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LCI METHODOLOGY AND DATABASES

Product lifetime approaches in life cycle assessments of circular economy

Adeline Jerome[1] · **Maria Ljunggren**[1] · **Fabrice Mathieux**[2] · **Silvia Bobba**[2] · **Fulvio Ardente**[2]

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Abstract
Purpose Life cycle assessment (LCA) has been widely used to assess the environmental benefits of lifetime extension, a circular economy strategy for reducing product impact. However, although such LCA results are sensitive to product lifetime, the selection between existing lifetime modelling approaches has not been discussed so far. Therefore, this study aims to provide recommendations on the selection of suitable lifetime modelling approaches for LCAs of lifetime extension.
Methods Three modelling approaches have been used to express product lifetime in the life cycle inventory and impact assessment: single values, a no-fixed value or a distribution. They are compared using two different illustrative cases of mattress remanufacturing and high-voltage electric motor repair. Typical questions that are answered with each approach are formulated, and recommendations are provided for suitable approaches to various LCA goals.
Results and discussion LCA results with all three approaches can be used to compare a baseline to an alternative with lifetime extension. However, each approach answers different typical, more detailed questions. A modelling approach using single values is suitable for identifying hotspots and burden-shifting. Using a no-fixed value informs on the range of validity of the results and a quantified lifetime break-even value for lifetime extension to be environmentally beneficial. Finally, using a lifetime distribution over a population provides information on the spread and average change in environmental impact when lifetime extension is implemented over this population.
Conclusions This diversity of typical questions demonstrates the importance of choosing the lifetime modelling approach based on the goal of LCA of lifetime extension. The most common approach with a single and fixed lifetime value cannot always be adequate for LCAs of lifetime extension.
Recommendations Practitioners are recommended to define the goal of their LCA and select a lifetime modelling approach adapted to this goal. To support this selection, the study synthesises suitable modelling approaches for typical questions in public policy and business applications.

Keywords Lifetime extension · Reuse · Repair · Remanufacturing · LCA methodology · Lifespan · Obsolescence · Service lifetime

1 Introduction

Extending the lifetime of products has been advanced as fundamental for the circular economy (CE) (Bocken et al. 2016). Strategies such as reuse, repair or remanufacturing are suggested to reduce products' environmental impacts. Life cycle assessment (LCA) is widely used to estimate the impact of such lifetime extension. For instance, in policy development, LCA has been used to prioritise circular strategies to implement for different groups of products and to set ecodesign requirements and product labelling (Sala et al. 2021). In business, LCA is a common tool in product design, market communication (e.g. ecolabels) and regulatory compliance (Baumann and Tillman 2004) including applications to CE (Böckin et al. 2020). In scientific research, LCA is a common assessment method for understanding changes in environmental impacts generated by circular strategies (Harris et al. 2021; Sassanelli et al. 2019).

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✉ Adeline Jerome
adeline.jerome@chalmers.se

[1] Chalmers University of Technology, Gothenburg, Sweden

[2] European Commission, Joint Research Centre (JRC), Ispra, Italy

LCAs of lifetime extension strategies highlight that product lifetime is crucial for the results and conclusions regarding these strategies (Ardente and Mathieux 2014; Jerome et al. 2023; Richter et al. 2024). Extending the product lifetime might not always lead to environmental impact reduction (for example, in different contexts of use for e-scooter sharing in Severengiz et al. (2021)). When lifetime extension results in environmental benefits, the extent of those benefits varies significantly with the assumed extension of the lifetime value (Jerome and Ljunggren 2025). For instance, using a reusable event tent five times results in a 42% reduction in global warming impact compared to a single-use alternative, whilst using it only twice results in a 27% reduction (Kaddoura et al. 2019). In Ardente and Mathieux (2014), the reduction in global warming impact from repairing a washing machine is more than two times smaller when considering a lifetime extension of 1 year instead of 4 years. Also, lifetime extension does not necessarily result in environmental impact reduction compared to replacement. It depends on how long the initial lifetime before extension is and how long the additional lifetime after extension will be. For example, a repaired product has to be used for a minimum additional lifetime to pay off the impact of the repair (Ardente and Mathieux 2014; Jerome et al. 2023), and this minimum additional lifetime value increases with the initial lifetime (Jerome et al. 2023). For energy-using products for which energy efficiency may improve over time, continuing to use an existing product through repair might be more impactful than producing and using a more energy-efficient one (e.g. washing machines (Ardente and Mathieux 2014; Boldoczki et al. 2020), refrigerators (Boldoczki et al. 2020; Iraldo et al. 2017) and servers (Ardente et al. 2018)). The longer the initial lifetime, the bigger the difference in energy efficiency between an old and a new product could be, so the chance for lifetime extension not being beneficial in comparison to replacement.

The concept of product lifetime is not trivial (den Hollander et al. 2017; Jerome and Ljunggren 2025). Product lifetime refers to the use phase of products, but the terminology and its definitions are not unified (Murakami et al. 2010). Jerome and Ljunggren (2025) identify three types of lifetime based on Cooper (2010) and Diener (2017):

1. The *service lifetime* is the time between acquisition and end-of-use.
2. The *technical lifetime* is the time from the acquisition until the product no longer has the physical capacity to function. It is as long as or longer than the service lifetime.
3. The *use time* is the effective time during which the product is actually in use, thus excluding periods within the service lifetime when the product is not in use.

Modelling product lifetime in LCA is not only challenging due to the different types of lifetime but also due to a lack of information about product lifetime and its uncertainty and variability (Cooper 2010; Günther and Langowski 1997; Pohl et al. 2019). Studies of lifetime extension often concern future strategies for which experience about their implementation may be limited. When lifetime information exists, it is often uncertain as it is predicted with historical data or product durability tests (Cooper 2010). In addition, product lifetime varies across users due to differences in user behaviour (Cooper 2010; Pohl et al. 2019; Polizzi di Sorrentino et al. 2016).

In LCAs of lifetime extension, these challenges have been addressed to various extents through different modelling approaches. Based on the review of 65 cases of LCA of lifetime extension, three main approaches have been identified (Jerome and Ljunggren 2025):

– The lifetime modelling approach with single values, hereafter *Single*: The most common approach, using a single, fixed lifetime value in LCA calculations. Variations and uncertainties are addressed by doing calculations for different values.
– The modelling approach using a no-fixed value, *No-Fixed*: The lifetime is left as a variable in the inventory and the function for calculating environmental impacts. LCA results are calculated for a range of variable values, and the results can be plotted against the product lifetime.
– The approach with a distribution, *Distribution*: A distribution of lifetime values representing a population of users to use the product is used, and calculations for each element of the population are made. LCA results show the distribution of environmental impact values across the population. It has been found in only one of the reviewed cases (Bressanelli et al. 2022).

However, little guidance exists on which modelling approach to select, neither in LCA standards nor in literature (Jerome and Ljunggren 2025). As product lifetime has been shown in LCA as key for the environmental benefits of lifetime extension, developing recommendations for product lifetime modelling could support a more structured and conscious choice of approach. Methods for predicting the lifetime of components in LCAs of buildings have been developed and compared (Goulouti et al. 2020; Grant and Ries 2013; Morales et al. 2021; Silvestre et al. 2015), but the methods and recommendations are specific to buildings and not generally applicable to other products. Some of the methodological challenges for LCA of circular strategies, such as multifunctionality allocation of recycling or the choice of functional unit with multiple use cycles, have sparked discussions (Hellweg et al. 2023), but good practises for LCA of lifetime extension have not yet been discussed.

Therefore, this article identifies which product lifetime modelling approach to choose for what LCA goal. To this end, the three lifetime modelling approaches are applied in illustrative cases and compared. Departing from the conclusions obtained from the comparison, typical questions answered by LCA results are developed, and recommendations are provided.

2 Method

This study builds on three steps. First, the three product lifetime modelling approaches and lifetime sensitivity analysis identified by Jerome and Ljunggren (2025) are applied to two cases of lifetime extension strategies. The study specifically focuses on (1) a spring mattress, a consumer product with a lifetime that is typically several years but varies across users, and (2) a high-voltage (HV) electric motor, an energy-using product used in industry with a lifetime of several dozens of years. These products are very different in material composition and use patterns and illustrate the effect of non-energy-using and energy-using use phases. The methodology used for this step is further detailed in the subsections below.

Second, the LCA results obtained with each approach are interpreted and compared. Typical questions answered by the results are developed to highlight the differences in the information provided by applying each modelling approach.

Finally, guidance on selecting modelling approaches given a specific LCA goal is developed based on the identified typical questions.

2.1 Goal and scope definition of the LCAs

For each case, cradle-to-grave attributional LCAs were carried out for a baseline and an alternative where the lifetime is extended through remanufacturing (mattress) or repair (motor). In the baseline, the product is used and disposed of through a mix of recycling, incineration and landfilling. In the extended lifetime alternative, the product is used for the same amount of time as in the baseline, remanufactured or repaired and used for an additional lifetime before being disposed of in the same manner as in the baseline. Product replacement with exactly the same product (and thus the same lifetime) is addressed with the baseline environmental impact per year of use. Replacement with a different product fulfilling the same function but with other properties (e.g. with different energy efficiency or other materials) is not addressed.

The aim is to test different lifetime modelling approaches when comparing a product in a baseline situation to an alternative with a lifetime extension. Hence, the main question to be answered by the comparative LCAs with each modelling approach is:

> What is the difference in environmental impact between a baseline and an alternative with a lifetime extension?

A cut-off approach has been applied for the allocation of the end-of-life phase, as the focus is on the product lifetime modelling. Modelling and calculations have been carried out on Python with brightway (Mutel 2017) (the code is available at https://github.com/AdelineJerome/lifetime-approaches-lca), and background data were modelled with average data from the ecoinvent 3.9.1 cut-off database (Wernet et al. 2016). The impact categories calculated are the ones suggested by the environmental footprint method (EF v3.1) (Andreasi Bassi et al. 2023) as implemented in ecoinvent. Although the LCAs can provide insights into the specific cases investigated, they primarily serve as *illustrations of the modelling approaches*. Lesser attention has thus been paid to data collection and other steps required if they were primarily to be LCA studies of the empirical cases themselves.

The different cases and their product lifetime modelling approaches are briefly described below. More detailed information is available in Supplementary Information (SI) 1 (Section S1).

2.2 Description of the cases

2.2.1 Remanufacturing of spring mattresses

The composition of a spring mattress, as well as energy requirements for mattress production, is based on Lanoë et al. (2013) and represents a Portuguese producer in 2010. Quantities are for a one-person 1 × 2 m spring mattress essentially made of steel springs, polyurethane foam and a polyester and cotton fabric cover. The mattress is considered sufficient for comfortable bedding (no additional mattress is required).

It is assumed that no maintenance or washing occurs during use. At end-of-life, the mattress is assumed to be collected for treatment, where steel springs are recycled and the foam and textile cover incinerated.

As an alternative with a lifetime extension strategy, the mattress is remanufactured as suggested by Glew et al. (2012): the old textile and foam are replaced, and the steel springs are reused. The energy required for the remanufacturing process is retrieved from Glew et al. (2012) using an estimation by a British mattress manufacturer.

The functional unit is 1 year of use of a one-person 1 × 2 m spring mattress.

2.2.2 Repair of HV electric motors

The case, based on Jerome et al. (2023), addresses HV electric motors, big electric motors used in the industry to, e.g. drive fans and compressors in the oil and gas or pulp and paper industries. The motors run continuously until failure, except during planned maintenance for 2 weeks per year. In this case, the functional unit is thus 1 year of use of an HV motor with 16,000 kW output running full time except for 2 weeks. The case is based on an HV induction motor made of steel, copper and plastics and is collected for recycling at end-of-life (Jerome et al. 2023). Since the most frequent failure occurs in the copper windings in the static part of the motor (Thorsen and Dalva 1999), it is assumed that the repair involves replacing the faulty copper windings with new ones, following the description in Jerome et al. (2023).

2.3 Lifetime modelling

For each of the cases, the product lifetime is modelled using the three modelling approaches following the conclusions from Jerome and Ljunggren (submitted). Different lifetime data sources are used: literature and manufacturing companies for *Single*, no data are required for *No-Fixed*, and user surveys are used for *Distribution*.

Sensitivity analysis for both the initial and additional lifetime is carried out for each approach:

- A testing of several lifetime values for *Single*: different lifetime values are selected and used in LCA calculations,
- A break-even analysis for *No-Fixed*: the lifetime value at which the ranking between the baseline and the alternative with lifetime extension is flipped,
- A probabilistic simulation with *Distribution:* a sample of lifetime values representing the lifetime distribution is propagated to the LCA results. The *Distribution* approach in itself can be considered a sensitivity analysis.

2.3.1 Remanufacturing of spring mattresses

Information on mattress lifetime duration and the reasons for users to change mattresses is available through user surveys conducted by the International Sleep Products Association (Perry 2023) and the company Sleep Doctor (Shane 2023), both conducted on a sample of adults in the USA in 2022.

The reasons for mattress replacement are more related to preferences in materials, firmness and size than signs of lower fulfilment of mattress function due to changes in users' physical health (Shane 2023). Therefore, the service lifetime of the product is considered. The reported mean value for the service lifetime is 8.3 years in 2022 (Perry 2023), used for *Single*. Other lifetime values for sensitivity analysis with *Single* were selected to be representative of low (4 years) and high (20 years) lifetime values. The distribution amongst the respondents is used to estimate the lifetime distribution over a population of 10,000 spring mattresses in Fig. 1 (see SI1, Section S2.1), used for *Distribution*.

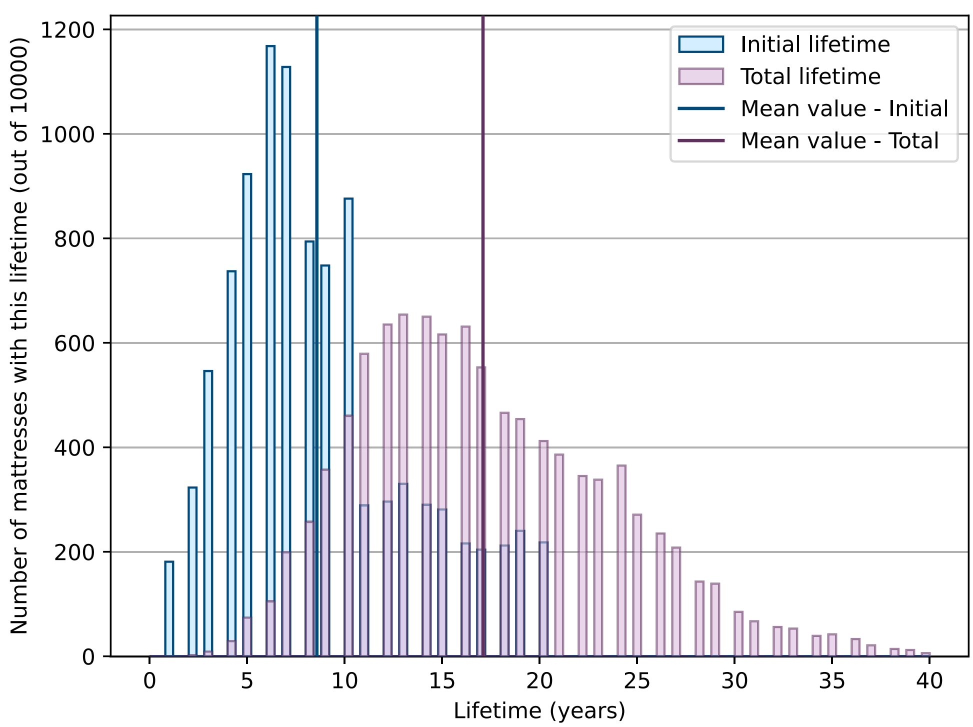

Fig. 1 Distribution of the service lifetime of mattresses without remanufacturing (initial lifetime, blue bars) and with remanufacturing (total lifetime = initial lifetime + additional lifetime provided by the remanufacturing, purple bars). The two distributions are superposed on the same figure, using transparent filling colours

No information is available on the lifetime of remanufactured mattresses. Since remanufacturing can be defined as a process to restore a product to a state as good as new (Sundin 2004), it was assumed that a mattress could have the same service lifetime and be replaced for the same reasons as new mattresses. Therefore, the same set of values as for the initial lifetime was used for *Single*. Besides, the resulting distribution over the same population of 10,000 mattresses as for the baseline was calculated (see SI1, Section S2, and Fig. 1) and used for *Distribution*.

2.3.2 Repair of HV electric motors

No information was found on the duration of the lifetime of electric motors with an output power as high as the studied motor in Jerome et al. (2023). However, the lifetime of motors has been reported to increase with their output power. A mean lifetime value of 20 years was reported for motors with an output between 75 and 250 kW (de Almeida et al. 2008; Walters 2000), and a mean lifetime value of 29.3 years with a range between 25 and 38 years was observed for motors with an output above 95 kW in Hasanuzzaman et al. (2011). Based on these data for motors with lower output powers, the lifetime of the specific motor with an output of 16,000 kW was conservatively estimated to be 20 years and used for *Single*.

Since HV motors are commonly run until failure (Jerome et al. 2023), it was assumed that HV motors are used for their full technical lifetime. A survey on HV motors in offshore petrochemical industries shows that failure rates increase with the age of motors (Thorsen and Dalva 1999). These data are used to estimate a lifetime distribution over a population of 50,000 HV motors (see SI1, Section S2, and Fig. 2). The study does not comment on the high failure rate of young motors (0–5 years) compared to older ones (5–15 years) but suggests that the starting procedure of the surveyed motors contributes to failures.

As for mattresses, no data on the lifetime of repaired motors were found. For testing *Distribution*, it was assumed that the motor after repair has the same technical lifetime as a new motor and thus with the same distribution as a new motor (see SI1, Section S2, and Fig. 2).

For sensitivity analysis with *Single*, a set of lifetime values with a low (1 year), mean (20 years) and high (40 years) value was selected based on the obtained distribution and tested for both the initial and additional lifetime.

2.4 Presentation of LCA results

The LCA results for each alternative (i.e. the baseline and extended lifetime alternative) are presented per functional unit, which is in both cases expressed as 1 year of use of the product (Section 2.2). This means that resources, emissions and waste flows in the extraction, production and end-of-life phases are divided by the lifetime, whereas the use phase represents 1 year. Since the lifetime differs between the two alternatives, the functional unit needs to account for time, and a functional unit expressed only as one product would be inappropriate for comparing the alternatives. With the

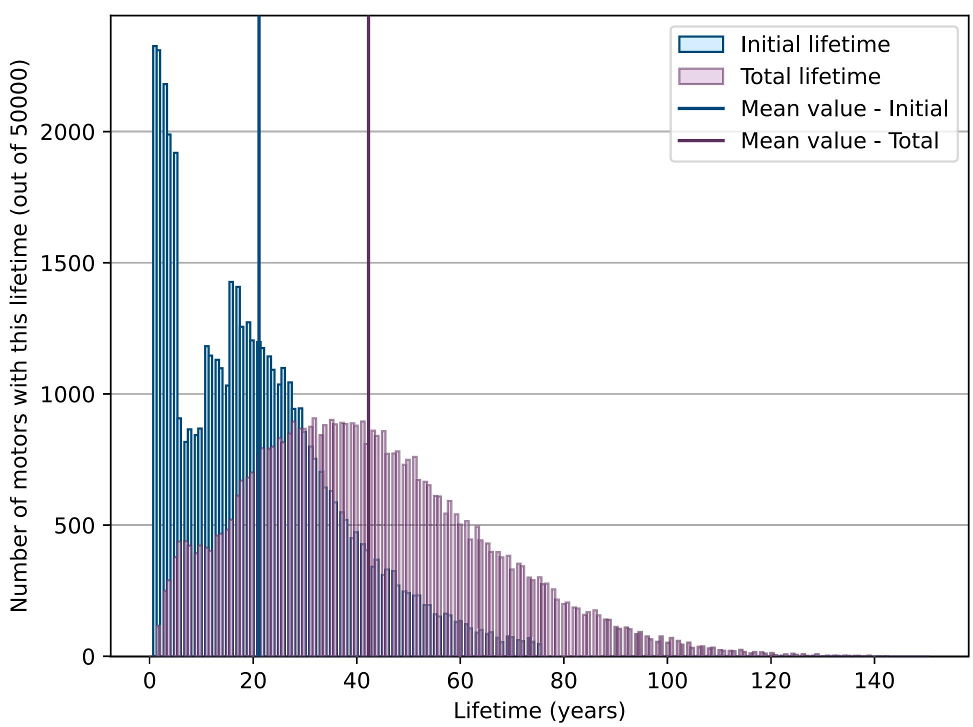

Fig. 2 Distribution of the technical lifetime of HV motors without repair (initial lifetime, blue bars) and with repair (total lifetime = initial lifetime + additional lifetime, purple bars) to be used with *Distribution*. The two distributions are superposed on the same figure, using transparent filling colours

choice of 1 year of use as the functional unit, the impacts of products with different total lifetimes can be compared.

With *Single*, one environmental impact value is obtained for each alternative (Fig. 3). With *No-Fixed*, the environmental impact is expressed as a function of the lifetime. With *Distribution*, environmental impact values for both alternatives are obtained for each product in the assessed population. LCA results are presented as bar charts for the single values with *Single*, plots against the lifetime with *No-Fixed*, and histograms for representing the lists obtained with *Distribution* (Fig. 3).

The results from sensitivity analysis are presented in the same figure as the LCA results with additional bars with different lifetime values for the *Single* modelling approach and with the resulting environmental impact distribution presented as a histogram for the *Distribution* modelling approach.

3 Results and discussion

Each of the lifetime modelling approaches results in largely similar types of results for the two cases and across environmental impact categories. Thus, the results of global warming GWP100 impact are presented, whereas others are presented in the supplementary information (SI1, Section S6). Besides, the results and discussion are mainly supported by the results from the mattress case, adding complementing or contrasting results from the HV motor case. Any result for the HV motor not presented here is available in SI1, Section S5.

3.1 Modelling lifetime using single values

For all lifetime modelling approaches, the main question to be answered with the LCA results is "What is the difference in environmental impact between a baseline and an alternative with a lifetime extension?". However, each lifetime modelling approach can provide various information that answers different, more detailed questions. Based on testing the approaches, it is possible to formulate several typical questions that each modelling approach can address.

With *Single*, one value of the lifetime at a time is presented. One value for the initial and the additional lifetimes is chosen, and several for a sensitivity analysis. Results are shown for the environmental impact expressed per lifetime unit and, to illustrate the crucial inclusion of time in the

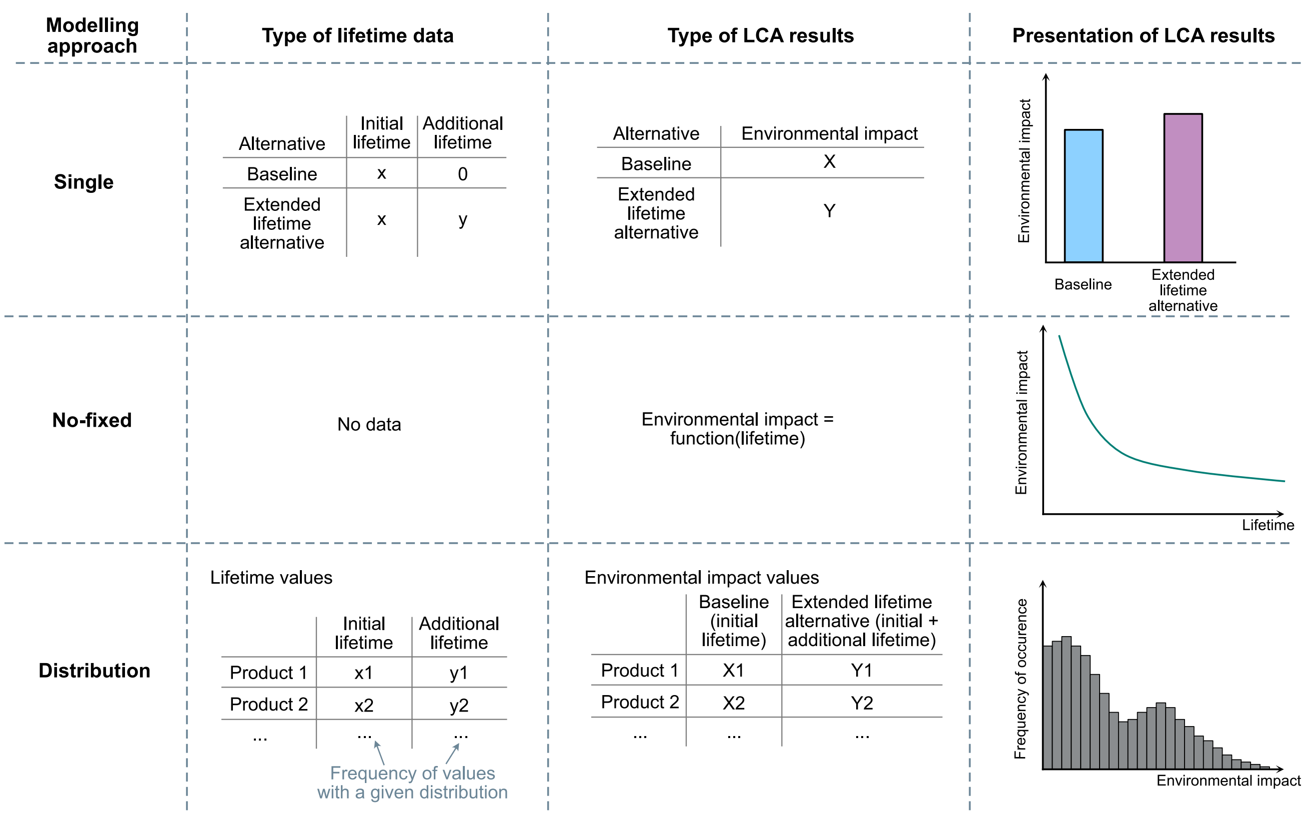

Fig. 3 Representation of the type of lifetime data, LCA results and presentation of LCA results for the three lifetime modelling approaches as used for the calculations and analysis of results

functional unit, per product (excluding time) for selected lifetime values in Fig. 4 (all results are in S1, Section S5).

When environmental impacts are expressed per product, the lifetime value does not influence the results for the mattress (Fig. 4a). For products with an impact during use, such as the HV motor, the longer the lifetime value, the higher the environmental impacts are when expressed per product (Fig. 4b). When environmental impacts are expressed per functional unit which includes a unit of time, it is clearly shown that the lifetime value influences the results (Fig. 4c, d): the contribution from production, repair and end-of-life treatment phases is reduced with higher lifetime values since it is divided by the lifetime (Fig. 4c, d), and the contribution of use is the impact of 1 year of use (Fig. 4d). Thus, this demonstrates that analysis of lifetime extension strategies should account for the time, and results presented per product are inappropriate for comparisons involving different lifetimes.

Several typical questions are suitable to be answered by the results and sensitivity analysis with *Single* based on the testing (Fig. 4c, d):

- *What is the difference in environmental impact between a baseline and an alternative with lifetime extension for a specific lifetime value?* The environmental impact of the baseline and alternatives with lifetime extension can easily be compared.
- *What is the contribution of different processes or life cycle phases to the environmental impact?* For instance, it is possible to conclude that the production is dominant and remanufacturing results in a comparable but lower impact than production for global warming for the mattress (Fig. 4c).
- *For which assessed lifetime values does lifetime extension reduce the environmental impact of a product?* Indeed, a minimum additional lifetime is required for lifetime extension to be beneficial. So, a short additional lifetime does not result in a lower environmental impact per functional unit than a product with the same initial lifetime. For instance, a mattress used for 8.3 years ("baseline (8.3 y.)" in Fig. 4b) results in lower global warming than a mattress used for 8.3 years and remanufactured to be used 4 additional years ("reman. (8.3 +4 y.)") but

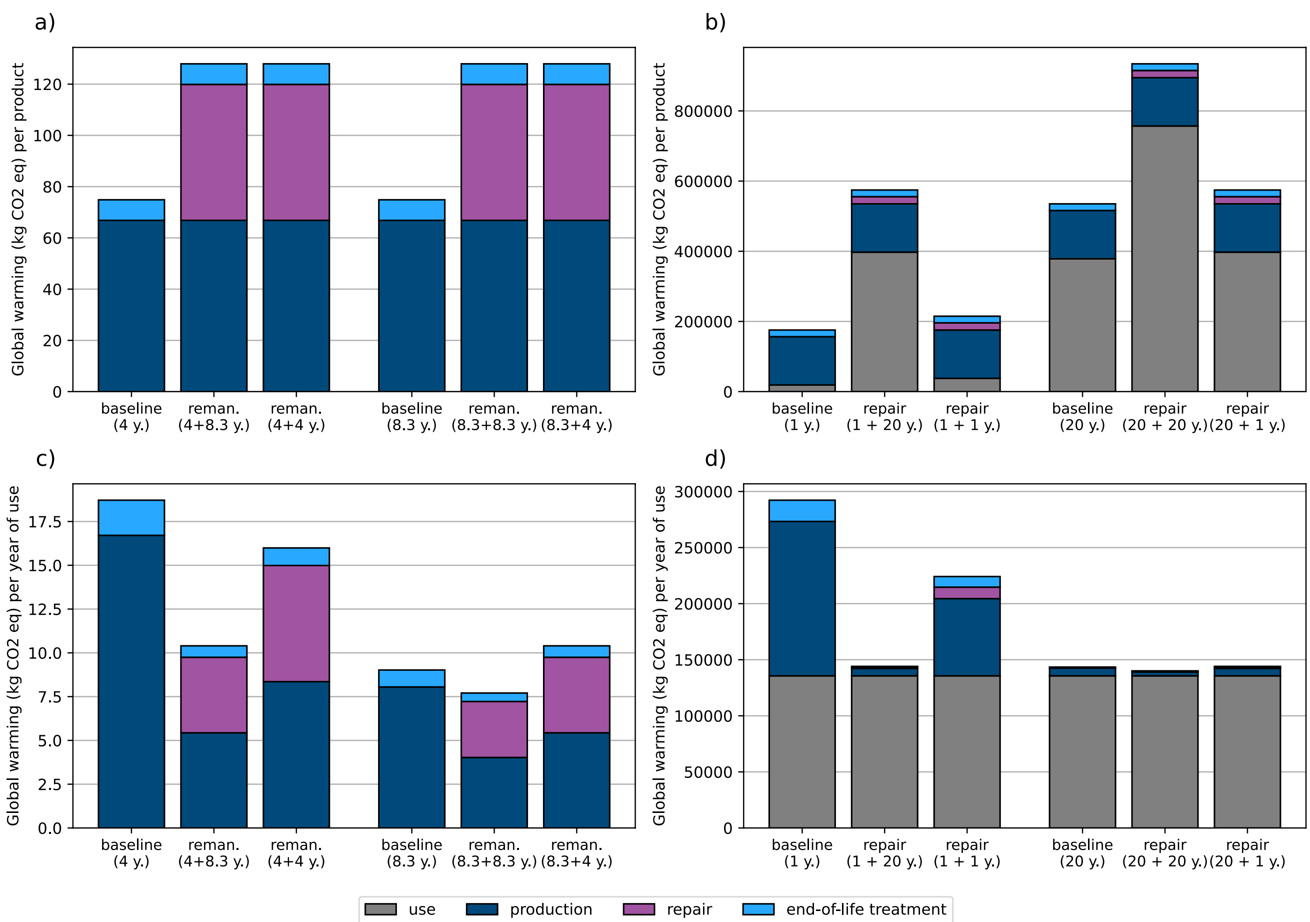

Fig. 4 Global warming impact for the mattress and HV motor case **a** per mattress, **b** per motor, **c** per year of mattress use and **d** per year of motor use for different baseline and lifetime extension scenarios with *Single* (reman. = remanufacturing, y. = years)

in higher global warming than a remanufactured mattress used for twice as long ("reman. (8.3 + 8.3 y.)"). The value of the required additional lifetime can be estimated to be between 4 and 8.3 years.

3.2 Modelling using no fixed values

With *No-Fixed*, the lifetime value is left variable. As a result, the environmental impact as a function of the total lifetime of the product can be plotted (Fig. 5). From a wide range of lifetime values, a suitable range to display in the figure was selected for variations to be visible.

The figure can be used to identify the minimum additional lifetime necessary to pay off the impact of the lifetime extension action (e.g. the mattress remanufacturing), i.e. for the alternative with lifetime extension to have a lower impact per year of use than the baseline. As an example, the environmental impact at an initial lifetime of 8.3 years corresponds to 9.0 kg CO_2 eq per year of use. The same value of environmental impact for the remanufacturing alternative corresponds to a total lifetime of 14.2 years or, in other words, the minimum total lifetime (i.e. initial and additional lifetime) for lifetime extension to result in a lower impact than the baseline alternative, called break-even lifetime value. The required additional lifetime in this example is thus 5.9 years. Higher additional lifetime values further reduce the environmental impact of the remanufacturing alternative.

Figure 5 also shows that the higher the initial lifetime, the higher the required additional lifetime for this case. This is because the environmental impact gradually flattens out with increasing lifetimes, as the impact per mattress is estimated to remain constant over time. For example, one additional year after an initial lifetime of 5 years leads to a reduction of the impact by 1/30 (1/5 of the impact after a 5-year lifetime to 1/6 of the impact after a 6-year lifetime), whilst one additional year after a lifetime of 10 years leads to a reduction by 1/110. Besides, the older the product, the lower the impact per year of use, so it takes a longer additional lifetime, but still below the initial lifetime, to match the low impact of an older product. In practise, when deciding to repair or replace a product with an identical one and the products' characteristics are expected to remain constant over time, it is environmentally preferable to replace the old product with a new product and *use it as long as* the old one if the old product is unlikely to last long after repair.

To further focus on analysing the break-even value, a sensitivity analysis is done with a break-even analysis. The value of the lifetime ratio for the lifetime extension

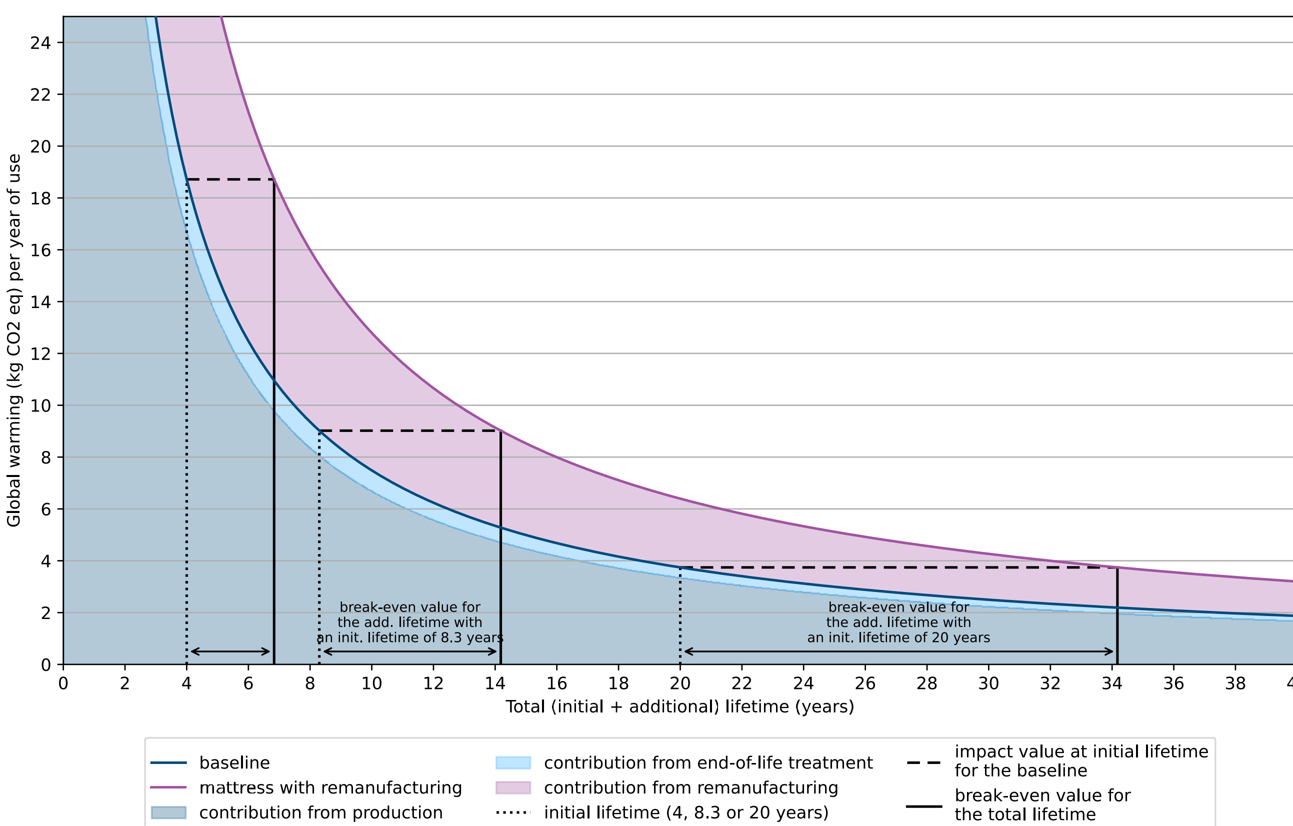

Fig. 5 Global warming impact for the baseline and a mattress with remanufacturing and the baseline per year of use depending on the total lifetime with *No-Fixed*. Examples of break-even values are shown for an initial lifetime of 4, 8.3 and 20 years

alternative to be beneficial is calculated (see SI1, Section S4) and plotted (Fig. 6):

$$\frac{L_{add}}{L_i} = \frac{I_r}{I_p + I_{eol}} \tag{1}$$

with

L_i the initial lifetime,

L_{add} the additional lifetime,

I_p the environmental impact of the production, including material production and product manufacturing (cradle-to-gate),

I_{eol} the environmental impact of the end-of-life treatment, including all impacts occurring after use,

I_r the environmental impact of all activities related to the lifetime extension (e.g. preparation for repair, additional transport, material production for the repair, end-of-life treatment of replaced materials).

The minimal additional lifetime for lifetime extension to be beneficial therefore depends on the initial lifetime of the product, as identified on Fig. 5, and the impact of all activities in the product's life cycle except the use phase. It also depends on the ratio of the impact from repair to the combined impact from production and end-of-life treatment. For instance, for mattress remanufacturing after an initial use of 8.3 years and for global warming, the minimum additional lifetime is 5.9 years (Fig. 6), explaining the lifetime break-even value of 14.2 years visible on Fig. 5. In contrast, the minimum additional lifetime for the HV motor repair is only 1.1 years for the same initial lifetime (Fig. 6) because the repair involves replacing a less extensive share of the product compared to mattress remanufacturing. From Eq. (1), it is also clear that the minimum additional lifetime is lower than the initial lifetime if the impact for the lifetime extension activity is lower than for the production and end-of-life treatment. In some cases, the environmental impacts during the use phase could change after the lifetime extension activity as, for example, repair can negatively affect energy efficiency (Jerome et al. 2023). Equation (1) then needs to be replaced by Eq. (2), which is available in SI1, Section S4.

Thus, several typical questions can be answered with *No-Fixed*:

– *How does the environmental impact vary with product lifetime?* This evolution would be provided for the impact of the product with (purple line on Fig. 5) and without (blue line) lifetime extension and for the impact difference between the two alternatives (purple area on Fig. 5).
– *What is the range of lifetime values for lifetime extension to be beneficial?* Or, for a more precise question: *what is the break-even lifetime value for lifetime extension to*

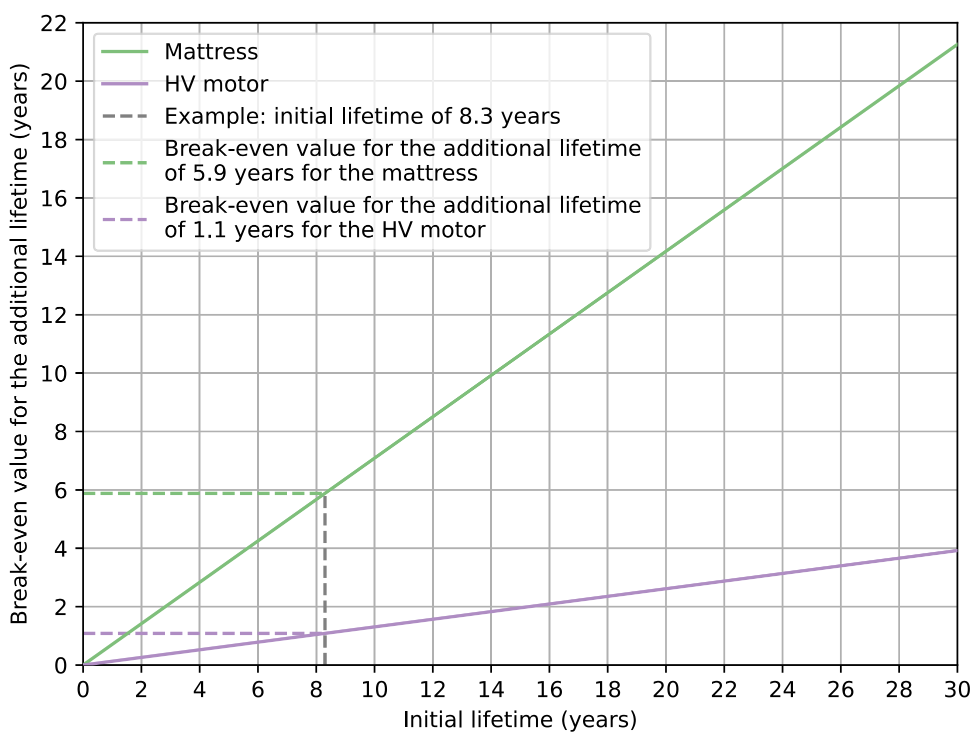

Fig. 6 Results of the sensitivity analysis with *No-Fixed*: additional lifetime at break-even between the environmental impact of a remanufactured and a non-remanufactured mattress as a function of the initial lifetime

be beneficial? Unlike when using *Single*, a minimum required additional lifetime is directly calculated rather than estimated through iterative approximation.

Additionally, if different contributions are also calculated as a function of the lifetime, it is possible to answer:

– What is the contribution of different activities or life cycle phases to the environmental impacts?

3.3 Modelling with a distribution

With *Distribution,* it is possible to calculate the environmental impact of all products within a specific population. This population represents, e.g. the individual products used by different users in a product's market. Accounting for a product lifetime distribution in the mattress and HV motor cases, results of the comparison of the environmental impact per functional unit for 10,000 mattresses and 50,000 motors for a baseline and alternative with lifetime extension are presented in Fig. 7 (the table of results is presented in SI2).

Figure 7a, b presents how many mattresses (respectively motors) in the population (*y*-axis) result in a given range of environmental impact per functional unit (*x*-axis). The histograms represent the distribution of the environmental impact per year of use of the 10,000 mattresses (respectively 50,000 motors) in the population for both all products of the population for the baseline (blue bars) and with lifetime extension (purple bars). High bars represent frequent environmental impact values in the population.

By comparing the distributions for the baseline and the alternative with lifetime extension, it is possible to identify changes in the frequency of environmental impact occurrence. For instance, the blue bars above 15 kg CO_2 eq in Fig. 7a highlight a high frequency of mattresses with a high impact per year of use, and thus a significant group of users disposing of the mattress after a short initial lifetime. The purple distribution shows a lower frequency of high environmental impact, indicating that lifetime extension of mattresses would be effective for user groups changing their mattress frequently. The mean environmental impact value of the population for the baseline and the alternative with lifetime extension can be calculated and shows that mattress remanufacturing results in an environmental impact reduction on average for the analysed population (from 14.6 to 9.5 kg CO_2 eq per year of use in Fig. 7a).

To identify the number of mattresses from the population for which remanufacturing results in an impact reduction, it is possible to calculate and plot the difference in the environmental impact of the baseline and the alternative with lifetime extension (Fig. 8).

Figure 8 shows a high frequency of a small or no difference in global warming between the alternative with lifetime extension and the baseline. However, on average, the impact reduction is 5.0 kg CO_2 eq due to a few mattresses with a high impact reduction. Thus, remanufacturing is much more beneficial for a small part of the analysed population than for a large part.

Similarly to the mattress case, repaired HV motors result in a reduction of the mean environmental impact value compared to non-repaired motors in the analysed population of motors (from 158 to 142 tons CO_2 eq per year of use in Fig. 7b). This reduction is higher than the one calculated with *Single* for a motor with an initial lifetime of 20 years and an additional lifetime of 20 years (from 143 to 140 tons CO_2 eq per year of use in Fig. 4d). This is due to the high failure rate of young motors (see Section 2.3.2). Motors that fail early have a high impact per year of use. Repairing these

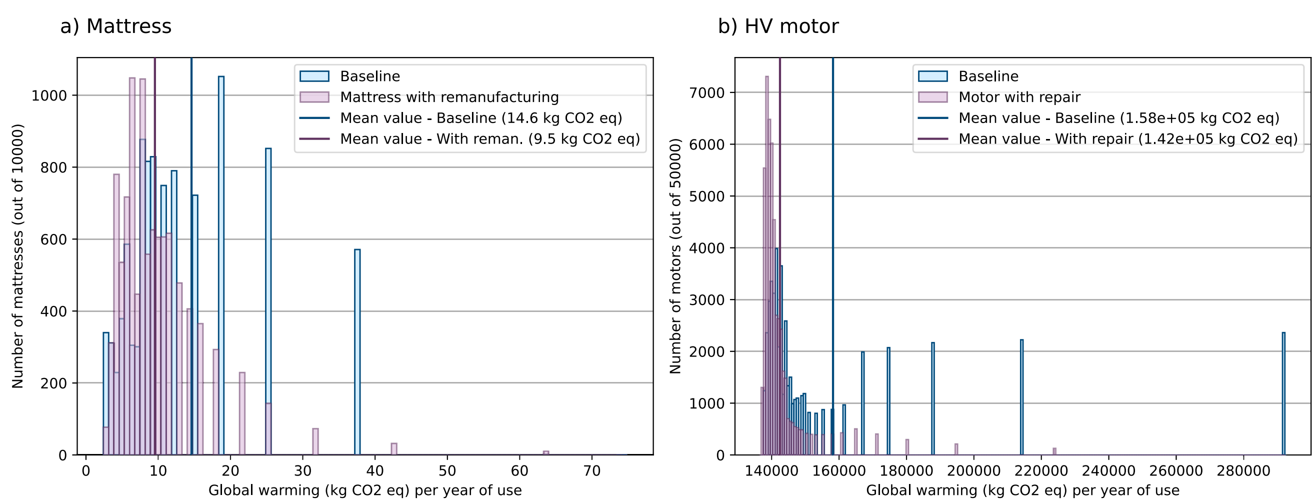

Fig. 7 Distribution of the global warming impact of **a** mattresses and **b** HV motors for the baseline (blue bars) and with lifetime extension (purple bars) per year of use with *Distribution*. The two distributions are superposed on the same figure, using transparent filling colours

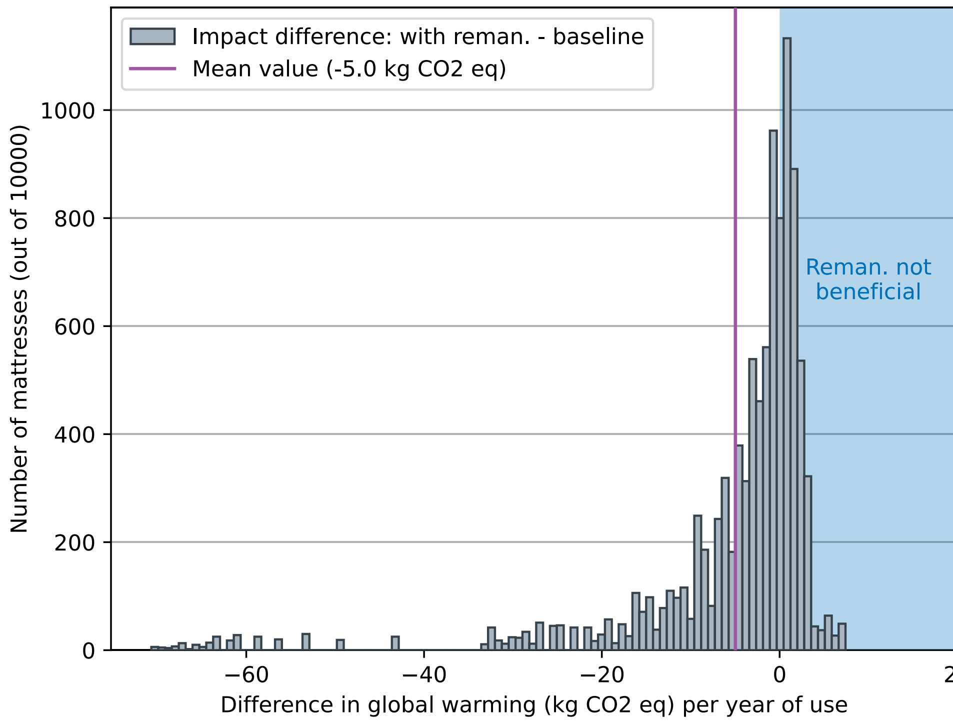

Fig. 8 Distribution of the relative impact between the compared alternatives, i.e. the difference of impact between the alternative with lifetime extension and the baseline for the case of the remanufactured mattress with *Distribution*

motors significantly reduces this impact. Since early failures are common in the analysed motor population, calculating the mean impact value across the population emphasises the average benefits of repairs for a population with frequent early failure. It also highlights that using a *Single* approach with average lifetime values, e.g. from statistical analysis (Palacios-Munoz et al. 2019; Sabbaghi and Behdad 2017) or calculated with stock-based models (Proske 2022), does not result in the same impact as the average environmental impact on the population.

Figures 7 and 8 cannot be used to trace back each combination of initial and additional lifetimes that results in improvements. Instead, the full table of results over the population has to be used. In a histogram, products that could have different lifetime values but comparable environmental impacts are grouped in the same bar. For instance, an initial lifetime of 4 years followed by an additional lifetime of 8.3 years ("reman. (4 + 8.3 y.)" in Fig. 4b) results in the same impact of 10 kg CO_2 eq per functional unit as an initial lifetime of 8.3 years followed by an additional lifetime of 4 years ("reman. (8.3 + 4 y.)"). Both combinations are thus gathered in the same purple bar around 10 kg CO_2 eq per functional unit in Fig. 7a.

Distribution can thus be used to answer several typical questions:

– *What is the distribution of the environmental impact for 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?*

However, the question of why lifetime extension is not beneficial for some products in the population is more easily addressed through the other modelling approaches (*Single* or *No-Fixed*).

Product lifetime and its extension are partly reliant on uncertain consumer behaviour (den Hollander et al. 2017; Hellweg et al. 2023; Pohl et al. 2019) which varies with user groups (Cooper 2010). As lifetime extension does not necessarily result in environmental impact reduction depending on product lifetime values, a more widespread use of *Distribution* seems appropriate for an understanding of lifetime extension strategies to be used or avoided in different population groups.

3.4 Suitability for different decision-making contexts

The identified typical questions suitable to be addressed by the different modelling approaches are summarised in Table 1. The questions to be answered in any LCA should be defined in the goal and scope definition (ISO 2006a, b). Consequently, the goal of the LCA needs to be clearly defined so that an appropriate lifetime modelling approach can be chosen. Despite the goal and scope definition being an essential point of departure in any LCA, it is often poorly reported

Table 1 Typical questions answered by the different lifetime modelling approaches

	Modelling approach			Examples of decision-making contexts	
	Single	*No-Fixed*	*Distribution*	In public policy	In business
What is the difference in environmental impact between a baseline and an alternative with lifetime extension for a specific lifetime value?	X			- Communication to citizens about the benefits of a policy targeting a given lifetime extension	- Market communication on the benefits of lifetime extension
What is the contribution of different processes or life cycle phases to the environmental impacts?	X	(possible)		- Identification of hotspots for prioritisation of policy measures	- Identification of hotspots for prioritising changes in product design
How does the environmental impact vary with respect to product lifetime?		X		- Learning about the relationships between product lifetime and life cycle environmental performance	- Support for design considerations of product durability
What is the range of lifetime values for lifetime extension to be beneficial?		X		- Comparison of a range of policy measures - Identification of minimum requirements for lifetime extension to be beneficial	- Support for developing lifetime extension business offers - Communication to users about lifetime requirements for environmental benefits
For which assessed lifetime values does lifetime extension reduce the environmental impact of a product?	X	X		- Evaluation of policy measures	- Evaluation of business offers with lifetime extension - Marketing of a lifetime extension offer to consumers
What is the break-even additional lifetime value for lifetime extension to be beneficial?	(X) (with a selection of single values covering a range which contains the break-even value)	X		- Identification of different types of minimum requirements for lifetime values (e.g. mandatory minimum warranty of repaired products, lifetime values to be used in reporting/labels/declarations)	- Identification of appropriate variables of a business offer - Communication to users about minimum lifetime requirements for environmental benefits
What is the distribution of the environmental impact for a population?			X	- Identification of hotspots for prioritisation of policy measures in a given market - Monitoring of policy measures effectiveness (ex-ante analysis)	- Identification of the difference in environmental impact across customer groups
How does the distribution change with lifetime extension?			X	- Evaluation of policy measures to promote lifetime extension in a given market	- Identification of typical customer groups to target with lifetime extension offerings to get the most significant gains for the product portfolio
Does lifetime extension result in an environmental impact reduction on average over a population?			X	- Identification of whether policy measures promoting lifetime extensions are beneficial for a given market	- Identification of whether the lifetime extension is beneficial for the entire targeted customer base
How is the environmental impact reduction or increase distributed over a population?			X	- Identification of unexpected impact from a policy intervention in a given market	- Identification of uncertainties and risks related to lifetime extension

(Nordelöf et al. 2014; Roßmann et al. 2021). Rightfully, the goal of an LCA might be challenging to define in practise (Grant and Macdonald 2009), but the product lifetime modelling is yet another of the several methodological choices required, which again emphasises the importance of the goal and scope definition.

Besides the questions to be answered by the LCA, the goal also states the "reasons for carrying out the study" (i.e. the application) and "the intended audience, i.e. to whom the results of the study are intended to be communicated" (ISO 2006a, b) referred to as "decision-making context" in this study. LCA decision-making contexts are diverse (Baumann and Tillman 2004; Sala et al. 2021) and, outside academic contexts, can be grouped under two main categories: in policy decision-making (e.g. at local, regional, national or global scales) and in business decision-making (e.g. product design, purchasing, communication). For both, examples of applications for each typical question are suggested in Table 1.

For instance, in a European-level policy decision-making context, lifetime is currently an increasingly important aspect to be considered. Lifetime modelling can hence be essential when looking for effective single-market ecodesign requirements, notably during preparatory studies under the new Ecodesign for Sustainable Products Regulation (European Commission 2024). Table 1 suggests possible combinations of lifetime modelling approaches to select and evaluate lifetime extension measures:

- For identifying potential policy measures, *Single* could be used for hotspot identification amongst processes and environmental impact categories and *Distribution* for identification of user groups resulting in high environmental impacts.
- For evaluating these measures, *No-Fixed* could be used to assess the range of lifetime values (also called targets in this context) for which lifetime extension would be beneficial and *Distribution* to assess the potential average environmental impact reduction for the European market.
- For deciding on the value for minimum lifetime values for, e.g. warranties of repaired products offered by businesses or durability requirements for products entering the European market, a break-even analysis with *No-Fixed* could be used.

In a business decision-making context, a manufacturing company may aim at reducing the overall impacts of its product portfolio by studying the option of repair through extending the lifetime of its product, such as the HV motor manufacturing company in Jerome et al. (2023). In such a case, *Distribution* could be used to assess the average environmental benefits for their customer base and to identify customer groups for which environmental benefits are the highest. After identifying average lifetime values, marketing to the targeted customers could be done using *Single*.

When choosing a suitable lifetime modelling approach, the data requirements and the accessibility of the results for the intended audience of the LCA need to be considered in the goal and scope definition. For the intended audience, the figures generated with *No-Fixed* and *Distribution* are, in principle, richer in information than with *Single*. With *No-Fixed*, an evolution with lifetime is displayed, and with *Distribution*, a distribution informing on a mean value and spread of values has to be understood. An audience expecting a straightforward conclusion might prefer results from *Single*. In that case, the results from other modelling approaches can support a suitable selection of lifetime values. For instance, for illustrating the mean environmental impact value over a population, the combination of initial lifetime and additional lifetime resulting in this mean value can be identified with results from *Distribution* to then be used as single values with *Single*.

Each lifetime modelling approach requires different data, with some more challenging to acquire. One data point is required for *Single*, but several values to be tested as sensitivity analysis may be preferred. No data is required for implementing *No-Fixed*. A distribution for *Distribution* is built on other data needs, such as market studies with user surveys and interviews. For products with little data on actual practises, compromises between the lifetime data collection required for the goal of the LCA and time constraints might have to be made. For instance, in this study for the HV motor case, the initial lifetime distribution had to be assumed and the additional lifetime distribution developed with strong assumptions due to a lack of data, and the mattress case used data on lifetime distribution from the US. Ideally, the data should reflect the specific population addressed in the study. Still, if efforts on lifetime data collection are not possible, the goal of the LCA might have to be changed to use approaches with available lifetime data. Due to the development of circular strategy implementation, more information on lifetime may be made available for a large range of products in the future.

3.5 Limitations and further research

The comparison of approaches for lifetime modelling is illustrated on simple cases of LCA of lifetime extension. For example, the replacement of the initial product with a product with different properties (e.g. energy efficiency or material composition) is not addressed, although variations of these properties might have a significant impact on the LCA results of lifetime extension (see examples with variations in energy efficiency in Ardente and Mathieux (2014), Boldoczki et al. (2020) or Hummen and Desing (2021)). It highlights that other essential aspects, such as the choice of baseline to be compared to lifetime extension, might influence the interpretation of the LCA results and are worth studying further. Also not explored is the ratio of products unsuitable for lifetime extension after initial use, which is a variable with a strong influence on the LCA results (André et al. 2019). Its exclusion may lead to the overestimation of the benefits of lifetime extension (Proske 2022). Further studies could explore the influence of the modelling of such crucial variables on the conclusions presented in Table 1.

The lifetime modelling approaches compared were identified in a review of existing LCAs of product lifetime extension (Jerome and Ljunggren 2025). Additional approaches, such as the combination of MFA and LCA in Heeren et al. (2013) and Röck et al. (2021), might be a starting point for developing other lifetime modelling approaches. Additionally, Pohl et al. (2019) point to existing methods from behavioural science to model user behaviour related to the use phase in LCA. The LCA modelling approaches based on these methods remain to be developed (Polizzi di Sorrentino et al. 2016) and could be an avenue for further research.

4 Conclusion

As the interest in lifetime extension strategies such as reuse, repair and remanufacturing increases with the development towards a more circular economy, developing the methodology for assessing such strategies in LCA becomes increasingly important. This paper contributes by comparing lifetime modelling approaches in LCAs of lifetime extension and shows that LCA results address different typical questions.

A modelling approach using single values provides information suitable to answer questions related to hotspots and burden-shifting identification. Using no fixed value informs on a range of validity of the results and a quantified lifetime break-even value for lifetime extension to be environmentally beneficial. Finally, a modelling approach using a lifetime distribution over a population provides information on the spread and average change in environmental impact when lifetime extension is implemented over this population.

Therefore, the common way of modelling the lifetime as a single value can be inadequate for LCAs of lifetime extension strategies. Instead, the approach should be chosen based on the goal of the LCA and especially the questions to be answered by the assessment. This paper provides guidance for selecting relevant modelling approaches given a specific LCA goal.

Additionally, the testing of the approaches illustrated that comparing alternatives with different total lifetimes is only suitable when using a functional unit that integrates the lifetime unit, such as expressing LCA results per year instead of per product. It shows that LCA methodological choices for suitable decision-making support on lifetime extension are not limited to the selection of lifetime modelling approaches. Further research could extend the provided guidance to include other methodological aspects, such as the functional unit or system boundaries.

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Data availability The life cycle inventory for the manufacturing of HV electric motors is confidential. The rest of the data is openly available at: https://github.com/AdelineJerome/lifetime-approaches-lca

Declarations

Competing interests The authors declare no competing interests.

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