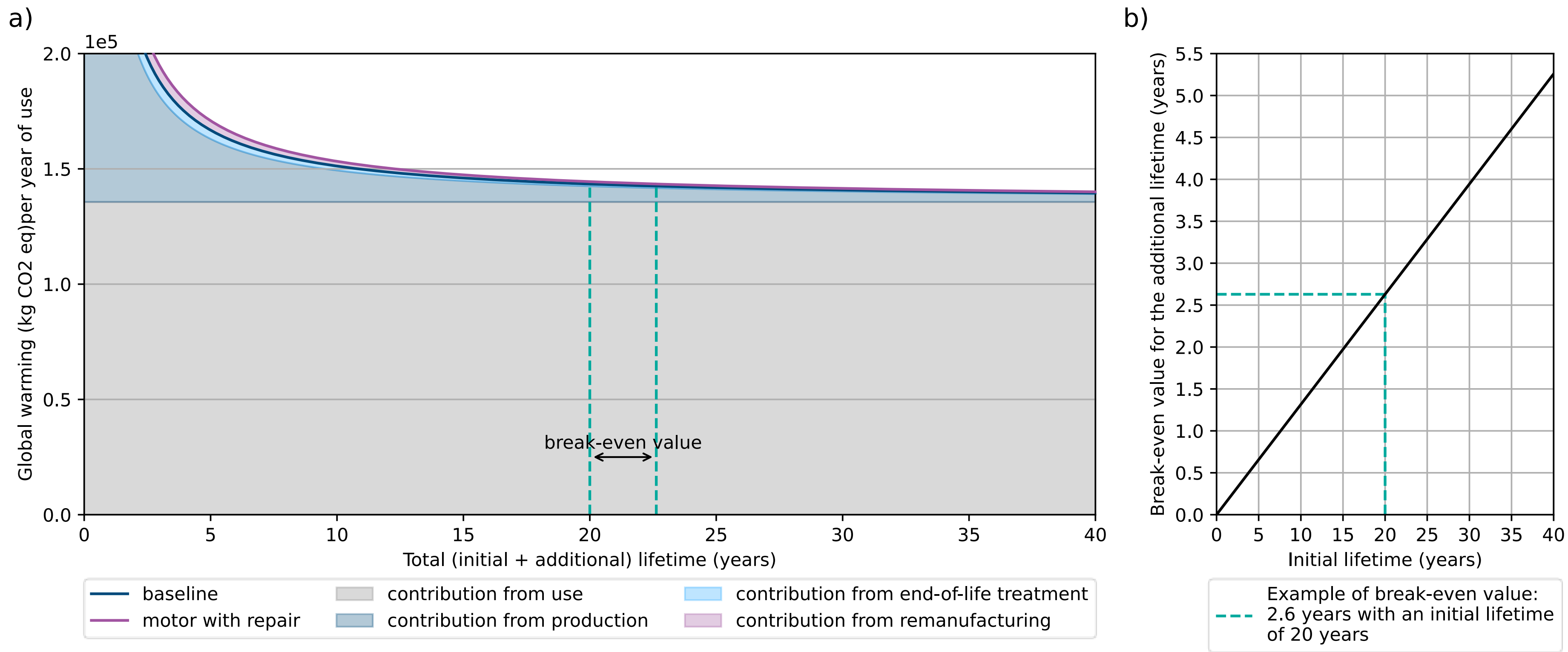

Figure 10. a) LCA results with the no-fixed value approach and b) results from the sensitivity analysis by break-even value analysis for the repaired motor case (Paper III).

Distribution

This approach requires information about how the lifetime of the product is distributed in a population of product users. In other terms, the frequency of products which reach a given lifetime value in the population is required for all possible lifetime values. The collected data can take various forms, such as parameter values for a distribution (e.g., a normal or Weibull distribution (Aktas and Bilec, 2012; Kim and Yum, 2008; Severengiz et al., 2021)) that fit the lifetime distribution, the results of a user survey in which users state the lifetime value of their last replaced product (for the remanufactured mattress case in Paper IV) or the results of a survey on failure rates at different ages (for the repaired motor case in Paper IV). The procedure to translate survey results into lifetime distributions is described in the supplementary information of Paper IV. For the repaired HV motor case, the results of a failure rate survey are used to derive the distribution for the initial lifetime. The same distribution is used for the additional lifetime, as the repaired motor is assumed to have the same technical lifetime as a new motor.

The distribution of initial and additional lifetime values is expressed as a list of possible lifetime values and their corresponding frequency in the given population. Then, the lifetime values are simulated according to the lifetime distribution for a sample of products with a generator of random numbers following the distribution. The sample size should be large enough so that the distribution of the lifetime values is correctly represented. For example, in the case of the HV motor with possible lifetime values ranging from 1 to 75 years and a mean value of 20 years (Paper IV), the generation of a sample of four motors could result in a list of lifetime values of 10, 24, 25 and 60 years which is not representative of the range of possible values and not having a mean value close to 20 years. After several trials, a sample size of 50 000 motors was judged sufficient as several sample generations resulted in similar distributions with a mean value close to 20 years. A larger sample would be possible but would unnecessarily increase the computing time. The lifetime value data is then a list of 50 000 initial and additional lifetime values representative of their distribution in a population.

For each product of the sample, the environmental impact for the baseline and alternative with lifetime extension is calculated following the equations (5.1). The LCA results are then a list of environmental impact values for each product in the sample, meaning 50 000 values for the baseline and 50 000 values for the alternative with lifetime extension for the repaired motor case (Paper IV). The mean environmental impact value in the sample can be calculated as the sum of the values divided by the sample size. The standard deviation can also be calculated with appropriate calculation tools to measure the spread of values in the sample.

The results are presented as histograms, with the environmental impact per lifetime unit as the x-axis and the number of products in the sample with this environmental impact as the y-axis (Figure 11). The histogram represents the distribution of environmental impact values in the sample of products. The results can be presented with the histograms for the baseline and the alternative with lifetime extension of the same figure to compare the distributions (Figure 11a) or as the histogram of the difference in environmental impact ($I_{LE} - I_{base}$) (Figure 11b).

The typical questions answered by the results with the distribution approach are:

- *What is the distribution of the environmental impact in a population?*
- *How does the distribution of environmental impacts change with lifetime extension?*
- *Does lifetime extension result in an environmental impact reduction on average over a population?*
- *How is the environmental impact reduction or increase distributed over a population?*

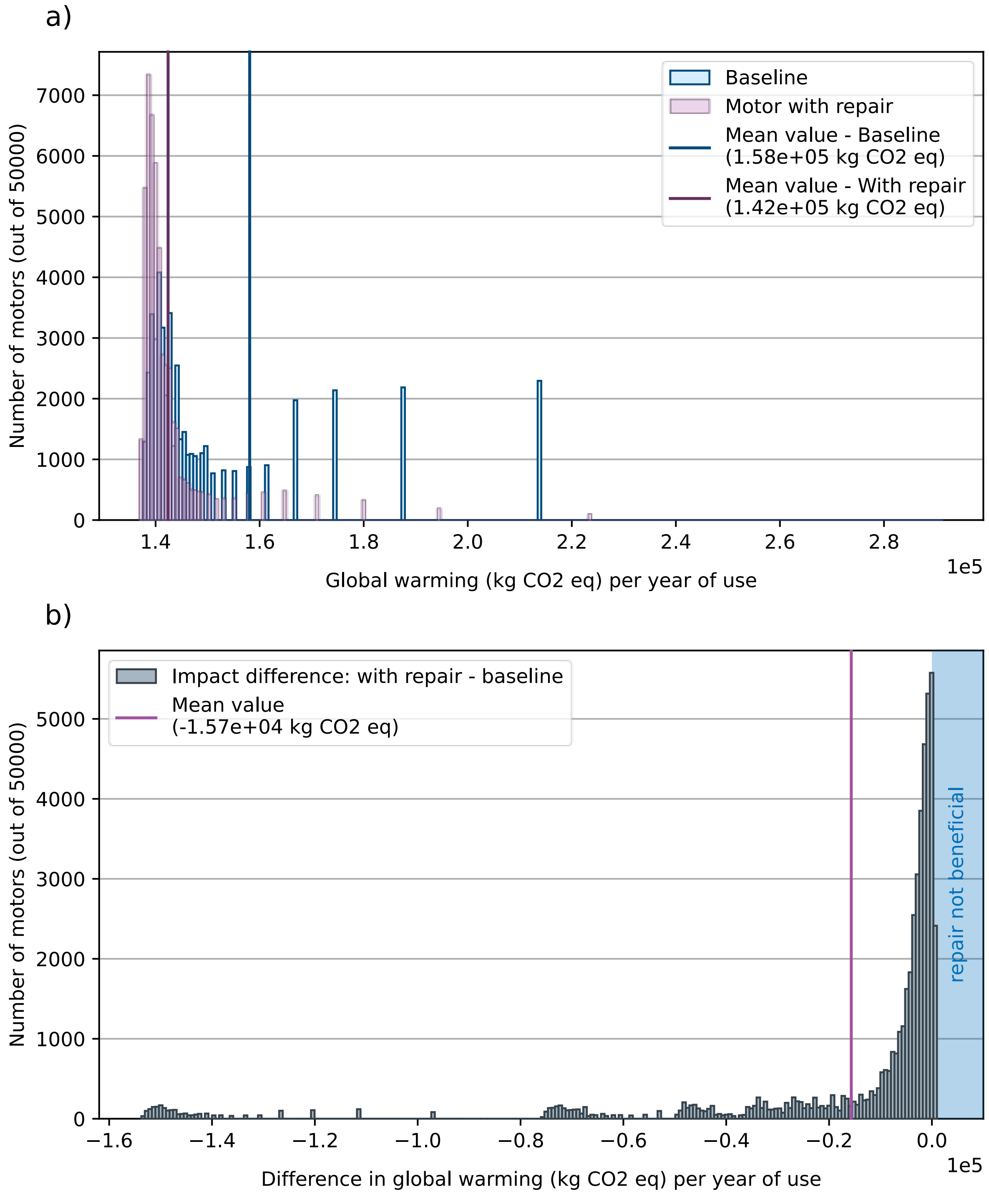

Figure 11. LCA results with the distribution approach, also used as sensitivity analysis, for the repaired motor case for global warming (Paper III) presented a) with the distribution of environmental impacts for the baseline (blue bars) and with lifetime extension (purple bars) and b) with the distribution of the relative impact, i.e., the difference of impact between the alternative with lifetime extension and the baseline.

5.2.4 **Selecting a modelling approach for integrating lifetime in equations**

The description of the three approaches for integrating lifetime in equations highlights differences that guide practitioners' decisions when selecting LCA methodology for assessing lifetime extension.

First and foremost, the results obtained with different approaches answer different typical questions. Therefore, the choice of approach can be determined by the questions to be answered, which are defined in the LCA goal. Particularly, the goal is defined based on the intended application of the assessment, which may differ between actors (Baumann and Tillman, 2004). Outside academia, these applications can be grouped under policy-making and business applications. To link the typical questions identified in section 5.3.2 to concrete examples of LCA applications, Table 4 provides examples of policy-making and business applications for each typical question and the corresponding approaches to integrate lifetime in equations.

Another aspect that might be decisive in selecting a suitable approach is the lifetime data requirements. Each approach requires different data, some more challenging to acquire. For products with little data on actual practices, compromises between the lifetime data collection required for the goal of the LCA and time constraints might have to be made. Ideally, the goal and scope of the LCA would decide the approach, but if efforts on lifetime data collection are not possible, the goal of the LCA might have to be changed so that approaches with available lifetime data are used instead.

Finally, the no-fixed value and distribution approaches yield figures that are richer in information than the bar charts obtained with a single-value approach. The former displays the evolution of the environmental impact with the lifetime, and the latter displays the distribution of environmental impact values from which a mean value and spread of values can be analysed. The audience of the LCA, identified in the goal and scope definition, might not be used to analyse rich data representations. Therefore, the single-value approach might be preferred and can, in such cases, be used in combination with another approach. For example, for presenting the results from the repaired HV motor case in Paper II, the no-fixed value approach is used to display the range of validity of the results and the single-value approach is used with lifetime values taken as examples to support the interpretation of results.

To summarise, a precise goal and scope definition, including the questions to be answered and the intended audience, is a crucial point of departure for selecting a lifetime modelling approach.

Table 4. Examples of LCA applications with their corresponding typical question and related approach for integrating lifetime in equations.

Examples of LCA applications in policy-making and business	Typical question	Suitable approach
Communication of the benefits of lifetime extension Communication to citizens Market communication	What is the difference in environmental impact between a baseline and an alternative with lifetime extension for a specific lifetime value?	Single value
Identification of hotspots Prioritisation of policy measures Prioritisation of changes in product design	What is the contribution of different processes or life cycle phases to the environmental impacts?	Single value (No-fixed value also possible)
Evaluation of alternatives Evaluation of policy measures Evaluation of business offers	For which assessed lifetime values does lifetime extension reduce the environmental impact of a product?	Single value and No-fixed value
Learning about the relationship between lifetime and environmental performance Support to design policy measures Support for design considerations of product durability	How does the environmental impact vary with respect to product lifetime?	No-fixed value
Identification of a range of lifetime values for which lifetime extension is beneficial Support for developing policy measures Support for developing business offers	What is the range of lifetime values for lifetime extension to be beneficial?	No-fixed value

Identification of minimum lifetime requirements Identification of a value to be used in reporting/ labels/ declarations Identification of appropriate variables of a business offer	What is the break-even additional lifetime value for lifetime extension to be beneficial?	No-fixed value
Analysis of a user population Identification of hotspots in a population for prioritisation of policy measures Identification of differences in environmental impact across users	What is the distribution of the environmental impact for a population?	Distribution
Evaluation of alternatives over a population Evaluation of policy measures in a given population Evaluation of offerings targeting user groups to get the most significant gains for the product portfolio	How does the distribution change with lifetime extension?	Distribution
Evaluate whether lifetime extension is beneficial over a population Evaluation of policy measures in a given population Evaluation of offerings on the entire targeted user base	Does lifetime extension result in an environmental impact reduction on average over a population?	Distribution
Identification of population groups for which lifetime extension results in high/low/no environmental benefits Identification of unexpected impact from a policy measure in a given population Identification of unexpected impact from an offering to the user base	How is the environmental impact reduction or increase distributed over a population?	Distribution

6 Discussion

The work presented in this dissertation focuses on the environmental assessment of lifetime extension strategies. It clarifies the differences between two existing assessment methods, i.e., CE indicators and LCA, and defines LCA methodological choices related to product lifetime modelling. Both have implications for assessment practices. The results contribute to the body of knowledge on the environmental assessment of CE strategies. The focus on lifetime extension strategies allows the consideration of challenges specific to a sub-group of CE strategies, such as the importance of including the resources used during the use phase or the crucial role of product lifetime in the assessment results.

The most surprising observation in this work is perhaps the gap between the importance given to, on the one hand, lifetime extension in definitions of CE and in incoming public policies and, on the other hand, the limited attention to lifetime extension in CE indicators (section 5.1.1) and product lifetime modelling reporting observed in LCAs (section 5.2.2). In assessments, the predominant concern seems to be the closing of material loops. A majority of CE indicators have material recycling in focus (Kristensen and Mosgaard, 2020; Moraga et al., 2019) (Paper I) and major discussions on LCA methodology are related to accounting for material quality degradation generated by recycling (Hellweg et al., 2023) and the handling of multi-functionality (e.g., generation of biogas with composting or of energy with incineration) with different allocation methods (Schrijvers et al., 2016). Numerous LCAs of lifetime extension have been published, but a more general analysis of methodology for lifetime extension does not seem to receive the same level of scrutiny, highlighting a critical area for future research and developments.

For the choice of LCA methodology, the results provide definitions of product lifetime in the context of LCA, consolidate LCA methodology with a more structured way to model product lifetime and clarify the differences in information provided by different lifetime modelling approaches. Overall, it contributes to clarifying methodological requirements for assessing lifetime extension with LCA, focusing on product lifetime. In their letter to the editor, Cottafava et al. (2024)

urge clear methodological requirements for the reliability and comparability of LCA studies comparing single-use and reusable packaging. They suggest systematic break-even analysis and transparent reporting of key variables, including the return rate for reuse and the packaging lifetime. It shows the relevance of the methodological considerations presented in this dissertation, insisting on the clear reporting of lifetime modelling and the consideration of sensitivity analysis for product lifetime, and calls for similar clarifications for other key variables. Moreover, the methodological considerations also support the call for a better consideration of obsolescence in LCA from Richter et al. (2024), with the reporting of types of obsolescence being highlighted as an essential part of the product lifetime definition in the assessment of lifetime extension.

6.1 **Assessment method for lifetime extension**

Three main differences between CE indicators and LCA for assessing lifetime extension have been identified in the present research.

1. The type of information provided is different. LCA assesses environmental impacts, while CE indicators capture changes in resource flows. It has been argued that some material footprint indicators can be used as a proxy for estimating some environmental impacts (e.g., damages to biodiversity and human health (Steinmann et al., 2017)). However, no such correlation is observed between the results from CE indicators and LCA on the cases in Paper I, even if the addressed environmental impact categories were different to biodiversity and human health impacts. Therefore, LCA is better suited for assessing environmental impacts and CE indicators for changes in material flows, such as the mass ratio of reusable components in the product.

2. The assessment method influences the possible coverage of the parts of the product system. With LCA, the system boundaries are decided by the practitioner based on the goal of the study. With CE indicators, the system boundaries are decided by their definition and vary between indicators (Paper I). A set of indicators with different coverages is then required to ensure that all necessary flows and processes are accounted for. This conclusion from Paper I confirms recommendations from previous CE indicators reviews on using a set of indicators instead of a single indicator to cover a wide range of aspects and strategies (Corona et al., 2019; Moraga et al., 2019; Parchomenko et al., 2019; Saidani et al., 2019). However, material and energy flows in the use phase, maintenance and repurposing are not accounted for by any of the reviewed CE indicators. The former is important for the resource performance of the lifetime extension of energy-using products, and the latter for cases of maintenance and repurposing. Therefore, it becomes clear from the present research that not all flows and processes can be accounted for by one of the existing CE indicators. More generally, this observation highlights that knowing what is included and what is left out of the assessment is essential when choosing a method.

3. Changes in absolute mass and total lifetime are not necessarily visible with CE indicators. The former is essential when comparing alternatives with different product designs, while the latter is crucial when comparing alternatives with varying lifetimes. Among the reviewed CE indicators, only the RNL indicator makes visible changes in product mass, as the functional unit is the basis of comparison. Additionally, six out of 36 indicators account for changes in the lifetime value.

The three differences highlighted above all point to the need to clarify the goal and system boundaries of CE indicators and LCA by adding a level of detail essential for selecting an assessment method. Between CE indicators and LCA, previously identified differences in goal and scope were related to the number of pillars of sustainable development (environmental, economic and social development) addressed by the methods (Corona et al., 2019), while Paper I identifies a difference in the types of impact assessed. Between CE indicators, differences in the life cycle phases addressed (Helander et al., 2019), CE strategies in focus (Kristensen and Mosgaard, 2020; Saidani et al., 2019) and intended use of the results (e.g., communication, decision-making, learning) (Saidani et al., 2019) were mapped, while Paper I adds more granularity to differences in scope by mapping accounted flows and processes. The latter was essential to identifying shortcomings of reviewed CE indicators for assessing lifetime extension, such as the absence of indicators accounting for maintenance, repurposing or resources in the use phase.

The choice of research method in Paper I influenced the level of detail of the analysis of CE indicators and comparison with LCA. When applying indicators to cases, one must understand the specific flows and processes accounted for to collect the necessary data. Moreover, the identified difference in types of impact comes from the interpretation of results from the two methods. This supports the importance of testing and comparing assessment methods to understand them (Meadows, 1998).

6.2 Lifetime modelling and methodology for LCA of lifetime extension

Product lifetime in LCA previously received attention as regards the difficulty in quantifying its value (Günther and Langowski, 1997) and for the large influence of lifetime values on the LCA results of buildings (Goulouti et al., 2020; Grant and Ries, 2013). For the latter, statistical models (Morales et al., 2021; Silvestre et al., 2015) and datasets (Aktas and Bilec, 2012; Goulouti et al., 2020) based on real lifetime data have been developed to overcome the limited availability of lifetime data values and variability. It signals that more accurate data accounting for variability is an advancement in LCA methodology, echoing the title of the SETAC Europe 26th LCA symposium: "Making LCA Meaningful: Good Data, Better Models, Sustainable Decisions".

However, the results from the present research provide lifetime modelling approaches with low data requirements and emphasise the difference in typical questions answered by different approaches. More complexity in the LCA model reflecting the reality does not necessarily increase the quality of the decision support aimed by the assessment. Instead, the LCA goal directs the choice of lifetime modelling approach to be used and, therefore, the data collection.

The typical way of modelling the lifetime as a single value is not adequate for all studies, as much as striving for more extensive lifetime data collection is not always necessary. This observation further stresses the importance of the goal and scope definition step for methodological choices in LCA. However, the LCA goal is often poorly stated in LCA studies (Nordelöf et al., 2014; Nyqvist, 2024; Roßmann et al., 2021), justifying an emphasis on the role of goal definition in guiding methodological decisions and on the precise and transparent reporting of every LCA methodological step.

7 Limitations and implications

7.1 Limitations

The work presented in this dissertation aims to support the development of guidance for assessment practices of lifetime extension. To do so, it analysed existing CE indicator methodologies and LCA modelling practices based on published academic studies. This choice of research method is helpful for clarifying existing methodological aspects, but it limits the analysis to what has been done instead of what could be done. For example, the work departs from the analysis of different lifetime modelling approaches for suggesting possible LCA applications in section 5.4, but the list of applications is not exhaustive. Alternatively, departing from the assessment needs of different practitioners to later develop lifetime modelling approaches that provide suitable information would ensure comprehensive coverage of assessment practices, which methodological guidelines would then need to consider. Similarly, the conclusions on the choice of assessment method are based on the analysis of existing CE indicators and not the potential that CE indicators could have after further developments. Therefore, other conclusions might be drawn in future studies.

Additionally, the work is centred on assessment methodology and does not include the perspective of other assessment practitioners than the academic contributors to this research. The conclusions have not been tested in practice outside of this work and, therefore, do not consider other practical challenges that may be faced or the reality of assessment practices in other contexts. For example, the goal might be defined iteratively during the assessment and expecting a clear goal definition when selecting an assessment method might be less realistic in such studies. Additionally, the challenge of obtaining relevant lifetime data is not addressed in this work, and only an adaptation of the assessment goal to data availability is suggested. As reliable data on product lifetimes are hardly available because of, for example, high variations across geographical locations, time or user groups (Cooper, 2010), the data availability challenge needs to be further addressed for practical recommendations to practitioners.

Finally, for the selection of assessment methods, the work focuses on two assessment methods, indicators and LCA, although other ESA methods have been used to assess CE and lifetime extension, such as MFA or input-output analysis (Harris et al., 2021; Roos Lindgreen et al., 2022; Sassanelli et al., 2019). The conclusions are, therefore, limited in the range of assessment goals that environmental assessments can cover. Extending the work to other methods would allow a more comprehensive overview of possibilities and limitations when selecting an assessment method.

7.2 **Further research**

As mentioned in the discussion, this research highlights the analysis of assessment methodology for lifetime extension as a critical area for future research and development.

Specifically, further research is required to develop concrete methodological guidelines for the environmental impacts of lifetime extension. Integrating the perspective of assessment practitioners to understand assessment needs in different contexts (e.g., academia, businesses or policy-making) and challenges specific to lifetime extension strategies would ensure the relevance and practicability of these recommendations. For example, testing the lifetime modelling framework for the actual assessment needs of different practitioners would increase its feasibility in different contexts.

Another avenue for research would be to widen the scope of the research presented in this dissertation. The comparison of assessment methods by testing them on cases could be extended to methods other than CE indicators and LCA, such as MFA. This would provide a better understanding of how CE indicators compare to other assessment methods. The comparison could be made with a higher level of detail by testing the methods on cases rather than analysing method descriptions, as was done in previous method reviews (e.g., in Walzberg et al. (2021) or Corona et al. (2019)). For example, this research highlights differences in the visibility of changes in absolute product mass in the assessment results that would be difficult to identify by analysing the method descriptions. For LCA methodology, this work focused on product lifetime modelling, but other requirements might be necessary for the assessment to provide relevant information for decision-making. For example, international standards do not provide any specific requirements about including a lifetime unit in the functional unit (ISO, 2006a, 2006b), although it is necessary when comparing alternatives with different total lifetimes, such as when assessing lifetime extension (section 5.2.1).

Finally, the results point to ideas for further development of CE indicators and LCA methodology. Several shortcomings have been identified for CE indicators, such as the choice of a product as the basis of comparison instead of the product function or the lack of indicators accounting for resource flows in the use phase, maintenance or repurposing. These can be the point of departure for developing new CE indicators or improving existing ones. Moreover, the presented framework to model product lifetime in LCAs of lifetime extension comes from the analysis of existing studies. Thus, the framework can be developed by analysing other LCA studies than cases of lifetime extension or other assessments of lifetime extension.

7.3 **Implications for assessment practitioners**

Even though a broad panel of practitioners has not validated the practicability of the conclusions presented in this dissertation, several points can serve as guidance for future assessments of lifetime extension.

The assessment goal has a central role in the choice of assessment method and LCA methodology. Therefore, a clear definition of this goal is essential to be developed to guide the choice of, e.g., CE indicators and product lifetime modelling in LCA.

Additionally, one should be mindful of the flows and processes in the product system to be included in the assessment when defining the scope of the study to avoid missing significant changes from lifetime extension. It guides the selection of CE indicators as they account for different flows and processes. Additionally, resource flows in the use phase, and processes for maintenance and repurposing are not accounted for by any of the reviewed indicators in Paper I. When studying the lifetime extension of energy-using products and cases of maintenance and repurposing, these flows and processes can be included by complementing the assessment with another assessment method, additional indicators or new indicators.

For LCAs of lifetime extension, precise and complete reporting of lifetime modelling would ensure a transparent interpretation of assessment results. In the reviewed LCAs of lifetime extension, an unprecise and incomplete reporting of product lifetime modelling limits the interpretation and reproducibility of LCA results (section 5.2.2). The lifetime modelling framework (section 4.3) acts as a reminder of the different steps to be reported and the different options to choose from. It also defines a terminology that supports a more precise reporting of lifetime modelling.

Moreover, when defining the functional unit for the LCA, a time unit is necessary when comparing alternatives with different total lifetimes, such as when assessing lifetime extension (section 5.2.1).

8 Conclusions

Assessing the environmental benefits of product lifetime extension is crucial to guide the choice and implementation of these strategies. However, little guidance exists for assessment practitioners on how to assess lifetime extension. This research develops knowledge about environmental systems analysis methodology for lifetime extension. It highlights methodological considerations on the selection of assessment method, namely between LCA and CE indicators, and LCA methodology to deliver decision support on lifetime extension in line with the goal of the assessment.

Selecting LCA or CE indicators depends on the desired type of assessment results. CE indicators provide information on changes in resource flows and LCA information on environmental impacts. Additionally, selecting the method also influences the scope of the system for the assessment. In LCA, the system boundaries are defined by the assessment practitioner. With CE indicators, the flows and processes accounted for are decided by the indicator definition. Therefore, sufficient coverage of the system to capture changes from lifetime extension needs to be reflected upon during the assessment method selection. Specifically, existing CE indicators do not account for material or energy use in the use phase, maintenance, and repurposing, although they are important flows and processes in some cases of lifetime extension. They need to be accounted for with other assessment methods when necessary.

LCA results of lifetime extension are strongly influenced by the product lifetime, but the methodology related to how the lifetime is defined and modelled in the calculations has not yet been described and structured. This is reflected in the imprecise and incomplete product lifetime modelling reporting practices in LCAs. This reserach suggests a framework to model product lifetime in three steps: 1) the lifetime definition, 2) integration in equations, and 3) sensitivity analysis. The framework also points to essential information to be reported in each step for a transparent methodology and interpretation of results, such as whether the full technical lifetime and periods of idleness are included in the lifetime, the reasons for obsolescence and the data sources for lifetime data.

In particular, three approaches to represent lifetime in equations are identified from existing practices: with a single value, no fixed value (i.e., left variable) or distribution over a population. Different approaches are required for the LCA to answer different questions. Therefore, the goal of the LCA influences how lifetime is modelled.

Lifetime extension has received less attention than other CE strategies, such as recycling, on specific methodological challenges and requirements when assessing environmental impacts. Lifetime extension strategies are under-represented in the strategies that CE indicators focus on, and no general recommendations for LCA methodology to assess lifetime extension are available. The work presented in this dissertation is a first step towards more informed methods and methodological choices to assess lifetime extension. It makes sense of existing practices with a clear description and structure to guide these choices and opens the door to further research to develop assessment methodologies and methodological recommendations. These recommendations are intended to foster assessment practices that support decision-making in implementing efficient strategies to reduce the environmental impacts of products.

References

Abagnato, S., Rigamonti, L., Grosso, M., 2024. Life cycle assessment applications to reuse, recycling and circular practices for textiles: A review. Waste Management 182, 74–90. https://doi.org/10.1016/j.wasman.2024.04.016

Aktas, C.B., Bilec, M.M., 2012. Impact of lifetime on US residential building LCA results. Int J Life Cycle Assess 17, 337–349. https://doi.org/10.1007/s11367-011-0363-x

Alcalde-Calonge, A., Sáez-Martínez, F.J., Ruiz-Palomino, P., 2022. Evolution of research on circular economy and related trends and topics. A thirteen-year review. Ecological Informatics 70, 101716. https://doi.org/10.1016/j.ecoinf.2022.101716

André, H., Ljunggren Söderman, M., Nordelöf, A., 2019. Resource and environmental impacts of using second-hand laptop computers: A case study of commercial reuse. Waste Management 88, 268–279. https://doi.org/10.1016/j.wasman.2019.03.050

Ardente, F., Mathieux, F., 2014. Environmental assessment of the durability of energy-using products: method and application. Journal of Cleaner Production 74, 62–73. https://doi.org/10.1016/j.jclepro.2014.03.049

Arksey, H., O'Malley, L., 2005. Scoping studies: towards a methodological framework. International Journal of Social Research Methodology 8, 19–32. https://doi.org/10.1080/1364557032000119616

Bakker, C., Wang, F., Huisman, J., den Hollander, M., 2014. Products that go round: exploring product life extension through design. Journal of Cleaner Production 69, 10–16. https://doi.org/10.1016/j.jclepro.2014.01.028

Bakkes, J.A., van den Born, G.J., Helder, J.C., Swart, R.J., Hope, C.W., Parker, J.D.E., 1994. An Overview of Environmental Indicators: State of the art and perspectives (No. RIVM Rapport 402001001), Environment Assessment Technical Reports. Rijksinstituut voor Volksgezondheid en Milieu RIVM.

Baumann, H., Tillman, A., 2004. The hitch hiker's guide to LCA : an orientation in life cycle assessment methodology and application. Studentlitteratur, Lund, Sweden.

Baumann, H., Tillman, A.-M., Molander, S., 1999. Det specifika med miljösystemanalysen. Chalmers University of Technology.

Björklund, A.E., 2002. Survey of approaches to improve reliability in LCA. Int J LCA 7, 64–72. https://doi.org/10.1007/BF02978849

Blomsma, F., Brennan, G., 2017. The Emergence of Circular Economy: A New Framing Around Prolonging Resource Productivity. Journal of Industrial Ecology 21, 603–614. https://doi.org/10.1111/jiec.12603

Bobba, S., Mathieux, F., Ardente, F., Blengini, G.A., Cusenza, M.A., Podias, A., Pfrang, A., 2018. Life Cycle Assessment of repurposed electric vehicle batteries: an adapted method based on modelling energy flows. Journal of Energy Storage 19, 213–225. https://doi.org/10.1016/j.est.2018.07.008

Bocken, N.M.P., de Pauw, I., Bakker, C., van der Grinten, B., 2016. Product design and business model strategies for a circular economy. Journal of Industrial and Production Engineering 33, 308–320. https://doi.org/10.1080/21681015.2016.1172124

Böckin, D., Tillman, A.-M., 2019. Environmental assessment of additive manufacturing in the automotive industry. Journal of Cleaner Production 226, 977–987. https://doi.org/10.1016/j.jclepro.2019.04.086

Böckin, D., Willskytt, S., André, H., Tillman, A.-M., Ljunggren Söderman, M., 2020. How product characteristics can guide measures for resource efficiency — A synthesis of assessment studies. Resources, Conservation and Recycling 154, 104582. https://doi.org/10.1016/j.resconrec.2019.104582

Bovea, M.D., Ibáñez-Forés, V., Pérez-Belis, V., 2020. Repair vs. replacement: Selection of the best end-of-life scenario for small household electric and electronic equipment based on life cycle assessment. Journal of Environmental Management 254, 109679. https://doi.org/10.1016/j.jenvman.2019.109679

Bracquené, E., Dewulf, W., Duflou, J.R., 2020. Measuring the performance of more circular complex product supply chains. Resources, Conservation and Recycling 154, 104608. https://doi.org/10.1016/j.resconrec.2019.104608

Bressanelli, G., Saccani, N., Perona, M., 2022. Investigating Business Potential and Users' Acceptance of Circular Economy: A Survey and an Evaluation Model. Sustainability 14, 609. https://doi.org/10.3390/su14020609

Cooper, T., 2010. The Significance of Product Longevity, in: Longer Lasting Products. Routledge.

Corona, B., Shen, L., Reike, D., Rosales Carreón, J., Worrell, E., 2019. Towards sustainable development through the circular economy—A review and critical assessment on current circularity metrics. Resources, Conservation and Recycling 151, 104498. https://doi.org/10.1016/j.resconrec.2019.104498

Cottafava, D., Brussa, G., Cavenago, G., Cespi, D., Rigamonti, L., Bala, A., Beigbeder, J., Refalo, P., Sazdovski, I., 2024. Requirements for comparative life cycle assessment studies for single-use and reusable packaging and products: recommendation for decision and policy-makers. Int J Life Cycle Assess 29, 909–911. https://doi.org/10.1007/s11367-024-02291-0

Cradle to Cradle Products Innovation Institute, 2016. Cradle to Cradle Certified: Product Standard version 3.1.

Creswell, J.W., 2018. Research design : qualitative, quantitative, and mixed methods approaches / John W. Creswell, PhD, Department of Family Medicine, University of Michigan, and J. David Creswell, PhD, Department of Psychology, Carnegie Mellon University.

Crowe, S., Cresswell, K., Robertson, A., Huby, G., Avery, A., Sheikh, A., 2011. The case study approach. BMC Medical Research Methodology 11, 100. https://doi.org/10.1186/1471-2288-11-100

Dara, C., Hachem-Vermette, C., Assefa, G., 2019. Life cycle assessment and life cycle costing of container-based single-family housing in Canada: A case study. Building and Environment 163, 106332. https://doi.org/10.1016/j.buildenv.2019.106332

De Pascale, A., Arbolino, R., Szopik-Depczyńska, K., Limosani, M., Ioppolo, G., 2021. A systematic review for measuring circular economy: The 61 indicators. Journal of Cleaner Production 281, 124942. https://doi.org/10.1016/j.jclepro.2020.124942

De Saxce, M., Pesnel, S., Perwuelz, A., 2012. LCA of bed sheets – some relevant parameters for lifetime assessment. Journal of Cleaner Production 37, 221–228. https://doi.org/10.1016/j.jclepro.2012.07.012

Decorte, Y., Van Den Bossche, N., Steeman, M., 2023. Guidelines for defining the reference study period and system boundaries in comparative LCA of building renovation and reconstruction. Int J Life Cycle Assess 28, 111–130. https://doi.org/10.1007/s11367-022-02114-0

den Hollander, M.C., Bakker, C.A., Hultink, E.J., 2017. Product Design in a Circular Economy: Development of a Typology of Key Concepts and Terms. Journal of Industrial Ecology 21, 517–525. https://doi.org/10.1111/jiec.12610

Diener, D., 2017. Scrap happens, but does it have to? On the potential of increasing machine component reuse. Chalmers University of Technology.

Dunn, J., Ritter, K., Velázquez, J.M., Kendall, A., 2023. Should high-cobalt EV batteries be repurposed? Using LCA to assess the impact of technological innovation on the waste hierarchy. Journal of Industrial Ecology 27, 1277–1290. https://doi.org/10.1111/jiec.13414

Elia, V., Gnoni, M.G., Tornese, F., 2017. Measuring circular economy strategies through index methods: A critical analysis. Journal of Cleaner Production 142, 2741–2751. https://doi.org/10.1016/j.jclepro.2016.10.196

Ellen MacArthur Foundation, 2019. Circularity indicators - an approach to measuring circularity.

European Commission, 2024a. Regulation (EU) 2024/1781 of the European Parliament and of the Council of 13 June 2024 establishing a framework for the setting of ecodesign requirements for sustainable products, amending Directive (EU) 2020/1828 and Regulation (EU) 2023/1542 and repealing Directive 2009/125/EC (Text with EEA relevance).

European Commission, 2024b. Directive (EU) 2024/1799 of the European Parliament and of the Council of 13 June 2024 on common rules promoting the repair of goods and amending Regulation (EU) 2017/2394 and Directives (EU) 2019/771 and (EU) 2020/1828 (Text with EEA relevance).

European Commission, 2023. Measuring progress towards circular economy in the European Union – Key indicators for a revised monitoring framework.

European Commission, 2020. A new Circular Economy Action Plan For a cleaner and more competitive Europe.
European Commission, 2008. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (Text with EEA relevance).
Figge, F., Thorpe, A.S., Givry, P., Canning, L., Franklin-Johnson, E., 2018. Longevity and Circularity as Indicators of Eco-Efficient Resource Use in the Circular Economy. Ecological Economics 150, 297–306. https://doi.org/10.1016/j.ecolecon.2018.04.030
Finnveden, G., Moberg, Å., 2005. Environmental systems analysis tools – an overview. Journal of Cleaner Production 13, 1165–1173. https://doi.org/10.1016/j.jclepro.2004.06.004
Gallopín, G.C., 1996. Environmental and sustainability indicators and the concept of situational indicators. A systems approach. Environ Model Assess 1, 101–117. https://doi.org/10.1007/BF01874899
Glew, D., Stringer, L.C., Acquaye, A.A., McQueen-Mason, S., 2012. How do end of life scenarios influence the environmental impact of product supply chains? comparing biomaterial and petrochemical products. Journal of Cleaner Production 29–30, 122–131. https://doi.org/10.1016/j.jclepro.2012.02.005
Goulouti, K., Padey, P., Galimshina, A., Habert, G., Lasvaux, S., 2020. Uncertainty of building elements' service lives in building LCA & LCC: What matters? Building and Environment 183, 106904. https://doi.org/10.1016/j.buildenv.2020.106904
Grant, A., Ries, R., 2013. Impact of building service life models on life cycle assessment. Building Research & Information 41, 168–186. https://doi.org/10.1080/09613218.2012.730735
Grant, M.J., Booth, A., 2009. A typology of reviews: an analysis of 14 review types and associated methodologies. Health Information & Libraries Journal 26, 91–108. https://doi.org/10.1111/j.1471-1842.2009.00848.x
Günther, A., Langowski, H.-C., 1997. Life cycle assessment study on resilient floor coverings. Int. J. LCA 2, 73–80. https://doi.org/10.1007/BF02978763
Harris, S., Martin, M., Diener, D., 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
Helander, H., Petit-Boix, A., Leipold, S., Bringezu, S., 2019. How to monitor environmental pressures of a circular economy: An assessment of indicators. Journal of Industrial Ecology 23, 1278–1291. https://doi.org/10.1111/jiec.12924
Hellweg, S., Benetto, E., Huijbregts, M.A.J., Verones, F., Wood, R., 2023. Life-cycle assessment to guide solutions for the triple planetary crisis. Nat Rev Earth Environ 4, 471–486. https://doi.org/10.1038/s43017-023-00449-2

Hummen, T., Desing, H., 2021. When to replace products with which (circular) strategy? An optimization approach and lifespan indicator. Resources, Conservation and Recycling 174, 105704. https://doi.org/10.1016/j.resconrec.2021.105704

Igos, E., Benetto, E., Meyer, R., Baustert, P., Othoniel, B., 2019. How to treat uncertainties in life cycle assessment studies? Int J Life Cycle Assess 24, 794–807. https://doi.org/10.1007/s11367-018-1477-1

IRP, 2019. Global Resources Outlook 2019: Natural Resources for the Future We Want. A Report of the International Resource Panel. United Nations Environment Programme., Nairobi, Kenya.

ISO, 2006a. ISO 14040:2006 Environmental management – Life cycle assessment – Principles and framework.

ISO, 2006b. ISO 14044:2006 Environmental management – Life cycle assessment – Requirements and guidelines.

Jerome, A., 2022. Repair or replace? Guidance from indicators and life cycle assessment on circular economy strategies for energy-using products. Chalmers University of Technology.

Kaddoura, M., Kambanou, M.L., Tillman, A.-M., Sakao, T., 2019. Is Prolonging the Lifetime of Passive Durable Products a Low-Hanging Fruit of a Circular Economy? A Multiple Case Study. Sustainability 11, 4819. https://doi.org/10.3390/su11184819

Kim, J.S., Yum, B.-J., 2008. Selection between Weibull and lognormal distributions: A comparative simulation study. Computational Statistics & Data Analysis 53, 477–485. https://doi.org/10.1016/j.csda.2008.08.012

Kirchherr, J., Yang, N.-H.N., Schulze-Spüntrup, F., Heerink, M.J., Hartley, K., 2023. Conceptualizing the Circular Economy (Revisited): An Analysis of 221 Definitions. Resources, Conservation and Recycling 194, 107001. https://doi.org/10.1016/j.resconrec.2023.107001

Koroma, M.S., Costa, D., Philippot, M., Cardellini, G., Hosen, M.S., Coosemans, T., Messagie, M., 2022. Life cycle assessment of battery electric vehicles: Implications of future electricity mix and different battery end-of-life management. Science of The Total Environment 831, 154859. https://doi.org/10.1016/j.scitotenv.2022.154859

Kristensen, H.S., Mosgaard, M.A., 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

Krych, K., Pettersen, J.B., 2025. Long-term lifetime trends of large appliances since the introduction in Norwegian households. Journal of Industrial Ecology n/a. https://doi.org/10.1111/jiec.13608

Lanoë, T., Simões, C.L., Simoes, R., 2013. Improving the environmental performance of bedding products by using life cycle assessment at the design stage. Journal of Cleaner Production 52, 155–164. https://doi.org/10.1016/j.jclepro.2013.03.013

Linder, M., 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, 121096. https://doi.org/10.1016/j.jclepro.2020.121096

Ljunggren Söderman, M., André, H., 2019. Effects of circular measures on scarce metals in complex products – Case studies of electrical and electronic equipment. Resources, Conservation and Recycling 151, 104464. https://doi.org/10.1016/j.resconrec.2019.104464

Lonca, G., Muggéo, R., Imbeault-Tétreault, H., Bernard, S., Margni, M., 2018. Does material circularity rhyme with environmental efficiency? Case studies on used tires. Journal of Cleaner Production 183, 424–435. https://doi.org/10.1016/j.jclepro.2018.02.108

Lundin, M., 2003. Indicators for Measuring the Sustainability of Urban Water Systems - A Life Cycle Approach. Chalmers University of Technology, Gothenburg, Sweden.

Lundqvist, U., 2000. On Sustainability Indicators and Sustainable Product Development. Chalmers University of Technology, Gothenburg, Sweden.

Luthin, A., Crawford, R.H., Traverso, M., 2024. Assessing the circularity and sustainability of circular carpets — a demonstration of circular life cycle sustainability assessment. Int J Life Cycle Assess 29, 1945–1964. https://doi.org/10.1007/s11367-024-02359-x

Martin, M., Heiska, M., Björklund, A., 2021. Environmental assessment of a product-service system for renting electric-powered tools. Journal of Cleaner Production 281, 125245. https://doi.org/10.1016/j.jclepro.2020.125245

Meadows, D., 1998. Indicators and Information Systems for Sustainable Development (A Report to the Balaton Group). The Sustainability Institute.

Merli, R., Preziosi, M., Acampora, A., 2018. How do scholars approach the circular economy? A systematic literature review. Journal of Cleaner Production 178, 703–722. https://doi.org/10.1016/j.jclepro.2017.12.112

Mesa, J., Esparragoza, I., Maury, H., 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

Moraga, G., Huysveld, S., Mathieux, F., Blengini, G.A., Alaerts, L., Van Acker, K., de Meester, S., Dewulf, J., 2019. Circular economy indicators: What do they measure? Resources, Conservation and Recycling 146, 452–461. https://doi.org/10.1016/j.resconrec.2019.03.045

Morales, M.F.D., Passuello, A., Kirchheim, A.P., Ries, R.J., 2021. Monte Carlo parameters in modeling service life: Influence on life-cycle assessment.

Journal of Building Engineering 44, 103232. https://doi.org/10.1016/j.jobe.2021.103232

Murakami, S., Oguchi, M., Tasaki, T., Daigo, I., Hashimoto, S., 2010. Lifespan of Commodities, Part I. Journal of Industrial Ecology 14, 598–612. https://doi.org/10.1111/j.1530-9290.2010.00250.x

Mutel, C., 2017. Brightway: An open source framework for Life Cycle Assessment. Journal of Open Source Software 2, 236. https://doi.org/10.21105/joss.00236

Niero, M., Kalbar, P.P., 2019. Coupling material circularity indicators and life cycle based indicators: A proposal to advance the assessment of circular economy strategies at the product level. Resources, Conservation and Recycling 140, 305–312. https://doi.org/10.1016/j.resconrec.2018.10.002

Nordelöf, A., Messagie, M., Tillman, A.-M., Ljunggren Söderman, M., Van Mierlo, J., 2014. Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment? Int J Life Cycle Assess 19, 1866–1890. https://doi.org/10.1007/s11367-014-0788-0

Nyqvist, E., 2024. Looking at goals and scopes in LCA: Environmental assessment of carbon capture and utilisation for technology development. Chalmers University of Technology.

OECD, 1982. Product durability and product life extension : their contribution to solid waste management. OECD, Paris, France.

Parchomenko, A., Nelen, D., Gillabel, J., Rechberger, H., 2019. Measuring the circular economy - A Multiple Correspondence Analysis of 63 metrics. Journal of Cleaner Production 210, 200–216. https://doi.org/10.1016/j.jclepro.2018.10.357

Polizzi di Sorrentino, E., Woelbert, E., Sala, S., 2016. Consumers and their behavior: state of the art in behavioral science supporting use phase modeling in LCA and ecodesign. Int J Life Cycle Assess 21, 237–251. https://doi.org/10.1007/s11367-015-1016-2

Proske, M., Finkbeiner, M., 2020. Obsolescence in LCA–methodological challenges and solution approaches. Int J Life Cycle Assess 25, 495–507. https://doi.org/10.1007/s11367-019-01710-x

Razza, F., Briani, C., Breton, T., Marazza, D., 2020. Metrics for quantifying the circularity of bioplastics: The case of bio-based and biodegradable mulch films. Resources, Conservation and Recycling 159, 104753. https://doi.org/10.1016/j.resconrec.2020.104753

Reike, D., Vermeulen, W.J.V., Witjes, S., 2018. The circular economy: New or Refurbished as CE 3.0? — Exploring Controversies in the Conceptualization of the Circular Economy through a Focus on History and Resource Value Retention Options. Resources, Conservation and Recycling, Sustainable Resource Management and the Circular Economy 135, 246–264. https://doi.org/10.1016/j.resconrec.2017.08.027

Richter, J.L., Makov, T., Parajuly, K., Bakker, C., Fitzpatrick, C., 2024. Product lifetimes and industrial ecology. Journal of Industrial Ecology 28, 1355–1358. https://doi.org/10.1111/jiec.13489

Rivera, J.L., Lallmahomed, A., 2016. Environmental implications of planned obsolescence and product lifetime: a literature review. International Journal of Sustainable Engineering 9, 119–129. https://doi.org/10.1080/19397038.2015.1099757

Roos Lindgreen, E., Opferkuch, K., Walker, A.M., Salomone, R., Reyes, T., Raggi, A., Simboli, A., Vermeulen, W.J.V., Caeiro, S., 2022. Exploring assessment practices of companies actively engaged with circular economy. Business Strategy and the Environment 31, 1414–1438. https://doi.org/10.1002/bse.2962

Roßmann, M., Stratmann, M., Rötzer, N., Schäfer, P., Schmidt, M., 2021. Comparability of LCAs — Review and Discussion of the Application Purpose, in: Albrecht, S., Fischer, M., Leistner, P., Schebek, L. (Eds.), Progress in Life Cycle Assessment 2019. Springer International Publishing, Cham, pp. 213–225. https://doi.org/10.1007/978-3-030-50519-6_15

Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., 2017. How to Assess Product Performance in the Circular Economy? Proposed Requirements for the Design of a Circularity Measurement Framework. Recycling 2, 6. https://doi.org/10.3390/recycling2010006

Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., Kendall, A., 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, C., Rosa, P., Rocca, R., Terzi, S., 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

Schrijvers, D.L., Loubet, P., Sonnemann, G., 2016. Developing a systematic framework for consistent allocation in LCA. Int J Life Cycle Assess 21, 976–993. https://doi.org/10.1007/s11367-016-1063-3

Severengiz, S., Schelte, N., Bracke, S., 2021. Analysis of the environmental impact of e-scooter sharing services considering product reliability characteristics and durability. Procedia CIRP, 8th CIRP Global Web Conference – Flexible Mass Customisation (CIRPe 2020) 96, 181–188. https://doi.org/10.1016/j.procir.2021.01.072

Silvestre, J.D., Silva, A., de Brito, J., 2015. Uncertainty modelling of service life and environmental performance to reduce risk in building design decisions. Journal of Civil Engineering and Management 21, 308–322. https://doi.org/10.3846/13923730.2014.890649

Speck, R., Selke, S., Auras, R., Fitzsimmons, J., 2016. Life Cycle Assessment Software: Selection Can Impact Results. Journal of Industrial Ecology 20, 18–28. https://doi.org/10.1111/jiec.12245

Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., de Vries, W., de Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B., Sörlin, S., 2015. Planetary boundaries: Guiding human development on a changing planet. Science 347, 1259855. https://doi.org/10.1126/science.1259855

Steinmann, Z.J.N., Schipper, A.M., Hauck, M., Giljum, S., Wernet, G., Huijbregts, M.A.J., 2017. Resource Footprints are Good Proxies of Environmental Damage. Environ. Sci. Technol. 51, 6360–6366. https://doi.org/10.1021/acs.est.7b00698

Steubing, B., Koning, D. de, Haas, A., Mutel, C.L., 2020. The Activity Browser — An open source LCA software building on top of the brightway framework. Software Impacts 3. https://doi.org/10.1016/j.simpa.2019.100012

UNEP, 2017. Resource Efficiency: Potential and Economic Implications. A report of the International Resource Panel.

van den Berge, R., Magnier, L., Mugge, R., 2023. Until death do us part? In-depth insights into Dutch consumers' considerations about product lifetimes and lifetime extension. Journal of Industrial Ecology 27, 908–922. https://doi.org/10.1111/jiec.13372

Walker, S., Coleman, N., Hodgson, P., Collins, N., Brimacombe, L., 2018. Evaluating the Environmental Dimension of Material Efficiency Strategies Relating to the Circular Economy. Sustainability 10, 666. https://doi.org/10.3390/su10030666

Walzberg, J., Lonca, G., Hanes, R.J., Eberle, A.L., Carpenter, A., Heath, G.A., 2021. Do We Need a New Sustainability Assessment Method for the Circular Economy? A Critical Literature Review. Front. Sustain. 1. https://doi.org/10.3389/frsus.2020.620047

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int J Life Cycle Assess 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8

Willskytt, S., Tillman, A.-M., 2019. Resource efficiency of consumables – Life cycle assessment of incontinence products. Resources, Conservation and Recycling 144, 13–23. https://doi.org/10.1016/j.resconrec.2018.12.026

Winzer, J., Wagner, E., Nissen, N.F., Lang, K.-D., 2016. Developing an indicator setup to measure life-cycle conditions of electronic products, in: 2016 Electronics Goes Green 2016+ (EGG). Presented at the 2016 Electronics Goes Green 2016+ (EGG), pp. 1–8. https://doi.org/10.1109/EGG.2016.7829824

World Business Council for Sustainable Development, 2023. Circular Transition Indicators v4.0.