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LCI METHODOLOGY AND DATABASES

Product lifetime in life cycle assessments of circular economy strategies — A review and consolidation of methodology

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Abstract

Purpose Product lifetime is central to circular strategies that by lifetime extension could increase products' environmental performance. In life cycle assessment (LCA), little attention has been paid to product lifetime modelling, although the environmental benefit of lifetime extension can vary greatly with lifetime values. Since product lifetime modelling may have a significant effect on the results, this study identifies and explains existing approaches. The consolidation of methodology for lifetime extension in LCA can support practice as well as further development of methodology.

Methods A scoping literature review identified 67 LCA studies of lifetime extension containing 95 cases. The analysis focused on the case description of product lifetime and its integration in LCA calculations. Then, an overview of product lifetime modelling approaches and guidance for selecting them were developed and summarised into a product lifetime modelling framework which follows LCA methodological steps.

Results and discussion Lifetime modelling differs in terms of (1) the lifetime definition, specifying in the goal and scope definition whether periods of idleness and the full technical lifetime are included, (2) the lifetime integration in equations either using a single value, no fixed value or distribution over a population in the inventory analysis and impact assessment and (3) the lifetime sensitivity analysis during interpretation. However, unclear descriptions of lifetime definition and missing references to lifetime data sources in 63 and 26% of the cases, respectively, show that reporting of product lifetime modelling is insufficient for unambiguous interpretation of the results. Additionally, significant variations in LCA results observed through lifetime sensitivity analysis underscore the importance of product lifetime modelling in LCA of lifetime extension.

Conclusions Product lifetime modelling is not straightforward, as evidenced by the variety of definitions and existing approaches. The developed lifetime modelling framework offers LCA practitioners a more informed and structured approach to modelling lifetime extension in LCA, highlighting the importance of clear methodology requirements and further development.

Recommendations Given the significance of product lifetime for LCA of lifetime extension, along with the observed inconsistencies and often insufficient reporting practices, LCA practitioners are encouraged to carefully consider the definition, integration in equations and sensitivity of product lifetime and to report these aspects transparently. The new framework can support these considerations.

Keywords Lifetime extension · Reuse · Repair · Remanufacturing · Obsolescence · Product durability · LCA methodology

1 Introduction

Extending the lifetime of products is central to the circular economy (CE). Slowing resource loops by extending product lifetime by design or by sharing, reuse, repair, remanufacturing and repurposing is one of the three types of circular economy strategies, alongside closing and narrowing resource loops (Bocken et al. 2016). The significance of lifetime extension as a key strategy for advancing the CE and reducing the environmental footprint of products is highlighted by new requirements in the updated Ecodesign directives for extending product lifetime in the European Union (European Commission 2024).

For evaluating and prioritising CE strategies in product design and policy development, life cycle assessment (LCA) is frequently applied to study environmental impacts (Harris

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et al. 2021; Sassanelli et al. 2019). LCA methodological steps are defined by international standards (ISO 2006a, b) as (1) the goal and scope definition, (2) inventory analysis, (3) impact assessment and (4) interpretation. In the inventory analysis, the system of equations for the LCA calculations is established. In addition, the standards set how the studied system should be modelled: with elementary and product flows and processes to represent the life cycle of a product and the amount of these flows relative to a given functional unit.

The LCA methodology has been applied in numerous studies on lifetime extension strategies (Böckin et al. 2020). They have shown that lifetime extension strategies have the potential to increase products' environmental performance (Bakker et al. 2014; Böckin et al. 2020; Kaddoura et al. 2019). For instance, if all other variables are kept unchanged, using a product longer reduces the number of products required to be produced and the quantity of waste to be managed to deliver the same function, thus reducing the environmental impact related to resource extraction, production and waste management per unit of product function. However, studies also show that lifetime extension does not systematically improve environmental performance (Böckin et al. 2020; Richter et al. 2024). For instance, the transportation required for users to access and return a product in a rental system (Abagnato et al. 2024; Martin et al. 2021) or the washing of multiple-use products, replacing single-use products (Cottafava et al. 2024) might offset the benefits of lifetime extension.

In particular, the duration of the initial lifetime and the additional lifetime provided by lifetime extension greatly influence the benefit of lifetime extension. For example, Bovea et al. (2020) identifies that the repair of small household electrical and electronic equipment (EEE) is preferred to replacement when a technical failure occurs in the first 3 years. The resources invested in the repair lead to a lower environmental impact than the production of a new product for the additional lifetime provided, but not when repair occurs late since the remaining lifetime is too short to pay off the repair. A minimum additional lifetime necessary for lifetime extension to be beneficial can be calculated, for example, for the repair of EEE or electric motors (Ardente and Mathieux 2014; Jerome et al. 2023). Another example of the influence of the initial lifetime on the benefits of lifetime extension is when products' efficiency improves with technological development. For example, the remanufacturing of residential heating systems is preferable to product replacement only when the product fails early (Hummen and Desing 2021). With longer initial lifetimes, the difference in energy efficiency between the initial product and newer products increases so that energy savings outweigh the impact of producing a new product.

The product lifetime varies significantly with the type of products and users (Pohl et al. 2019; Richter et al. 2024). For instance, a product can be used more or less frequently (e.g., a chainsaw used once a year by a private owner or every day by a gardener), last the time of a single use only (e.g., food packaging) to several decades (e.g., buildings) and be ended when or before the product does not provide its function anymore. These differences are important to consider when selecting environmentally relevant lifetime extension strategies (Böckin et al. 2020), for example:

> If the product is discarded before reaching the end of its technical lifetime, reuse is possible and decreases the number of products required for the same unit of product function.
> If the product is infrequently used, sharing might decrease the number of necessary products, hence avoiding superfluous production.
> If part of the function remains at the end of use, the product can be repurposed for other uses.

In LCA, the way product lifetime is expressed as input to the system of equations in the life cycle inventory and life cycle impact assessment — here defined as *lifetime modelling* — significantly influences the results. For instance, the lifetime duration defines what processes are included (e.g., necessary replacement of elements of a building) and the scale of flows during the product use (e.g., energy used). Besides, using a functional unit which accounts for the lifetime is crucial when comparing products with different lifetimes, e.g. a more durable product with a less durable one or a product that is reused with one that is new.

In sum, product lifetime has been identified as key for LCA results, and the selection of lifetime extension strategies is highly variable with the type of product and its usage. Therefore, defining and modelling product lifetime is a crucial step for LCAs of lifetime extension. For example, clear methodological requirements related to product lifetime have been highlighted by Cottafava et al. (2024) as necessary for reliable and comparable LCAs comparing single-use and reusable packaging. However, there is no concrete guidance on how to define and model the product lifetime in LCA, e.g. in the international standards on LCA (ISO 2006a, b). The topic of product lifetime modelling in LCA has been discussed in the scientific literature for assessments of buildings (Decorte et al. 2023; Grant and Ries 2013). Methods have been developed to predict the lifetime of buildings and building elements, and the choice of method has been shown as crucial for LCA results (Grant and Ries 2013). To compare the renovation of a building with the reconstruction of a new one, Decorte et al. (2023) recommend using the same total lifetime for both buildings for a fair comparison. However, these recommendations are specific to buildings and not generally applicable to other products.

Methodological discussions for LCAs of CE strategies have been focusing on material recycling, such as accounting for material quality degradation (Hellweg et al. 2023) or allocating the impact to specific products (Saxegård et al. 2025; Schrijvers et al. 2016). Conversely, such methodological discussions for LCAs of lifetime extension are lacking (Cottafava et al. 2024). Methodologies to include temporal aspects in LCA have been developed (Beloin-Saint-Pierre et al. 2020; Su et al. 2021), for example, to study the effects over time when introducing a CE strategy (Koide et al. 2023) or to account for additional product stock required to compensate for the duration of product recycling (Sazdovski et al. 2022). However, product lifetime is not studied as a variable in the modelling and calculations for assessing product lifetime extension. Product lifetime is used in the calculation of some product-level circular economy indicators to assess lifetime extension (Jerome et al. 2022) such as in Figge et al. (2018) or Moraga et al. (2020). However, these indicators inform on variations in material flows with lifetime extension rather than environmental impacts which are assessed with LCA (Jerome et al. 2022).

For developing clear requirements on product lifetime modelling for LCAs of lifetime extension, the first step is to define available options for modelling product lifetime and when each option is appropriate. As such, an overview has not been done yet, this article aims to identify and analyse how product lifetime is accounted for in LCAs of lifetime extension. Especially, it aims to answer the following research questions: (1) How is the lifetime modelling reported in LCAs of lifetime extension? (2) How can lifetime modelling in LCA of lifetime extension be structured? Both are studied through a scoping review of LCA studies of lifetime extension. The elements involved in lifetime modelling and the different options for each element are described and then structured into a framework for lifetime modelling. This framework can provide guidance in the selection of suitable methodology for assessments of lifetime extension as well as initiate further development of lifetime modelling in LCA.

This paper first selects and defines key terminology related to product lifetime based on previous literature. It then outlines the method for the literature review, presents the resulting framework and finally discusses the findings and draws conclusions.

2 Terminology for studying product lifetime

Product lifetime can be defined as ending at the point in time when the product becomes obsolete, i.e. "falls into disuse" (Cooper 2010). Multiple technical, economic, social and psychological factors explain this obsolescence (Krych and Pettersen 2025; Richter et al. 2024). This article makes the distinction between product lifetime, defined as a time period, and product obsolescence, defined as the reason for the lifetime to be ended.

Several terms are related to product lifetime, for example, "lifetime", "lifespan", "technical lifetime", "use time" or "service life", sometimes used synonymously, sometimes referring to different time periods (Cooper 2010; Diener 2017; Murakami et al. 2010; Proske and Finkbeiner 2020). This paper distinguishes between four types of product lifetime found in the literature, based on the definitions from Cooper (2010), Diener (2017) and Proske and Finkbeiner (2020) (Fig. 1):

Service lifetime: the period between the start and end of a product's use, including periods when the product is not in use.
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. As the service lifetime, it includes periods when the product is not in use. The distinction between a technical lifetime and a service lifetime is crucial when users decide to replace a product that is still functional. In such cases, the service lifetime is shorter than the technical lifetime. However, when a product is used for its entire technical lifetime, the technical lifetime and service lifetime are equal.
Use time: the sum of periods during which the product is in use excluding periods of idleness. In other words, it corresponds to subtracting periods during which the product is not used (e.g., due to idling, maintenance and repair) from the service lifetime.
Technical use time: use time until the product does not have the physical capacity to function. It is the technical lifetime expressed without periods of idleness. The technical use time is relevant for products with a physical capacity to function limited by wear and tear, while technical lifetime is relevant for products with a physical capacity limited by ageing. For example, for a washing machine, the technical use time is the number of washing cycles that are technically possible, and the technical lifetime is the number of years until the machine does not have the capacity to function anymore due to material ageing. Similar to the difference between service and technical lifetime, distinguishing between use time and technical use time is important when users decide to replace a product that is still functional, resulting in a use time shorter than the technical use time.

For some products, the four types of lifetime are equal. For instance, single-use products are used once and after that disposed of and thus with a technical lifetime, service

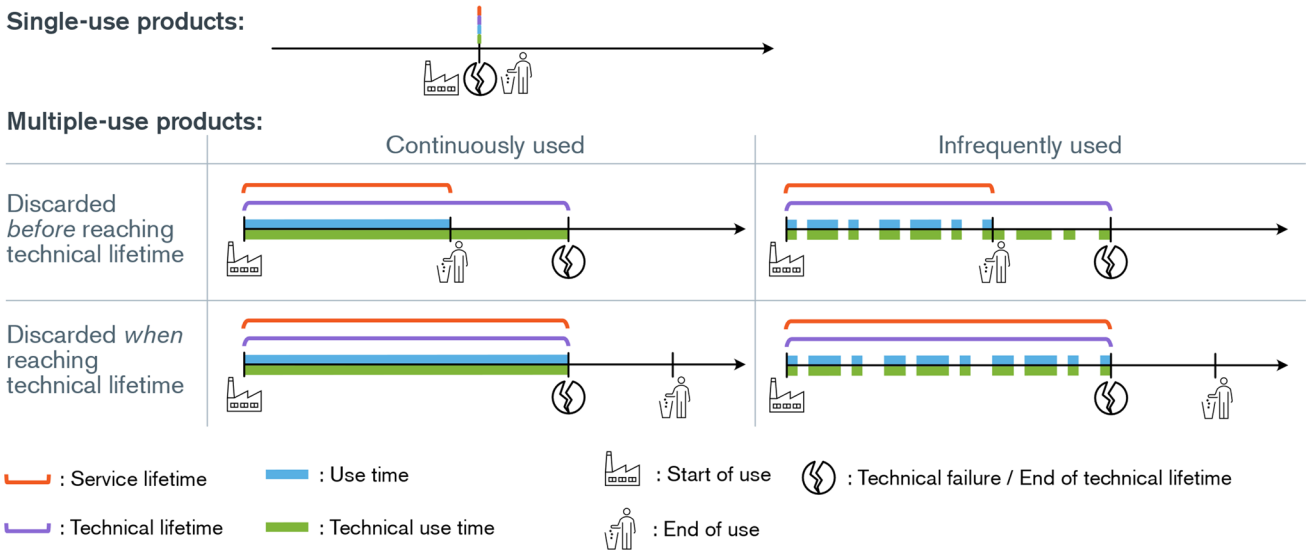


Fig. 1 Representation of the different types of product lifetime for different types of products

lifetime, use time and technical use time of one use (Fig. 1). For multiple-use products, whether different lifetime types refer to different periods depends on whether the product is continuously used and whether the product is discarded before reaching the end of the technical lifetime (Fig. 1).

Since this study focuses on lifetime extension strategies, a distinction is made between initial and additional lifetime. The initial lifetime is the lifetime considered before lifetime extension strategies are applied, while additional lifetime refers to the additional use time from more intensive use (e.g., through sharing) or the extended service lifetime of a product (e.g., additional use after repair) or a combination of both. The additional lifetime may be utilised by the first user or shifted to another user, but these changes are not accounted for in the definitions of product lifetime in this study.

The type of obsolescence describes the reason why a product falls into disuse. While different reasons can be identified (Cooper 2010; den Hollander et al. 2017; Diener 2017; Proske and Finkbeiner 2020; Rivera and Lallmahomed 2016; van den Berge et al. 2023), obsolescence can be grouped into two main categories:

Absolute obsolescence: when the product is not functional due to, e.g. product failure. When the reason for obsolescence is absolute, the technical lifetime and the service lifetime as well as the technical use time and use time represent the same period respectively.
Relative obsolescence: when the product falls into disuse before reaching its technical lifetime. It includes, for example, technological obsolescence when a more functional and advanced technology makes the product obsolete, economic obsolescence when maintenance and ownership costs become higher than product replacement, or aesthetic obsolescence when the product appearance is not "good enough", either due to wear and tear, fashion or change in the user's style. A comprehensive list of types of obsolescence is presented in Supplementary Information (SI). When there is relative obsolescence for a product, its service lifetime is shorter than the technical lifetime and the use time shorter than the technical use time.

For lifetime extension, the types of obsolescence influence the selection of lifetime extension strategies that are environmentally beneficial. For example, extending the technical lifetime by design for products for which relative obsolescence applies does not increase products' environmental performance since the additional lifetime will anyway not be utilised (Böckin et al. 2020). A consequence of the different types of lifetime and obsolescence for LCA studies is that the type of lifetime and its value need to be carefully selected. For example, for a product for which relative obsolescence applies, the value of the technical lifetime is higher than the service lifetime and would thus provide different results.

3 Method

The method consisted of three steps: (1) a scoping literature review (Arksey and O'Malley 2005; Grant and Booth 2009; Munn et al. 2018) to compile a list of LCAs of lifetime extension focused on product lifetime, (2) an analysis of product lifetime in these studies and (3) the development of a lifetime modelling framework that can serve as guidance for LCA practitioners and methodology developers.

3.1 Literature review

The literature review followed the PRISMA checklist for scoping reviews (Tricco et al. 2018). The search was done on 24 February 2025 on Scopus and Web of Science, combining keywords related to LCA (*life cycle assessment*, *LCA*), lifetime extension strategies (*circular**, reus*, *repair**, *remanufactur** and *repurpos**) and product lifetime (*lifetime*, *lifespan*, *durability* and *longevity*). No restrictions on the publication data were applied. Details on the search string are available in section S1 of the supplementary information (SI). A screening of the title, abstract and sometimes full text was done by the first author to select articles only presenting an LCA study of product lifetime extension and removed entries that were not articles, not in English, with no full text available, and articles for which the LCA methodology was not clearly explained. The search resulted in 899 distinct entries, and the selection was narrowed down to 61 articles after screening. Six relevant articles found in the reference list of the selected articles were added to the selection, leading to a total of 67 articles selected for analysis. Details on the inclusion and exclusion criteria are available in section S1 of the SI.

3.2 Analysis of the selected studies

Some articles present an LCA of several products, each with a different modelling of product lifetime. Each product is considered a separate case, resulting in 95 cases to be analysed. For all cases, alternatives with one or several lifetime extension strategies are compared to a baseline, i.e. the same product without applying lifetime extension strategies and discarded after end-of-life or replaced with the same product or its newer version.

Information on how product lifetime is accounted for in the LCA was analysed. The list of analysed components was gradually developed. The components were selected to describe the cases (product and circular strategies under study) and report any information on how product lifetime is accounted for in all steps of the LCA methodology. Certain components were selected prior to the analysis, e.g. the type of lifetime and obsolescence reported. Other components, such as lifetime partitioning between initial and additional lifetime, were identified and added during the analysis (Table 1). For each component, the analysis was done by interpreting the text based on a predefined list of entries, directly quoting the article or reporting a free-text description of the component (Table 1).

After the identification of all components, the free-text descriptions for the lifetime representation in equations and lifetime data sources were analysed with similar observations grouped under the same entry. The resulting list of possible entries for these two components is presented in the "Results" section.

3.3 Development of the lifetime modelling framework

After the analysis, eventual links between components were tested by a quantitative study carried out with the programming language R on RStudio. As highlighted in Sect. 2, the

Table 1 List of components included in the analysis. The predefined lists of entries are presented in the SI, in section S1.3

	Component in the analysis	Reporting by		
		Quoting the article	Following a predefined list of entries	Writing a descriptive free text
Component defined before doing the analysis	Product under study	x		
	Circular strategies under study		x	
	Terminology used in the article for product lifetime	x		
	Unit for the lifetime	x		
	Type of lifetime		x	
	Type of obsolescence mentioned		x	
Component defined while doing the analysis	Lifetime partitioning		x	
	Method for sensitivity analysis		x	
	Lifetime representation in equations			x
	Lifetime data sources			x

product lifetime differs for products with different characteristics. To identify links between product lifetime modelling and the types of product, the reported product under study was further categorised to distinguish between single-use and multiple-use products, energy-using and passive products, continuously and infrequently used products and products used until or before the end of the technical lifetime. This categorisation was chosen based on the product characteristics highlighted as relevant for selecting suitable circular strategies by (Böckin et al. 2020) and was done based on the name and reported characteristics of the products in the cases. In addition to testing of links between components, the characteristics of the different entries were identified while reading the cases.

A framework for modelling product lifetime in LCA of lifetime extension was developed by sorting the components defined during the analysis according to the steps in the LCA methodology.

4 Results

The components describing the modelling of product lifetime in the reviewed cases are grouped under three steps following the LCA methodological steps:

- The product lifetime definition in the goal and scope definition step, including the terminology used in the article, types of lifetime chosen, unit for the lifetime, the types of obsolescence mentioned and lifetime partitioning.
- The product lifetime integration in equations in the inventory analysis and impact assessment steps, including the lifetime representation in equations and lifetime data sources.
- The sensitivity analysis of product lifetime, in the interpretation step, including the method for sensitivity analysis.

In the following sections, the review results are summarised. Detailed results of the review are presented in the Appendix.

4.1 Description of reviewed cases

The reviewed cases span a range of circular strategies and products (Table 2). All lifetime extension strategies defined by Böckin et al. (2020) are covered, with reuse and repair being the most common. These lifetime extension strategies are in 14 cases combined with other circular strategies such as improved efficiency of, e.g. energy-using products.

The distinctions between continuously and infrequently used products and between products used until or before the end of the technical lifetime are sometimes unclear, see Sect. 4.2. However, distinctions between single-use and multiple-use products and between energy-using and passive products (Table 2) are clearly stated in the reviewed cases. No link has been found between the lifetime modelling and the type of product.

4.2 Product lifetime definition

The reviewed cases often use another product lifetime *terminology* than the one defined in Sect. 2, for example, "durability", "use lifetime" and "life". When the terms were clearly described, they could easily be translated and matched with the elements in the analysis structure.

The *type of lifetime* was analysed based on whether the lifetime includes periods of idleness or not, and if they span the full technical lifetime (Table 3). Due to unclear descriptions, the type of lifetime could not be identified in 33 cases out of 95. In 11 cases, it was not possible to identify whether periods of idleness are included, and in 28 cases, it was not possible to identify whether the lifetime spans the full technical lifetime because, for example, no information on obsolescence is provided. In 27 additional cases, interpretations during the analysis had to be made. For example, calculations in the use phase inventory with a frequency of use indicate that idleness is included in the lifetime definition.

Seven cases out of 95 do not include periods of idleness for products infrequently used (Table 3) and thus have a lifetime defined as the use time, which differs from the service lifetime. All other cases where the type of lifetime could have been identified define the lifetime as the same period as the service lifetime: either the product is continuously used and thus the use time and service lifetime are the same (see Fig. 1) or the lifetime includes periods of idleness.

By including periods of idleness when defining the lifetime as the service lifetime, the frequency of use of the product is made visible. In some cases, the frequency of use is important for estimating the benefits of a lifetime extension strategy. For instance, a system to increase the loading of washing machines is assumed to reduce the frequency of use, thereby extending the service lifetime of the washing machines (Bressanelli et al. 2022). This, in turn, decreases the number of washing machines needed per year of washing, thus lowering the environmental impact of washing machines. Another example is the renting of chainsaws that result in increased frequency of use (Martin et al. 2021). Although rented chainsaws are assumed to have a shorter service lifetime, fewer products are required for the same functional unit of 20 uses by different users. Consequently, the renting alternative results in lower environmental impacts than if each user owned a chainsaw.

In contrast, the frequency of use does not need to be assumed when defining the lifetime as the use time since

Table 2 Circular strategies and products under study in the reviewed cases

Circular strategies (number of cases)	Product under study		
	Single-use	Multiple-use and energy-using	Multiple-use and passive
Reuse (24)		PC, building, freezer, laptop, monitor, printer, refrigerator, stove, temporary pavilion and washing machine	T-shirt, trousers, building element, building portal frame, building structure, cotton roller towel, exterior infill wall, facade system, interior wall, shell jacket, sweater and wind tower
Repair (12)	Beach flag and event tent	High-voltage electric motor, kettle, laptop and smartphone	Balcony, mould insert, recycling bin, truck tire and waste inlet
Shift to multiple use (12)	Coffee cup, crate for food delivery, cup, cystoscope, duodenoscope, fork, laryngoscope, packaging for fresh food, sandwich storage, straw and surgical cap		
Repair and improve efficiency (9)		PC, building, frequency converter, mobile phone, television and washing machine	
Repurpose (9)		Battery and desktop computer	Phonebooth and wind turbine blade
Reuse and repair (9)		Desktop computer, laptop, monitor, printer, smartphone, vacuum cleaner, hand blender, coffee maker, heater, juicer, iron, sandwich maker, hair dryer and toaster	
Remanufacture (7)	Electrophysiology catheter (single-use medical equipment)	Air compressor, server, turbocharger and washing machine	Office storage locker, onshore oil and gas well
Increase technical lifetime by design (4)		Electric oven and refrigerator	Bed sheet and reinforced concrete slab
Reuse, increase technical lifetime by design and change material in product (2)			Facade system and kitchen
Maintain (1)			Window frame
Remanufacture and improve efficiency (1)		Video projector	
Repair and remanufacture (1)		Smartphone	
Repurpose and improve efficiency (1)			Shipping container
Reuse, remanufacture and change material in product (1)			building
Reuse and share (1)			Pair of jeans
Share and repair (1)		Chainsaw	

Table 3 Analysis of the type of lifetime and lifetime unit in the reviewed cases. Numbers in parentheses are the number of cases having the corresponding lifetime unit and type of lifetime

	Does the lifetime span the whole technical lifetime?		
Are periods of idleness included in the lifetime?	Yes (25 cases)	No (42 cases)	Not identifiable (28 cases)
Single use (15 cases)	number of uses (12)	(0)	number of uses (2) years (1)
Continuous use (32 cases)	years (2)	years (15)	years (15)
Yes (infrequent use) (30 cases)	years (5)	years (22)	years (3)
No (infrequent use) (7 cases)	km (1)	number of washes (2) kWh delivered (1) number of wears (2)	number of uses (1)
Not identifiable (11 cases)	years (4) none (one service life) (1)	(0)	years (6)

the periods of idleness are not included in the lifetime. For example, (Dunn et al. 2023) do not specify a frequency of use of repurposed electric vehicle batteries for energy storage, allowing for flexibility in the application of the energy storage. The other studies of battery repurposing in the review defined the lifetime as the service lifetime. The frequency of use is based on a specific application for illustration (Bobba et al. 2018) or assumed to be one cycle of charge–discharge per day "to demonstrate a generic example of battery operation" (Richa et al. 2017). Alternatively, the frequency of use is not mentioned, and the lifetime is directly expressed as a service lifetime (Koroma et al. 2022; Wilson et al. 2021).

The *unit for the lifetime* is predominantly expressed in years (Table 3). Other types of units represent the main reason for wear and tear of the product (e.g. number of washes for textile in Farrant et al. (2010) and Mölsä et al. (2022)) or to the function provided by the product (e.g. kWh delivered for batteries in Dunn et al. (2023), km driven for truck tyres in Lonca et al. (2018) or number of uses for clothes in Levänen et al. (2021)).

The choice of unit for the lifetime seems to be linked to the type of lifetime (Table 3). All cases that include periods of idleness, i.e. lifetime defined as the service or technical lifetime, express the lifetime in years. In all cases that exclude periods of idleness, i.e. lifetime is defined as use time or technical use time, a unit representing the product function or wear and tear is used. All cases of single-use products expressed the lifetime in "number of uses", except in Donahue et al. (2024) which express the lifetime of the multiple-use alternative replacing the single-use product in years and assume a frequency of use.

When the lifetime is expressed in years instead of a unit representing the product function, accounting for the calendar ageing of the product is possible. For instance, Bobba et al. (2018) estimate the lifetime of repurposed batteries as the service lifetime in years, accounting for the degradation of battery performance with both the number of charging cycles and calendar time and conclude that the performance degradation affects the environmental benefits of battery repurposing. A time unit is also suitable for accounting for technology development during the service lifetime. For example, Ardente and Mathieux (2014) include the difference in energy efficiency of washing machines produced at different times and convert the lifetime of washing machines from the use time in a number of washing cycles to a service lifetime in years.

The *type of obsolescence* is mentioned in only 34 out of 95 cases (see Table 5 in the Appendix). This observation supports the difficulty in analysing the type of lifetime and especially whether the lifetime spans the full technical lifetime (Table 3). However, this information has been identified as useful for evaluating the suitability of lifetime extension strategies to improve the environmental performance of products (Böckin et al. 2020).

Lifetime partitioning into an initial and an additional lifetime is done in most reviewed cases (84 out of 95), but the reason is never explained. However, as the data on the initial lifetime are often based on existing consumption patterns and data on the additional lifetime on possible changes in consumption patterns, partitioning the lifetime may be convenient to separate variables with different data sources and uncertainties. Besides, partitioning provides information on the timing of repair actions, which is crucial to consider for products with significant technology development. For example, in the study by Proske (2022) on smartphone repairs and upgrades, the type of upgrade would differ with the initial lifetime. Finally, partitioning is used in seven cases where the system boundaries start after the initial use of the product. In 11 cases, there is no partitioning between the initial and additional lifetime and the lifetime is defined as a total lifetime. The timing of the repair actions during the lifetime is then left undecided and assumed to not affect the repair and lifetime extension.

4.3 Product lifetime integration in equations

Information about the product lifetime integration in equations, when available, was found within the description of collected data in the inventory analysis and calculation setup in the impact assessment. The *lifetime representation in equations* in the 95 cases could be classified into three generic approaches (Table 4):

With a single value: one value of the lifetime is used in the equations. It includes all cases of single-use products, for which the initial lifetime is set as one use.
With no fixed value: the lifetime is left variable in the equations.
With a distribution: the lifetime values among a population are presented as a distribution (e.g. frequency of occurrence for each lifetime value) in the equations and passed on through LCA calculations to a distribution of resulting environmental impacts. The LCA results are then represented as a distribution showing variations in the frequency of environmental impact values in the user sample with lifetime extension.

The *data sources* used for the lifetime value could be categorised into:

Assumptions: the value was assumed without further reference to any source of information,
Manufacturing company: a company reported the value to the authors of the study.
Literature: the value was found in scientific articles or reports with LCAs, interpreted national statistics or survey results.
Calculated based on technical parameters: the value was calculated based on technical parameters (e.g. colour fastness for textiles, capacity for batteries).
Calculated based on statistical data: the value was estimated based on the probability of failure of different components over time and the probability of product replacement due to this failure.
Expert judgement: the value was estimated by experts.
Measured data: the value was measured as the lifetime of an existing product by the authors of the study, either on a case or on a laboratory test.
Product warranties: the value corresponded to warranties issued by manufacturers.
User survey: the value was part of the questions asked about a product to a selected population of users.
Standard: the value was based on the product performance to be achieved fixed in a standard, such as the Eurocodes for buildings, national standards for building energy and environmental performance calculation, or European standards on concrete performance.

The occurrence of the approaches for lifetime representation in equations and corresponding data sources is presented in Fig. 2. It shows that the reporting of the approach and data source for the product lifetime is not done in all studies. How the lifetime is represented in the equations is not possible to identify in one case, and data sources for single values are not reported in 21% of cases (two cases out of 95 without lifetime partitioning, 10 and 13 cases for the initial and additional lifetime, respectively, for cases with lifetime partitioning) (Fig. 2).

The list of data sources used in each approach (Fig. 2) highlights a difference in data requirements. The approach using no fixed value does not require specific data sources as the lifetime is left as a variable, but only general knowledge of typical lifetime values to interpret the results. This approach is selected for the additional lifetime and not the initial lifetime (Fig. 2). It is used to overcome the lack of information on the additional lifetime, such as in Jerome et al. (2023), or to present the minimum additional lifetime to be achieved for reusable products to be less environmentally impactful than their single-use counterpart (Fetner and Miller 2021). A specific version of the single value approach requires no data on the initial lifetime since system boundaries are set to exclude the initial use of the product. This is selected in cases that compare the lifetime extension and additional use of an old product to the production and use of a new product. As argued in Legarth et al. (2003), the impact of the initial use is the same for both alternatives, so it can be omitted in the comparison. However, if there are differences in the production, initial use and collection rate and if the reusability rate is below one, this version of the single value approach is not suitable.

The approach using a lifetime distribution requires more data than the two other approaches. In Bressanelli et al. (2022), the only study using this approach, data collection was made with a user survey (Fig. 2) to account for various user profiles in a population. The study is the only one which makes explicit the variations between users in the LCA although they can significantly affect the environmental performance of CE strategies (Corona et al. 2024). In case there is no existing data on variations of the product lifetime value in a population, this is the approach requiring the most extensive data collection.

4.4 Sensitivity analysis of product lifetime

Many different sensitivity analysis methods have been used in LCA (Björklund 2002; Igos et al. 2019), but only five methods were used for studying the uncertainty and variability of product lifetime in the reviewed cases (Fig. 2):

Testing of different lifetime values: it is the most frequently used method. The list of tested values varies from

Table 4 Product lifetime modelling framework for LCAs of lifetime extension

Steps	Elements	Identified options			
Lifetime definition	Type of lifetime	*Service lifetime* • In cases of relative obsolescence • The frequency of use is made visible by including periods of idleness	*Technical lifetime* • In cases of absolute obsolescence • The frequency of use is made visible by including periods of idleness	*Use time* • In cases of relative obsolescence • The frequency of use is not visible	*Technical use time* • In cases of absolute obsolescence • The frequency of use is not visible
	Unit for the lifetime	*Time* • Examples: years • Includes periods of idleness and to make visible the frequency of use • Suitable for products that age with calendar time • Suitable for considering technology development over time		*Represents the function provided* • Examples: number of uses or cycles, energy stored or provided • Does not include eventual non-used time and the frequency of use • Not suitable for products that age with calendar time • Not suitable for considering technology development over time	
	Type of obsolescence	Reason for the lifetime to be ended: - *Absolute obsolescence*: product not functional due to, e.g. product failure - *Relative obsolescence*: product still functional when it falls into disuse due to, e.g. aesthetic or economic reasons			
	Lifetime partitioning	*Partitioning of initial/additional lifetime* • Timing of repair action known or assumed • Suitable for considering technology upgrades • Additional lifetime only in comparative studies with identical initial lifetimes		*No partitioning* (*total lifetime only*) • Timing of repair actions left undecided • Not suitable for considering technology upgrades	
Lifetime integration in equations	Lifetime representation in equations	*No fixed value*		*Single value*	*Distribution*
	Lifetime data source			Assumption Various data sources*	Survey to users
Sensitivity analysis	Parameter uncertainty and variability	Break-even analysis		Testing of different values Comparison with other variables	Probabilistic simulation

*Literature, manufacturing company, calculated based on technical parameters or statistical data, expert judgement, measured data, product warranties and standard

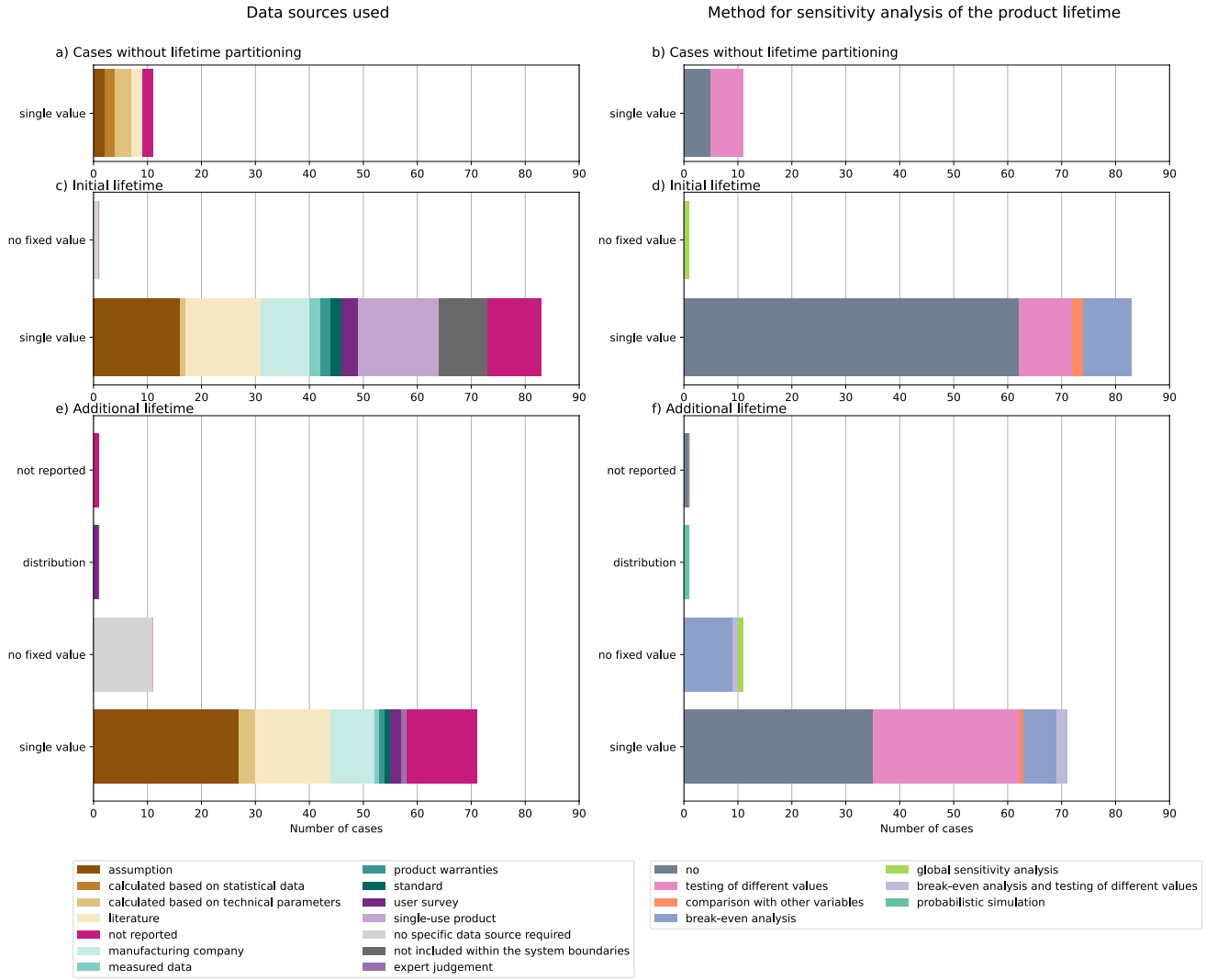


Fig. 2 lifetime representation in equations, data sources and sensitivity analysis methods identified in the reviewed cases. The results are presented separately for cases without partitioning (**a** and **b**) and for the initial lifetime (**c** and **d**) and additional lifetime (**e** and **f**) when partitioning is used. The data tables to plot the figure are presented in SI, section S3

one other value than the baseline (e.g. double the baseline value in Levänen et al. (2021) or 1 year less in Martin et al. (2021)), to numerous values between a minimum and maximum value (e.g.., with several bar charts in Kaddoura et al. (2019), or with plotting the environmental impact against the lifetime in Casals et al. (2017) and Palacios-Munoz et al. (2019)).

Break-even analysis: it calculates the lifetime value for which the ranking of preferred alternatives changes and thus provides information on threshold values for which conclusions hold. For instance, Wilson et al. (2021) identify that the minimum additional lifetime for battery repurposing to be environmentally preferable is 4.25 years, which is lower than the warranty periods generally found on the market for repurposed batteries. The study concludes that it is reasonable to assume that this minimum additional lifetime can be reached in practice even though no data on the additional lifetime is available.

Break-even analysis is the second most common method for the additional lifetime in cases with lifetime partitioning and is sometimes used in combination with testing of different lifetime values (for example in Accorsi et al. (2014), Jerome et al. (2023) and Wilson et al. (2021)).

Comparison with other variables: the variation in LCA results with different lifetime values is compared to the influence of other variables. LCA results are plotted as a bar chart with one bar per scenario, including a baseline scenario and scenarios where, one at a time, the value of one variable is changed. For instance, in Levänen et al. (2021), the influence of both the lifetime and transportation modes for product delivery is compared in the same figure. In Martin et al. (2021), the influence of the same

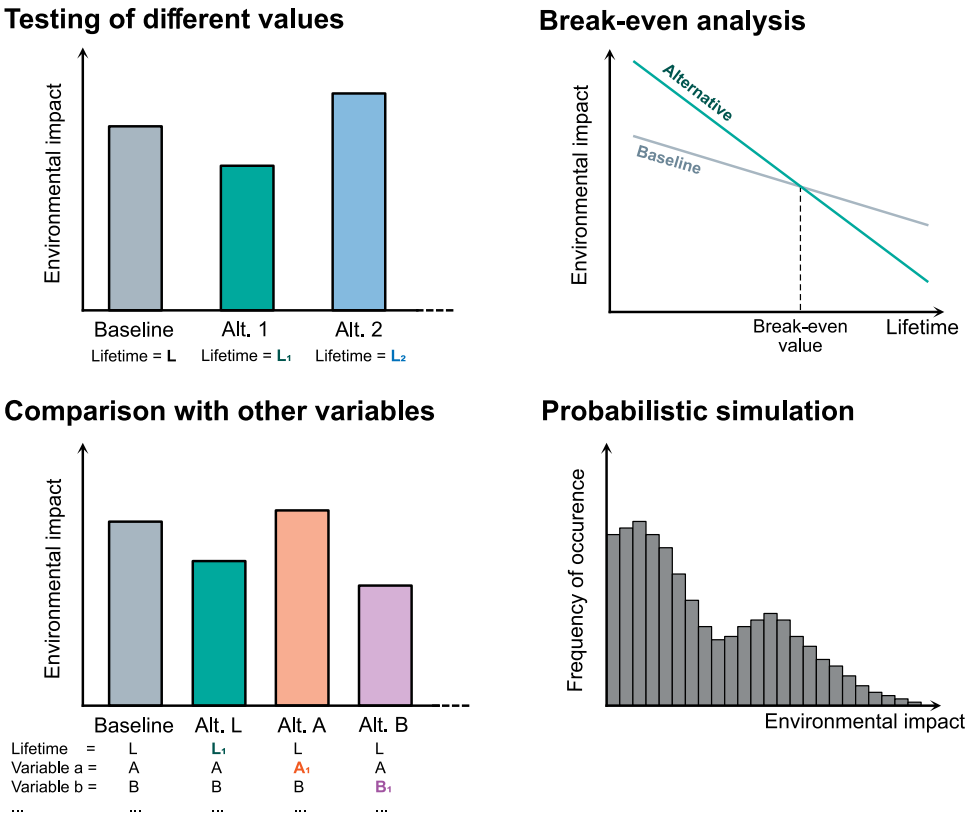
variables as well as transportation distances and the maintenance frequency is compared.

Probabilistic simulation: a sample of lifetime values representing uncertainty or variability distribution is generated, e.g. with a Monte Carlo sampling, and is propagated to the LCA results (Björklund 2002; Igos et al. 2019). The approach using a lifetime distribution can be considered a sensitivity analysis method in itself: in the only case using this approach (Bressanelli et al. 2022), the lifetime distribution is propagated to the LCA results using the values from a user survey as a sample.

Global sensitivity analysis: different variables, including the product lifetime, are given a distribution and the variations in LCA results and co-variations between the lifetime and other variables are calculated based on, e.g. Sobol indices (Igos et al. 2019). Van Gulck and Steeman (2023) use this method to identify the variables having the most influence on the LCA results.

The type of results obtained with each method is illustrated in Fig. 3.

All methods focus on parameter variability and uncertainty due to, e.g. data inaccuracy or data gaps (Bamber et al. 2020; Björklund 2002), in contrast to model uncertainty due to the "simplification of aspects that cannot be modelled within the LCA structure" (Björklund 2002) and choice uncertainty due to methodological choices, such as, e.g. allocation rules, functional unit and system boundaries (Björklund 2002).



Global sensitivity analysis

Variance and co-variance	Lifetime	Variable a	Variable b	...
Lifetime	xx			
Variable a	xx	xx		
Variable b	xx	xx	xx	
...	...	...	...	...

Fig. 3 Illustration of the typical results obtained with the sensitivity analysis methods used in the reviewed cases for product lifetime

The sensitivity of product lifetime values on LCA results is not always analysed (Fig. 2). When lifetime partitioning is done, a form of sensitivity analysis is carried out more often for the additional lifetime (48 cases out of 84, so in 57% of cases) than for the initial lifetime (28 cases out of 75 including the initial lifetime in the system boundaries so in 37% of cases).

Two of the sensitivity analysis methods are paired with the choice of approach to represent lifetime in equations. All cases using a no fixed value approach do a break-even analysis, and the case using a distribution approach does a probabilistic simulation (Fig. 2). This pairing matches data requirements for these sensitivity analysis methods: break-even analysis, such as an approach with no fixed value, does not require specific lifetime values and a lifetime distribution is required in the case of probabilistic simulation.

4.5 Lifetime modelling framework

The results identified different approaches for considering product lifetime in LCA of lifetime extension over three main steps: lifetime definition, integration in equations and sensitivity analysis. The results are synthesised into a framework for supporting LCA practitioners in modelling product lifetime (Table 4). It points to lifetime units and data sources identified as associated with the choice of type of lifetime and lifetime representation in equations respectively (dashed vertical lines in Table 4). The framework indicates that the lifetime definition step depends on the types of obsolescence: whether it is absolute or relative for the type of lifetime, and with or without ageing with calendar time for the lifetime unit. It also depends on whether the frequency of use is a variable of interest for the assessment for both the type of lifetime and the lifetime unit. Collecting this information on product use and obsolescence is therefore essential for selecting a lifetime modelling.

5 Discussion

5.1 Imprecise and incomplete reporting of product lifetime modelling

The results highlight imprecisions in the reporting of product lifetime definition in the reviewed LCAs. Unclear descriptions make it difficult to understand if the defined lifetime accounts for periods of idleness and full technical lifetime or not (in 63% of the reviewed cases) and the types of obsolescence (in 64% of the cases). 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. Besides, several terms for the product lifetime are used synonymously in the same study in 31 out of 95 cases. It shows a lack of precision when employing terms for the product lifetime and a lack of awareness of the differences in lifetime definitions.

Additionally, the results reveal incompleteness in reporting lifetime integration in LCA equations and data sources. The former cannot be identified in one case, and the latter is not reported in 21% of the reviewed cases. This information is crucial for ensuring a transparent LCA methodology. Reporting data sources is necessary to indicate 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 that of assumed data if the assumed data is more valid for the goal and scope of the study.

Therefore, the following guidance is suggested for future LCAs of lifetime extension:

- Consistent terminology: Do not use different lifetime terminology to indicate the same lifetime (e.g., lifetime and lifespan) since it can be misinterpreted.
- Precise terminology: Clearly report the lifetime used in the LCA by making clear whether periods of idleness are included and the full technical lifetime is covered.
- Consideration of reasons for obsolescence: Clearly report if the reasons for obsolescence are absolute or relative. A remaining technical lifetime at the end of the service life shows that extending the service lifetime to the full technical lifetime is possible.
- Transparent LCA methodology: Document and justify the data sources for product lifetime, both in the LCA and the sensitivity analysis. The estimated validity and uncertainty of the data might influence the interpretation of LCA results.

5.2 Importance of product lifetime for the LCA results

The results in the reviewed studies show that the LCA results of lifetime extension are very sensitive to the

product lifetime. In Bressanelli et al. (2022) which uses a lifetime distribution, the obtained distribution of environmental benefits with CE strategies compared to a conventional use varies between − 20 and + 80% depending on the user profile. In De Saxce et al. (2012), the use of two different lifetime calculation methods results in differences in LCA results of 14 and 26% on average and up to 60% for some samples, compared to the method chosen as the baseline. Besides, break-even analysis, in all the reviewed cases using this method, shows a range of product lifetime values for which lifetime extension is not beneficial and a range for which it is.

This sensitivity of LCA results demonstrates the importance of lifetime when studying lifetime extension strategies. Moreover, as variability and uncertainty in product lifetime seem unavoidable, e.g. due to the influence of user practices on product obsolescence (e.g. frequency of use, maintenance and aesthetic preferences) (Krych and Pettersen 2025; Richter et al. 2024) and the lack of information on the change of user practices over time after introducing lifetime extension strategies, careful consideration of this variable in sensitivity analysis is called for. These recommendations are in line with the call from Cottafava et al. (2024) for systematic break-even analysis and transparent reporting of key variables, including the return rate for reuse and the packaging lifetime to ensure the reliability and comparability of LCA studies comparing single-use and reusable packaging.

There is a low proportion of LCA studies reporting uncertainties in general (Bamber et al. 2020; Ross et al. 2002). The results from Sect. 4.4 provide a similar observation for the sensitivity analysis of product lifetime in LCAs of lifetime extension. Therefore, the additional guidance is suggested:

- Consideration of the lifetime in sensitivity analysis: Analyse the effect of uncertainty and variability of product lifetime values on the LCA results, both for the initial and additional lifetime.

5.3 Use of the framework

The framework for product lifetime modelling in LCA (Table 4) describes existing modelling practices, defining key steps and elements to follow. It also suggests a terminology for precise reporting. For each element, different options are presented, serving both as an overview of possible options and as a guide for LCA practitioners to ensure essential elements are not overlooked in methodology reporting.

To the best of our knowledge, this is the first study to present detailed guidance on product lifetime modelling applicable to LCAs of lifetime extension in general. Previous research has highlighted challenges in quantifying product lifetime value (Günther and Langowski 1997) and its large influence on LCA results of buildings (Goulouti et al. 2020; Grant and Ries 2013). While data and calculation models for the lifetime of buildings and their components have been developed (Aktas and Bilec 2012; Morales et al. 2021; Silvestre et al. 2015), these are generally applicable to other products and do not address the integration of lifetime into LCA equations.

5.4 Limitations and further research

The review method was not designed to capture all LCAs of lifetime extension. The searches focused on LCA studies with a focus on product lifetime, and the screening was carried out by one researcher and not validated by another person. A systematic review method identifying all LCAs of lifetime extension may result in a different accounting of lifetime modelling approaches in the literature as presented in Fig. 2. However, studies with additional innovative lifetime modelling could be expected to have been captured as the review focuses specifically on product lifetime modelling.

The proposed framework builds on existing literature and can serve as a starting point for further development of methodology. For example, the framework can be developed by analysing other LCA studies than cases of lifetime extension or other assessments of lifetime extension. In particular, other tools than a lifetime distribution might be used to address

variation between users, such as agent-based modelling (Hellweg et al. 2023), methods from behavioural science (Polizzi di Sorrentino et al. 2016), psychological evaluations to develop cause-effect chains in users' decisions (Klint 2024) or the identification of social practices based on social practice theory (Suski et al. 2024). Their integration into LCAs of lifetime extension to model product lifetime remains to be developed. Another opportunity for further development is investigating other sensitivity analysis methods available (Björklund 2002; Igos et al. 2019).

6 Conclusions

Although product lifetime can be decisive for the outcome in LCA of lifetime extension such as reuse or repair, there is little discussion on its modelling. This study reviews and analyses lifetime modelling in LCAs of lifetime extension.

The definition of product lifetime requires precision in the terms employed and their definitions. It is important to distinguish if the lifetime includes the time until the product breaks or is worn out (technical lifetime and technical use time) or if it considers earlier end of use (service lifetime and use time). It is also important to consider if periods of idleness of a product used infrequently are included (service and technical lifetime) or not (use time and technical use time).

However, this study identifies that the reporting of product lifetime modelling in LCAs of lifetime extension is often not clear. Among the reviewed studies, 63% have an unclear lifetime definition and 26% do not report the sources of lifetime values, which makes the lifetime modelling methodology insufficiently clear. Additionally, sensitivity analysis shows that LCA results are very sensitive to the initial and additional lifetime values but is done in 29% and 57% of the cases, respectively.

1. *The lifetime definition* in the goal and scope step, which involves:
   - *The type of lifetime* in focus: service lifetime, technical lifetime, use time or technical use time
   - *The unit* for the lifetime: either in time or representing the product function
   - *The type of obsolescence*associated with the product under study: either absolute for products used until not functional anymore, or relative for products still functional after falling into disuse
   - *The lifetime partitioning*: whether the total lifetime is partitioned into the initial and additional lifetime
2. The *lifetime integration in equations* in the inventory analysis and impact assessment steps, which involves the *lifetime representation in equations and data sources*: either as a single value from various sources, no fixed value (left as a variable) or distribution of values over a population collected via user surveys.
3. The *lifetime sensitivity analysis* in the interpretation step with *sensitivity analysis method(s)*.

The lifetime modelling approaches have different data requirements. For example, using no fixed value and a break-even analysis do not require specific lifetime values, while using a distribution over a population could require significant data collection.

For future LCA studies of lifetime extension, this study supports the product lifetime modelling by providing a list of approaches to choose from and provides concrete guidance for more articulated considerations of product lifetime. These results are also a first step in further development of product lifetime modelling. Given the significance of lifetime extension as a key strategy for advancing the CE in combination with the influence of lifetime on products' environmental performance, a clear methodology for product lifetime modelling in LCA is essential yet has been largely overlooked to date.

Appendix. Full results

Table 5 Review results

Ref	Case characterisation		lifetime definition					
	Product	Strategy	Terminology used in the article	Types of lifetime[1]		Types of obsolescence	Unit for the lifetime	Partitioning[1]
				Idleness included?	Full technical lifetime included?			
Priarone et al. (2021)	mold insert	repair	service life and life	?*	y	absolute	none (one service life)	y
Schischke et al. (2019)	smartphone	repair	use-time and years of use	cont use	?*	?	years	y
van Stijn et al. (2022)	kitchen	reuse, increase technical lifetime by design and change material in product	estimated service life	cont use	?*	?	years	y
van Stijn et al. (2022)	facade system	reuse, increase technical lifetime by design and change material in product	estimated service life	cont use	?*	?	years	y
Bertin et al. (2022)	building portal frame	reuse	life span, service life, lifetime and usage cycle	cont use	?*	?	years	y
Williams and Sasaki (2003)	PC	reuse and recycle	lifespan and lifetime	y*	n	technological	years	y
Boldoczki et al. (2020)	refrigerator	reuse	usage duration	cont use	n*	?	years	y
Boldoczki et al. (2020)	washing machine	reuse	usage duration	y*	n*	?	years	y
Boldoczki et al. (2020)	freezer	reuse	usage duration	y*	n*	?	years	y
Boldoczki et al. (2020)	stove	reuse	usage duration	y*	n*	?	years	y
Boldoczki et al. (2020)	printer	reuse	usage duration	y*	n*	?	years	y
Boldoczki et al. (2020)	monitor	reuse	usage duration	y*	n*	?	years	y
Boldoczki et al. (2020)	PC	reuse	usage duration	y*	n*	?	years	y
Boldoczki et al. (2020)	laptop	reuse	usage duration	y*	n*	?	years	y

Table 5 (continued)

Ref	Case characterisation		lifetime definition					
	Product	Strategy	Terminology used in the article	Types of lifetime[1]		Types of obsolescence	Unit for the lifetime	Partitioning[1]
				Idleness included?	Full technical lifetime included?			
Bovea et al. (2020)	vacuum cleaner, hand blender, coffee maker, heater, juicer, iron, sandwich maker, hair dryer and toaster	repair and reuse	life span	y*	y	?	years	y
Kitayama et al. (2024)	exterior infill wall	reuse	lifespan	cont use*	n*	?	years	y
Casals et al. (2017)	battery for EV	repurpose	lifetime	?*	y	?	years	y
Levänen et al. (2021)	pair of jeans	reuse, share and recycle	life	n*	?*	?	number of uses	y
Pamminger et al. (2021)	smartphone	repair and remanufacture	use time	cont use	?*	?	years	y
Joensuu et al. (2022)	building structure	reuse	service life	cont use*	n	?	years	y
Kouloumpis et al. (2023)	laptop	reuse and repair	lifespan, lifecycle and lifecycle use phase	y	n	technological	years	y
Kouloumpis et al. (2023)	monitor	reuse and repair	lifespan, lifecycle and lifecycle use phase	y	n	technological	years	y
Kouloumpis et al. (2023)	printer	reuse and repair	lifespan, lifecycle and lifecycle use phase	y	n	technological	years	y
Kouloumpis et al. (2023)	smartphone	reuse and repair	lifespan, lifecycle and lifecycle use phase	y	n	technological	years	y
Kouloumpis et al. (2023)	vacuum cleaner	reuse and repair	lifespan, lifecycle and lifecycle use phase	y	n	technological	years	y
Ardente et al. (2018)	server	remanufacture	life of product and lifetime	y*	?*	?	years	y
Sandez et al. (2024)	kettle	repair	lifetime	y*	y*	?	years	y
Durand et al. (2024)	refrigerator	reuse	lifetime and service lifespan	cont use*	n	?	years	y
Wilson et al. (2021)	battery for EV	repurpose	lifetime and life span	y	n*	?	years	y

Table 5 (continued)

Ref	Case characterisation		lifetime definition					
	Product	Strategy	Terminology used in the article	Types of lifetime[1]		Types of obsolescence	Unit for the lifetime	Partitioning[1]
				Idleness included?	Full technical lifetime included?			
Ardente and Mathieux (2014)	washing machine	improve efficiency and repair	lifetime	y*	?*	?	years	y
Martin et al. (2021)	chainsaw	reuse and repair	lifetime	y*	n*	?	years	y
Koroma et al. (2022)	battery for EV	repurpose and recycle	lifetime, useful life	y	n	?	years	y
Lonca et al. (2018)	truck tire	repair	lifetime	n	y	?	km	y
Iraldo et al. (2017)	refrigerator	increase technical lifetime by design	lifetime	?*	?*	?	years	y
Iraldo et al. (2017)	electric oven	increase technical lifetime by design	lifetime	?*	?*	?	years	y
Pérez-Martínez et al. (2021)	desktop computer	repurpose	lifespan	?*	y	?	years	y
Zanghelini et al. (2014)	air compressor	remanufacture and recycle	life span, useful life, use lifetime and lifetime	y	?*	?	years	y
Kim et al. (2024)	turbocharger	remanufacture	lifespan, life cycle and life	y	y*	absolute	years	y
Bobba et al. (2018)	battery for EV	repurpose	lifetime	y	n	absolute	years	y
Arrigoni et al. (2018)	temporary pavilion	reuse and recycle	life span, service life and lifespan	cont use*	n*	psychological	years	y
Farrant et al. (2010)	T-shirt and a pair of trousers	reuse and recycle	lifetime	n*	n	?	number of washes	y
Kouloumpis et al. (2023)	desktop computer	reuse and repair	lifespan, lifecycle and lifecycle use phase	y	n	technological	years	y
Dunn et al. (2023)	lithium-ion battery	repurpose and recycle	lifespan	n	n	?	kWh delivered	y
Mölsä et al. (2022)	cotton roller towel	reuse and recycle	lifetime	n*	n*	aesthetic	number of washes	y
Andrae (2018)	smartphone	repair and recycle	lifetime	cont use	?*	?	years	y
Gervásio et al. (2014)	wind tower	reuse	lifetime	cont use	?*	?	years	y
Kaddoura et al. (2019)	office storage locker	remanufacture	lifetime	cont use	n*	aesthetic and psychological	years	y
Kaddoura et al. (2019)	recycling bin	repair	lifetime	cont use	y	absolute	years	y

Table 5 (continued)

Ref	Case characterisation		lifetime definition					
	Product	Strategy	Terminology used in the article	Types of lifetime[1]		Types of obsolescence	Unit for the lifetime	Partitioning[1]
				Idleness included?	Full technical lifetime included?			
Claes et al. (2024)	interior wall	reuse	lifespan and lifetime	cont use*	n*	psychological, context-related	years	y
Cheung et al. (2018)	video projector	remanufacture and improve efficiency	lifetime and usage	y*	y*	?	years	y
Richa et al. (2017)	battery for EV	repurpose	service life and life span	y	n*	?	years	y
Carlisle and Friedlander (2016)	window frame	maintain	lifetime, durability, service life and life span	cont use*	n*	absolute, aesthetic and multiple factors in general	years	y
Accorsi et al. (2014)	packaging for fresh food	shift to multiple use	lifespan	n	y	?	number of uses	y
López-Muñoz et al. (2025)	duodenoscope	shift to multiple use	lifetime	n*	?*	?	number of uses	y
Kidane et al. (2025)	laryngoscope	shift to multiple use	lifespan	n*	?*	?	number of uses	y
Donahue et al. (2024)	surgical cap	shift to multiple use	disposal schedule	y	?*	?	years	y
Meister et al. (2023)	electrophysiology catheter (single-use medical equipment)	remanufacture	use duration	n*	y*		number of uses	y
Kemble et al. (2023)	cystoscope	shift to multiple use	lifetime	n*	y*	absolute	number of uses	y
Kaddoura et al. (2019)	beach flag	repair	lifetime and number of uses	n*	y	?	number of uses	y
Kaddoura et al. (2019)	event tent	repair	lifetime and number of uses	n*	y	?	number of uses	y
Del Borghi et al. (2021)	crate for food delivery	shift to multiple use	lifetime and number of uses	n*	y*	?	number of uses	y
Kröhnert et al. (2022)	building	reuse	lifetime	cont use	?*	?	years	y
Wittocx et al. (2022)	balcony	repair	lifetime, service life, life span, life-time and service lifetime	cont use*	?*	absolute	years	y
André (2024)	shell jacket	reuse	use span	n*	n*	relative	numbers of wears	y
André (2024)	shell jacket	reuse	use span	y*	n*	relative	years	y
Baboudjian et al. (2023)	cystoscope	shift to multiple use	useful life	n*	y*		number of uses	y

Table 5 (continued)

Ref	Case characterisation		lifetime definition					
	Product	Strategy	Terminology used in the article	Types of lifetime[1]		Types of obsolescence	Unit for the lifetime	Partitioning[1]
				Idleness included?	Full technical lifetime included?			
Jerome et al. (2023)	high-voltage electric motor	repair	lifetime	y*	y*	absolute	years	y
Fetner and Miller (2021)	straw	shift to multiple use	lifetime and number of uses	n*	y*	?	number of uses	y
Fetner and Miller (2021)	sandwich storage	shift to multiple use	lifetime and number of uses	n*	y*	?	number of uses	y
Fetner and Miller (2021)	coffee cup	shift to multiple use	lifetime and number of uses	n*	y*	?	number of uses	y
Fetner and Miller (2021)	fork	shift to multiple use	lifetime and number of uses	n*	y*	?	number of uses	y
Bressanelli et al. (2022)	washing machine	remanufacture	lifespan	y*	n*	aesthetic	years	y
Proske (2022)	smartphone	repair and reuse	use time	cont use*	n*	Absolute, aesthetic, psychological, systemic and technological	years	n
Palacios-Munoz et al. (2019)	building	repair and improve efficiency	lifespan	cont use*	n*	absolute and psychological	years	n
Proske (2022)	smartphone	repair and reuse	use time	cont use*	n*	absolute, aesthetic, psychological, systemic and technological	years	n
Sabbaghi and Behdad (2017)	laptop	repair	lifespan and usage time	y*	n*	absolute, economic and psychological	years	n
De Saxce et al. (2012)	bed sheet	increase technical lifetime by design	lifetime	?*	y	absolute	years	n
Van Belleghem et al. (2017)	reinforced concrete slab	increase technical lifetime by design	service life	?*	y	absolute	years	n
Palacios-Munoz et al. (2019)	building	repair and improve efficiency	lifespan	cont use*	n*	absolute, psychological	years	n
Temizel-Sekeryan et al. (2023)	building	reuse, remanufacture and change material in product	lifetime	cont use	?*	?	years	n
Palacios-Munoz et al. (2019)	building	repair and improve efficiency	lifespan	cont use*	n*	absolute and psychological	years	n

Table 5 (continued)

Ref	Case characterisation		lifetime definition					
	Product	Strategy	Terminology used in the article	Types of lifetime[1]		Types of obsolescence	Unit for the lifetime	Partitioning[1]
				Idleness included?	Full technical lifetime included?			
Kaddoura et al. (2019)	waste inlet	repair	lifetime	cont use	?*	?	years	n
Van Gulck et al. (2022)	facade system	reuse	lifespan	cont use	?*	?	years	n
Henao et al. (2024)	wind turbine blade	repurpose	life span	cont use*	n*	technological	years	y
Li et al. (2024)	onshore oil and gas well	remanufacture	lifetime	cont use*	y	?	years	y
Dara et al. (2019)	containers	repurpose and improve efficiency	service life and lifespan	cont use	?*	?	years	y
Schoch et al. (2023)	phonebooth	repurpose	lifetime	cont use	?*	?	years	y
Hu (2017)	building	repair and improve efficiency	life span	cont use	?*	technological, economic, aesthetic and psychological	years	y
Legarth et al. (2003)	television	repair and improve efficiency	time of use	?*	?*	?	years	y
Legarth et al. (2003)	mobile phone	repair and improve efficiency	time of use	?*	?*	?	years	y
Legarth et al. (2003)	PC	repair and improve efficiency	time of use	?*	?*	?	years	y
Legarth et al. (2003)	frequency converter	repair and improve efficiency	time of use	?*	?*	?	years	y
Van Gulck and Steeman (2023)	building element	reuse	lifespan	cont use*	n*	psychological	years	y

Ref	lifetime integration in equation					Sensitivity analysis				
	Representation in Eqs[2]				Data source[3]	Sensitivity analysis method[2]				
	Single value	No fixed value	Distribution	Out of system boundaries		Testing of different values	Break-even analysis	Comparison with other variables	Probabilistic simulation	Global sensitivity analysis
Priarone et al. (2021)	I,A				I: Assum, A: Assum		A			
Schischke et al. (2019)	I,A				I: Assum, A: Assum					
van Stijn et al. (2022)	I,A				I: Assum, A: Assum	I,A				
van Stijn et al. (2022)	I,A				I: Assum, A: Assum	I,A				

Table 5 (continued)

Ref	lifetime integration in equation					Sensitivity analysis				
	Representation in Eqs[2]				Data source[3]	Sensitivity analysis method[2]				
	Single value	No fixed value	Distribution	Out of system boundaries		Testing of different values	Break-even analysis	Comparison with other variables	Probabilistic simulation	Global sensitivity analysis
Bertin et al. (2022)	I,A				I: Assum, A: Assum					
Williams and Sasaki (2003)	I,A				I: Assum, A: Assum	I,A				
Boldoczki et al. (2020)	I,A				I: Assum, A: Lit	A	I			
Boldoczki et al. (2020)	I,A				I: Assum, A: Lit	A	I			
Boldoczki et al. (2020)	I,A				I: Assum, A: Lit	A	I			
Boldoczki et al. (2020)	I,A				I: Assum, A: Lit	A	I			
Boldoczki et al. (2020)	I,A				I: Assum, A: Lit	A	I			
Boldoczki et al. (2020)	I,A				I: Assum, A: Lit	A	I			
Boldoczki et al. (2020)	I,A				I: Assum, A: Lit	A	I			
Boldoczki et al. (2020)	I,A				I: Assum, A: Lit	A	I			
Bovea et al. (2020)	I,A				I: Assum, A: Lit	I				
Kitayama et al. (2024)	I,A				I: Assum, A: Comp	I				
Casals et al. (2017)	I,A				I: CalcT, A: CalcT	A				
Levänen et al. (2021)	I,A				I: Lit, A: Assum					
Pamminger et al. (2021)	I,A				I: Lit, A: Assum					
Joensuu et al. (2022)	I,A				I: Lit, A: Assum					
Kouloumpis et al. (2023)	I,A				I: Lit, A: Assum					
Kouloumpis et al. (2023)	I,A				I: Lit, A: Assum					
Kouloumpis et al. (2023)	I,A				I: Lit, A: Assum					
Kouloumpis et al. (2023)	I,A				I: Lit, A: Assum					
Kouloumpis et al. (2023)	I,A				I: Lit, A: Assum					
Ardente et al. (2018)	I,A				I: Lit, A: Assum					
Sandez et al. (2024)	I,A				I: Lit, A: Assum	I,A				
Durand et al. (2024)	I,A				I: Lit, A: Lit					
Wilson et al. (2021)	I,A				I: Lit, A: Lit	A	A			
Ardente and Mathieux (2014)	I,A				I: Lit, A:?	A				
Martin et al. (2021)	I,A				I: Comp, A: Assum			A		
Koroma et al. (2022)	I,A				I: Comp, A: Lit	A				
Lonca et al. (2018)	I,A				I: Comp, A: Comp					
Iraldo et al. (2017)	I,A				I: Comp, A: Comp		A			
Iraldo et al. (2017)	I,A				I: Comp, A: Comp		A			
Pérez-Martínez et al. (2021)	I,A				I: Comp, A: Comp	A				

Table 5 (continued)

Ref	lifetime integration in equation					Sensitivity analysis				
	Representation in Eqs[2]				Data source[3]	Sensitivity analysis method[2]				
	Single value	No fixed value	Distribution	Out of system boundaries		Testing of different values	Break-even analysis	Comparison with other variables	Probabilistic simulation	Global sensitivity analysis
Zanghelini et al. (2014)	I,A				I: Comp, A: Comp					
Kim et al. (2024)	I,A				I: Comp, A:?					
Bobba et al. (2018)	I,A				I: Meas, A: CalcT	I,A				
Arrigoni et al. (2018)	I,A				I: Meas, A: Stand					
Farrant et al. (2010)	I,A				I:?, A: Assum					
Kouloumpis et al. (2023)	I,A				I:?, A: Assum					
Dunn et al. (2023)	I,A				I:?, A: CalcT	A				
Mölsä et al. (2022)	I,A				I:?, A: Comp					
Andrae (2018)	I,A				I:?, A:?					
Gervásio et al. (2014)	I,A				I:?, A:?					
Kaddoura et al. (2019)	I,A				I:?, A:?					
Kaddoura et al. (2019)	I,A				I:?, A:?					
Claes et al. (2024)	I,A				I:?, A:?					
Cheung et al. (2018)	I,A				I:?, A: Warr		A			
Richa et al. (2017)	I,A				I: Warr, A: Lit	A				
Carlisle and Friedlander (2016)	I,A				I: Warr, A:?					
Accorsi et al. (2014)	I,A				I: Single, A: Assum	A	A			
López-Muñoz et al. (2025)	I,A				I: Single, A: Assum					
Kidane et al. (2025)	I,A				I: Single, A: Assum		A			
Donahue et al. (2024)	I,A				I: Single, A: Assum	A				
Meister et al. (2023)	I,A				I: Single, A: Comp	A				
Kemble et al. (2023)	I,A				I: Single, A: Meas					
Kaddoura et al. (2019)	I,A				I: Single, A:?	A				
Kaddoura et al. (2019)	I,A				I: Single, A:?	A				
Del Borghi et al. (2021)	I,A				I: Single, A:?					
Kröhnert et al. (2022)	I,A				I: Stand, A: Assum	A				
Wittocx et al. (2022)	I,A				I: Stand, A: Exp	A				
André (2024)	I,A				I: Surv, A: Surv	I,A				
André (2024)	I,A				I: Surv, A: Surv	I,A				
Baboudjian et al. (2023)	I				I: Single					
Jerome et al. (2023)	I	A			I: Comp	A	I,A			
Fetner and Miller (2021)	I	A			I: Single		A			

Table 5 (continued)

Ref	lifetime integration in equation					Sensitivity analysis				
	Representation in Eqs[2]				Data source[3]	Sensitivity analysis method[2]				
	Single value	No fixed value	Distribution	Out of system boundaries		Testing of different values	Break-even analysis	Comparison with other variables	Probabilistic simulation	Global sensitivity analysis
Fetner and Miller (2021)	I	A			I: Single		A			
Fetner and Miller (2021)	I	A			I: Single		A			
Fetner and Miller (2021)	I	A			I: Single		A			
Bressanelli et al. (2022)	I		A		I: Lit, A: Surv				A	
Proske (2022)	T				T: Assum	T				
Palacios-Munoz et al. (2019)	T				T: Assum	T				
Proske (2022)	T				T: CalcS					
Sabbaghi and Behdad (2017)	T				T: CalcS	T				
De Saxce et al. (2012)	T				T: CalcT	T				
Van Belleghem et al. (2017)	T				T: CalcT	T				
Palacios-Munoz et al. (2019)	T				T: CalcT	T				
Temizel-Sekeryan et al. (2023)	T				T: Lit					
Palacios-Munoz et al. (2019)	T				T: Lit					
Kaddoura et al. (2019)	T				T:?					
Van Gulck et al. (2022)	T				T:?					
Henao et al. (2024)	A			I	A: Assum					
Li et al. (2024)	A			I	A: Assum		A			
Dara et al. (2019)	A			I	A: Lit					
Schoch et al. (2023)	A			I	A:?					
Hu (2017)	A			I	A:?					
Legarth et al. (2003)		A		I			A			
Legarth et al. (2003)		A		I			A			
Legarth et al. (2003)		A		I			A			
Legarth et al. (2003)		A		I			A			
Van Gulck and Steeman (2023)		I,A								I,A

Symbols used in the table: [1]y: yes, n: no, cont use: continuous use,?: not reported or not possible to interpret from the text, *:assumptions made during interpretation. 2: I and A are used for the initial lifetime and additional lifetime, respectively, if lifetime partitioning is done. Otherwise, T stands for total lifetime. 3: Using the same I, A, T distinction: Assum: assumption, Comp: manufacturing company, Lit: literature, CalcT: calculated based on technical parameters, CalcS: calculated based on statistical data, Meas: measured data, Warr: product warranties, Stand: standard, Exp: expert judgement, Surv: user survey, single: single-use product,?: not reported.

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Data availability Data supporting the findings of this study are available within this published article and presented in Appendix A.

Declarations

Competing interests The authors declare no competing interests.

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