The International Journal of Life Cycle Assessment (2020) 25:495–507
https://doi.org/10.1007/s11367-019-01710-x

LCA COMMUNICATION AND LCA FOR ISO LABELS

Obsolescence in LCA–methodological challenges and solution approaches

Marina Proske[1,2] · **Matthias Finkbeiner**[3]

Received: 8 May 2019 / Accepted: 9 November 2019 / Published online: 26 November 2019

Abstract

Purpose Obsolescence, as premature end of use, increases the overall number of products produced and consumed, and thereby can increase the environmental impact. Measures to decrease the effects of obsolescence by altering the product or service design have the potential to increase use time (defined as the realized active service life) of devices, but can themselves have (environmental) drawbacks, for example, because the amount of material required for production increases. As such, paying special attention to methodological choices when assessing such measures and strategies using life cycle assessment (LCA) needs is crucial.

Methods Open questions and key aspects of obsolescence, including the analysis of its effects and preventative measures, are discussed against the backdrop of the principles and framework for LCA given in ISO 14040/44, which includes guidance on how to define a useful functional unit and reference flow in the context of real-life use time.

Results and discussion The open and foundational requirements of ISO 14040/14044 already form an excellent basis for analysis of the phenomenon obsolescence and its environmental impact in product comparisons. However, any analysis presumes clear definition of the goal and scope phase with special attention paid to aspects relevant to obsolescence: the target product and user group needs to be placed into context with the analysed "anti-obsolescence" measures. The reference flow needs to reflect a realized use time (and not solely a technical lifetime when not relevant for the product under study). System boundaries and types of data need to be chosen also in context of the anti-obsolescence measure to include, for example, the production of spare parts to reflect repairable design and/or manufacturer-specific yields to reflect high-quality manufacturing.

Conclusions Understanding the relevant obsolescence conditions for the product system under study and how these may differ across the market segment or user types is crucial for a fair and useful comparison and the evaluation of anti-obsolescence measures.

Keywords Durability · Functional unit · Lifetime · LCA · Obsolescence · Use time

1 Introduction

Obsolescence—the (premature) end of the active use of a product—leads to products being discarded and replaced earlier than necessary. Many products become "obsolete" before they cease to function, because technology has improved or because consumers want newer, more fashionable products. Such obsolescence can lead to environmental burdens as new goods are manufactured to replace products that largely serve the same function. In a positive sense, obsolescence can lead to the quicker adoption of more energy-efficient products (e.g. LED lighting). In the case of products likely to become obsolete before their useful life has ended, life cycle assessment (LCA) can misrepresent the impact of a product on a

Responsible editor: Chris Yuan

✉ Marina Proske
Marina.proske@izm.fraunhofer.de

[1] Technische Universität Berlin, Fakultät IV - Elektrotechnik und Informatik, Forschungsschwerpunkt Technologien der Mikroperipherik, Sekretariat TIB 4/2-1, Gustav-Meyer-Allee 25, 13355 Berlin, Germany

[2] Fraunhofer IZM, Department Environmental and Reliability Engineering, Gustav-Meyer-Allee 25, 13355 Berlin, Germany

[3] Technische Universität Berlin, Institute of Environmental Science & Technology, Sustainable Engineering, Straße des 17. Juni 135, 10623 Berlin, Germany

functional unit basis, if full lifetime use is assumed, instead of obsolescence-adjusted lifetime.

A large range of measures to reduce obsolescence and increase use time (meaning the realized service life) of products exist. They differ depending on the conditions underlying the obsolescence (see Section 2), and many target the way products are designed, built and marketed. However, while the intention to make products long lasting is to reduce the overall environmental impact, the latter is not always the derived actual result.

LCA can assess the effects of obsolescence at product level and the potential and trade-offs of "anti-obsolescence" measures. As part of this, the methodological choices, e.g. assigning a meaningful reference flow to the functional unit, have to be aligned with the specific goal of the study—as given by the ISO standards 14040/44 (ISO 14040: 2006, ISO14044: 2006; Finkbeiner et al. 2006).

In recent years, as LCAs and carbon footprints become more extensively used for individual product assessments, rather than comparative LCAs, such as product environmental footprint (PEF) and product category rules (PCR) go towards more aligned assumptions including defining lifetimes for entire product groups. This makes studies and especially comparisons more replicable, but the results are not automatically more realistic and reliable (see discussions from Finkbeiner 2014; Lehmann et al. 2016). Whereas this may have its rationale for product assessments, which are published without their corresponding studies and a full description of goals, scope and assumptions, it is not helpful to assess—and compare—product systems in the light of obsolescence. To do that, it is necessary to assess the realized use time of a device and the differences between the product systems.

This paper will show how obsolescence can be considered in LCA. This will be based on an introduction of obsolescence (Section 2), a description on which methodological choices have a significant impact when analysing obsolescence, resulting difficulties in the existing methodologies and first approaches to tackle them (Section 3) followed by the conclusions (Section 4).

This paper will address the question on a general methodological level but will use examples to clarify certain aspects. Thereby, we will cover three different types of products: clothes, an "up-to-date" electronic product such as a smartphone and "workhorses" such as a washing machine (Cox et al. 2013) to address different aspects of methodological requirements. The examples are provided in italics and can be skipped for quick reading.

2 Background—what is obsolescence?

Obsolescence is the (premature) end of a product's active use. That means it becomes obsolete for subjective or objective reasons. In the public discussion, obsolescence is often understood as "planned obsolescence", i.e. the deliberate shortening of the technical lifetime of a product (see e.g. Prakash et al. 2016). However, in real life, reasons for obsolescence and product replacement are much more diverse and complex. Dealing with broken products is only a small part of the picture, and also, replacing products that technically still work is a common thing (Prakash et al. 2016; Wieser et al. 2015).

In that context, the difference between technical lifetime and realized use time of a device is important. The ISO 14040/44 standards as well as many other guidelines do not define or reference use time and lifetime (ISO 14040: 2006; ISO14044: 2006). The ILCD handbook uses the terms average and technical lifetime without defining them (JRC 2010). According to PEF (2013), the "duration/life time" of a product is part of the functional unit under the aspect "how long" a function is provided. The standard ETSI ES 203199/ITU-L 1410 uses terms like operational lifetime, use time and replacement cycle without specific recommendations as to how they should be addressed, except in the "case of comparative assessment between ICT goods LCAs, the operating lifetime shall be set to equal. Differences in lifetime could only be accepted if they reflect differences in actual characteristics." In their specific technical reference on circular economy ETSI TR 103476 references "extension of durability is about extending the technical lifetime" and "implies the extension of operating lifetime". According to Thiebaud-Müller et al. (2018), lifetime and life span are used synonymously in literature.

In the following discussion, we will use the term lifetime to reference the technical lifetime until a product breaks or wears out, use time as the active service life at the first user, and extended lifetime as the technical lifetime including repair and refurbishment (see Fig. 1). Storage after active use (hibernation), irrespective of whether the product is still working or not, is not part of the lifetime and should therefore not be part of the functional unit (Thiebaud-Müller et al. 2018).

The main reasons for obsolescence and product replacement can be assigned to the following conditions (list adapted from Bertling et al. 2014; Prakash et al. 2016; Behrendt and Göll 2018; Proske and Jaeger-Erben 2019):

- Material/qualitative conditions relate to deficient capability of materials and components that lead to fast ageing of the product.
- Functional conditions cover developments where fast-changing technical and functional requirements on products make them dysfunctional.
- Economic conditions refer to losses of functionality due to high prices for consumables, maintenance and repair as well as comparable low costs for new products.

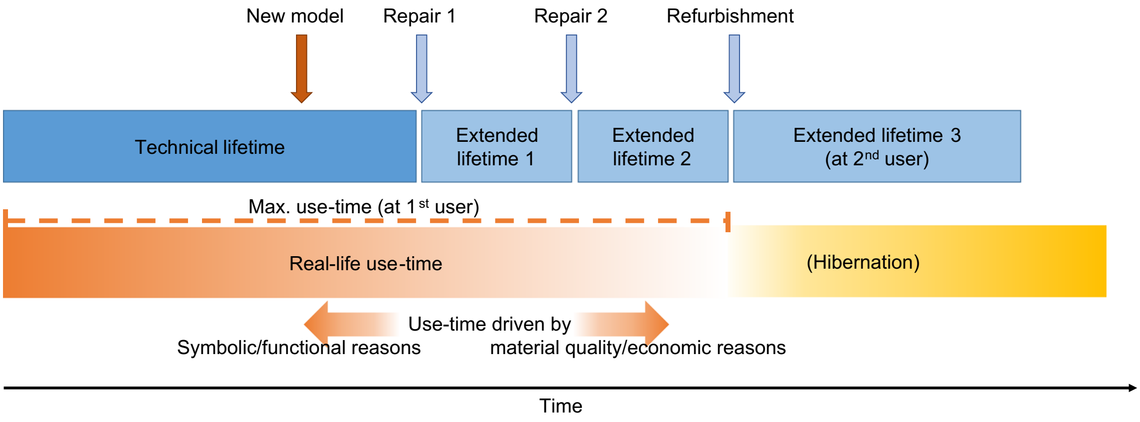


Fig. 1 Use time and lifetime of a product

- Symbolic conditions refer to consumer expectations and cultural values and relate to fashion and technological trends as well as changing consumer lifestyles.
- Knowledge-based conditions cover the limits of practical know-how on how to design or use/maintain/care for or repair a product.
- Context-related conditions relate to changes in a person's environment (i.e. need for a bigger fridge due to a changing size of household).

2.1 Why is obsolescence an LCA topic?

Obsolescence leads to the fact that products are replaced although they could still be used, leading in total to a higher production volume than necessary. Production, use and disposal of products cause various forms of environmental impact. By shortening the active use of a product and replacing it earlier than necessary, additional manufacturing and end-of-life impact is caused compared to a continuous use of the same product. In general, it is often assumed that using the same product longer is environmentally favourable. However, if efficiency gains occur within the product group (Cooper 2005), or if a product's efficiency "decreases with wear", lifetime extension can be counter-effective (Ardente and Mathieux 2014). Similarly, such effects can be observed for specific measures to achieve long-lasting products. More durable products can require more and different material (Ardente and Mathieux 2014), modular products might need magnet materials for attachment and gold-coated contacts for electrical connections (Schischke et al. 2016, ETSI TR 103476). Repairable products might be bigger overall and spare products need to be produced as well—sometimes before they are actually needed (Ardente and Mathieux 2014; Schischke et al. 2016).

As Middendorf et al. (2015) states under the term "EcoReliability" "[b]lindly maximizing reliability [i.e. technical lifetime in this context] leads to overdesign, thus wasting resources". "[T]rade-off between reliability and environment needs to be understood and quantified much better for future product and technology choices" (Middendorf et al. 2015 [inputs from author]). LCA has the potential to show exactly these trade-offs and possible hotspots which tip the scale. There are already LCA studies addressing optimal lifespans of products. For products with significant efficiency gains per generation, shorter product cycles might be beneficial as e.g. Richter et al. (2017) shows with the example of LEDs. However, according to Bakker et al. (2014b), several studies indicate that LEDs are a special example and recent electronic products should be used longer than their current median lifespan. Exemplary product LCAs regarding repairability (e.g. Proske et al. 2016) and durability (e.g. Bobba et al. 2015) exist as well showing that repair and durability increase the initial environmental impact from manufacturing, but reduce the overall environmental impact if products are actually used longer, in the case of Bobba et al. (2015) even when the replacement product would be more energy efficient. Nevertheless, there are some specific gaps and challenges to adequately address obsolescence in LCA. These will be identified, described and discussed in Section 3.

2.2 Measures to reduce obsolescence

Reducing obsolescence correlates closely with circular economy (CE) strategies to keep products and materials "in the loop". According to the Ellen MacArthur Foundation (2013), the corresponding strategies are (1) share, (2) maintain, prolong, (3) reuse, redistribute, (4) refurbish, remanufacture and (5) recycle.

Except recycling, these are ways to extend the use time of a product either by keeping the (still-working) product in use or by extending its lifetime and, thus, avoiding preliminary obsolescence. The correspondence between CE concepts and earlier presented conditions for obsolescence is as follows:

Sharing can lead to a better utilization of products and reduce the overall number of products when they are not

Table 1 Exemplary list of how "anti-obsolescence" measures impact the use time and the technical design

Strategy	Impact on use (−time)	Impact on design
Durability in context of longevity	+ Longer technical lifetime – Use time might not be limited by technical lifetime	- Might lead to lower energy efficiency - Might need more material
Durability in context of resilience against accidents and harsh use	+ reduces wear and breakage – Only relevant in case of accidents, how it effects the statistical use time across the market depends on rate of accidents	- Might lead to lower energy efficiency - Might need more material - Might hinder repair (Ardente and Mathieux 2014)
Repairability	+ Can extend technical lifetime – Users often do not consider repair (Jaeger-Erben and Hipp 2018)	- Might need more material - Might reduce resilience
Upgradability, adaptability	+ Increases "functional durability" (Makov et al. 2019) – Easy and cost-effective upgrades could even accelerate technical updates (Hankammer et al. 2017; Schischke et al. 2016)	- Might need more material - Might need additional valuable materials for contacts and maybe magnetic materials for attachment of modules (Schischke et al. 2016)

+ positive impact on use time, potential to prolong use; – negative or no impact on use time

individually owned, but it does not necessarily prolong their use time. However, the purchase decisions and relevant product characteristics are different for products, which are shared instead of used individually. The focus is likely to be more on the delivered service than on the product itself, which gives more priority to repairability and longevity in the decision. Furthermore, aesthetics are likely to be less relevant, reducing the risk of becoming obsolete due to falling out of style. Thus, obsolescence is indirectly addressed.

Maintenance including repair keeps products in use, reducing qualitative obsolescence as on-going maintenance can reduce breakages beforehand. However, qualitative obsolescence (short technical lifetime, fast wear and tear) can be a problem when maintenance and repair is not possible due to the product design (e.g. housings are glued and cannot be opened without destruction) or missing spare parts. Economic conditions can reduce the likelihood of repair when spare parts or maintenance/repair service is too expensive in comparison to new products or (an assumed) residual value.

Reuse and redistribution are, in the context of obsolescence, both connected to products, which are still working but not used by the original owner. This can be caused by functional, contextual and/or symbolic conditions. When the requirements from the original user have changed so that the product is no longer adequate, reuse by users with different functional requirements is a way forward. However, the residual value of the device and profit from resale can also be seen as a stimulus towards a new device. Thus, reuse and redistribution cure the heaviest symptoms of obsolescence but do not change the "mindset" towards a circular economy, if the desire for new products continues to be fuelled.

Refurbishment and remanufacturing are ways to redistribute used products by enhancing the functionality and/or residual value of the device, thereby reducing the effects of functional, qualitative and symbolic obsolescence.

If these usage-focussed strategies are "translated" into product design strategies, they lead to the design criteria for long-lasting products according to Van Nes and Cramer (2005) and Bakker et al. (2014a): Design for (1) reliability and robustness/durability, (2) repair and maintenance, (3) standardization and compatibility, (4) upgradability, (5) variability and (6) product attachment, which are necessary for longevity in general, but can also enhance reuse and refurbishment.

Obsolescence is closely linked, but not solely defined by, the product design. Table 1 shows exemplary "anti-obsolescence" measures and how they might increase the use time of the devices or miss the relevant aspect. This is further discussed in Section 3.2.1.

Business models and other downstream measures around reuse and refurbishment (e.g. so-called gap exploiter models according to Bakker et al. 2014a) are only touched upon in this paper. There is already work focussing on product/service systems (PSS) (e.g. Kjaer et al. 2018) or reuse (Cooper and Gutowski 2015).

3 Approach for considering obsolescence in LCA

Which requirements of LCA methodology need to be revised or need special attention in order to consider obsolescence in LCA? In fact, the open and foundational requirements of ISO 14040: 2006 and ISO14044: 2006 already allow the analysis of the phenomenon obsolescence—and its environmental effects in product comparisons—very well. However, to do that, certain methodological requirements of LCA need to be specified.

The goal and scope definition sets out the choice for functional units, reference flows, allocation methods and relevant data. It is therefore crucial for the overall direction of the LCA study. In order to consider obsolescence in LCA, we will therefore analyse and discuss how the following methodological requirements—defined within the goal and scope phase of an LCA—need to be addressed:

- Goal definition
- Functional unit and reference flow
- System boundaries
- Types and sources of data
- Allocation
- Allocation procedures for reuse and recycling

3.1 Goal definition

Gutowski (2018) described the problem that a new (technical) solution is often loaded with unrealistic expectations and hopes, which lead to unrealistic comparisons with the conventional solution. Similar risk exists regarding the assessment of durable designs and other "anti-obsolescence" measures. If a repairable product design is used to increase use time, but for the specific product category technical failure is not a prevalent replacement reason and/or the majority of users is already reluctant to repair devices, the calculation will show optimistic potentials e.g. for an environmental- or cost-sensitive user group, but a realistic market view would likely be much lower. Both ways would have their specific merits as long as they are aligned with the goal and reflected in the interpretation.

The goal definition should specify the intended application and audience. Regarding (measures against) obsolescence, this should include answering the following questions:

- What are the target products/product systems?

- Existing products on the market with different "qualities" i.e. durability, resilience?
- Different design alternatives independent from a specific manufacturer?
- Similar products with different business models (e.g. long-term contracts, reuse and upgrade contracts, PSS, etc.)?

- Who are the target users?

- "Average" use on the market?
- Individual versus collaborative use (e.g. sharing)?
- Individual user types with specific usage (e.g. "environmental conscious user", "techie")?

- What is the target strategy?

- What is the "anti-obsolescence" strategy that should be compared (e.g. durability, reparability)?
- Does this link to relevant obsolescence condition for the product under study?

Figure 2 shows an exemplary goal definition for three selected product examples: smartphones, washing machines and clothes, and the resulting expected types of impact on use time and possible rebound effects to show how these choices can influence the further definitions of functional unit and lifetime, data choices, etc. as it will be discussed in the following sections.

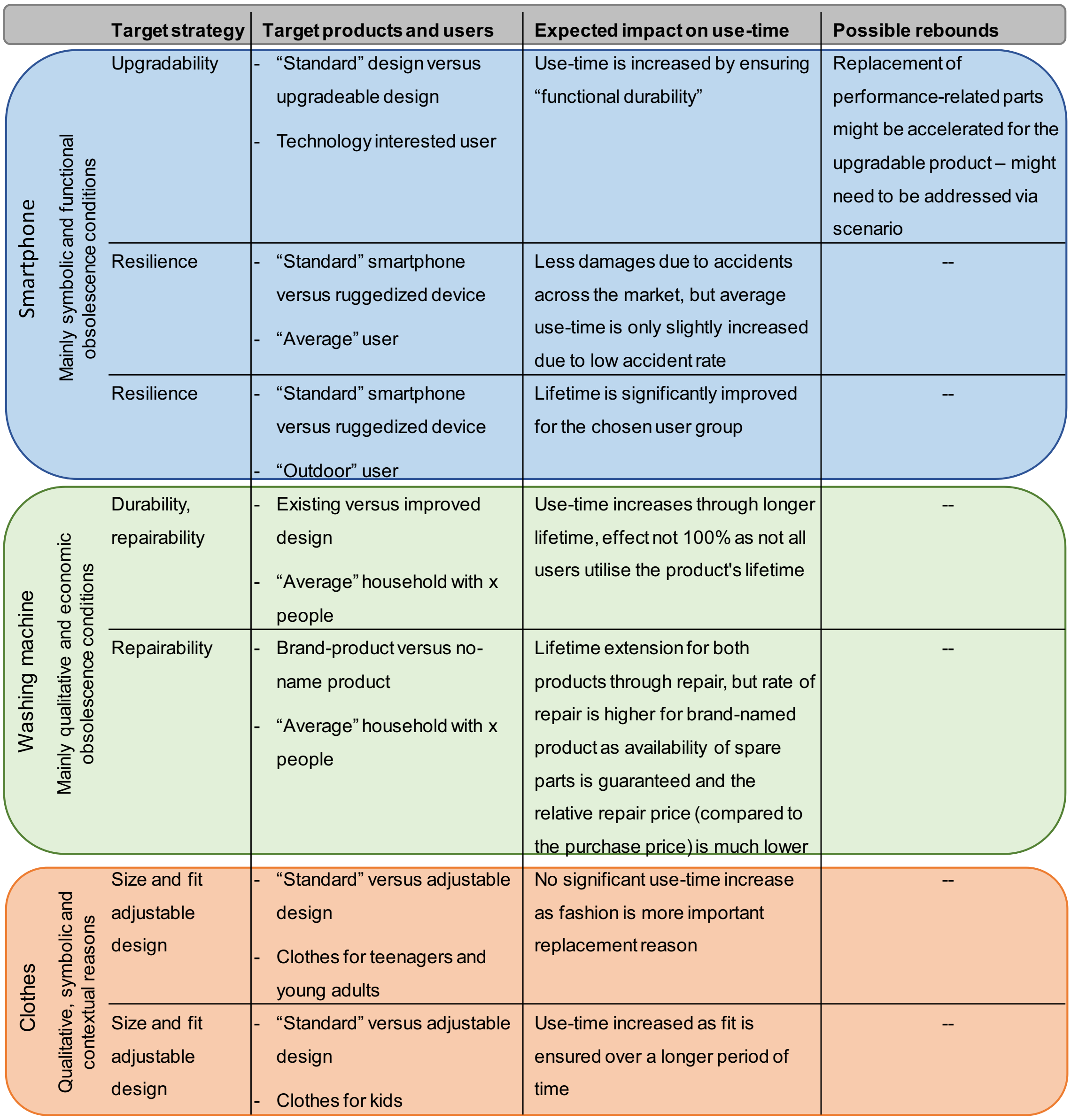
By defining the target product system, the level of comparison can be defined. It makes a difference whether two design strategies (e.g. standard versus repairable) or two products on the market with different product "quality" i.e. durability are compared. Additionally, the main obsolescence conditions depend on the product group, but can vary according to a specific user group.

*Example: The majority of smartphones is replaced due to contextual (new service contract) and functional/symbolic (new features in new devices) conditions. Technical failure plays a minor role in overall replacement reasons and are than more often associated with poor battery performance (e.g. Wieser et al. 2015). With regard to Fig. 2, a repairable device can reduce the impact of accidents, but will not significantly increase the statistical use time across the market. Focussing on a specific user group (*e.g. *users with a higher accident risk or environmentally conscious users who are more likely to conduct repairs in case of damage) can change the focus of the study, and it is therefore necessary to define the target users and target strategy. An anti-obsolescence measure such as upgradability could influence the functional unit as it might not only be necessary to have "a working smartphone to make calls, internet functionality, take photos, etc.", but to extend the functional unit to "comparable with current technology features and performance parameters". To define the target product is necessary as it impacts the choice of data types (as described in Section 3.4) when* e.g. *existing smartphones on the market from specific brands are compared or two fictional designs.*

3.2 Functional unit and reference flow

Defining a meaningful functional unit for the product system in question and assigning a correct reference flow is crucial for every LCA study, particularly when the goal is to use the results for comparisons.

In current product carbon footprints or PCRs, the functional unit is in many instances set to "the use of one product over a specific time" (Andrae and Vaija 2017) so reference flow and functional unit are mixed. Although this is not exactly defining the performance, it might be sufficient for non-comparative product LCAs and when very similar products are compared for an average usage. To analyse products which



		Target strategy	Target products and users	Expected impact on use-time	Possible rebounds
Smartphone	Mainly symbolic and functional obsolescence conditions	Upgradability	- “Standard” design versus upgradeable design - Technology interested user	Use-time is increased by ensuring “functional durability”	Replacement of performance-related parts might be accelerated for the upgradable product – might need to be addressed via scenario
		Resilience	- “Standard” smartphone versus ruggedized device - “Average” user	Less damages due to accidents across the market, but average use-time is only slightly increased due to low accident rate	--
		Resilience	- “Standard” smartphone versus ruggedized device - “Outdoor” user	Lifetime is significantly improved for the chosen user group	--
Washing machine	Mainly qualitative and economic obsolescence conditions	Durability, repairability	- Existing versus improved design - “Average” household with x people	Use-time increases through longer lifetime, effect not 100% as not all users utilise the product's lifetime	--
		Repairability	- Brand-product versus no-name product - “Average” household with x people	Lifetime extension for both products through repair, but rate of repair is higher for brand-named product as availability of spare parts is guaranteed and the relative repair price (compared to the purchase price) is much lower	--
Clothes	Qualitative, symbolic and contextual reasons	Size and fit adjustable design	- “Standard” versus adjustable design - Clothes for teenagers and young adults	No significant use-time increase as fashion is more important replacement reason	--
		Size and fit adjustable design	- “Standard” versus adjustable design - Clothes for kids	Use-time increased as fit is ensured over a longer period of time	--

Fig. 2 Exemplary and fictional comparison for three product groups with different anti-obsolescence strategies

differentiate exactly in the reference flow assigned to fulfil a similar performance, this approach does not work. It has to be defined what a useful functional unit has to take into account regarding the above-named strategies against obsolescence (see Section 2.2).

One critical aspect regarding the functional unit in the context of obsolescence is to assign a correct reference flow and thereby deal with the uncertainties in product use scenarios and use time (Cooper 2003; Reap et al. 2008). So, in the context of obsolescence, the relevant anti-obsolescence strategies resulting in an i.e. repairable design should not be seen as an “essential” feature which would make comparability impossible even with system expansion (ISO/TR 14049: 2012), but as a factor that can influence the use time and thereby the reference flow assigned to the functional unit.

In the following, three aspects are discussed that are relevant for the definition of the functional unit and the reference flow: use time versus lifetime (Section 3.2.1), resilience (Section 3.2.2) and the impact of use patterns and frequency of use (Section 3.2.3).

3.2.1 Defining the reference flow: use time or lifetime?

Besides defining a useful functional unit, the reference flow is crucial in the context of obsolescence: How many products are needed to fulfil a functional unit over 3 years: 3, 2 or only 1—and how does that vary between my compared systems?

In many assessments and guidelines (and even obsolescence discussions), use time and lifetime are either seen as the same aspect or it is just assumed that products are used until the end of their technical lifetime. However, this is not the case for many product groups which are replaced well before a technical failure (Jaeger-Erben and Hipp 2018; Prakash et al. 2016; Wieser et al. 2015). Günther and Langowski (1997) point out that "(1) consumer habits can influence lifetime, (2) the product lifetime is subject to non-systematic variations".

In the context of obsolescence, it is therefore necessary to assess the aspects which define the use time of the product systems under study and the relevant obsolescence conditions. These can be internal aspects such as product durability, technological progress and innovation cycles and external factors such as the duration of service contracts for smartphones or just "learned" replacement cycles, routines and habits (Polizzi di Sorrentino et al. 2016).

The resulting use time can be either equal to the lifetime or shorter. Both cases are described in the following.

Use time = lifetime If the use time is mainly determined by the technical lifetime, the latter can be used to define the reference flow. When comparing product systems, the focus would then also be on aspects and measures which increase or extend the technical lifetime: the easiest case would be when one product is more durable (based on a specific use pattern) than the other which can be proven by e.g. lifetime tests. However, there are still technical difficulties relating to how to plan and test product lifetime, but those are outside of the methodological considerations of LCA.

Other ways to extend the lifetime are by enabling or simplifying repair e.g. allowing repairs without the need for special tools or trained staff and/or reducing the risk of further damage when conducting a repair. The extended lifetime can then be used to determine the reference flow including spare parts. However, in that case, it should be reflected if repair is likely to happen depending on the product and user group. Similar to products being replaced while still working, surveys show that repair is often not considered as the assumed remaining life is too short and repair is assumed to be too expansive, but also because they are used as an excuse to buy "something new" (Jaeger-Erben and Hipp 2018). In such case, a repairable design would lead only to a marginal increase of the average use time.

According to Bakker et al. (2014a), enabling do-it-yourself repair is more effective to make repair happen and to extend the lifetime than the general availability of professional repair. So how the repairable design is implemented and if spare parts are easily available for consumers are also relevant aspects when assessing the actual lifetime extension potential across the market.

Use time < lifetime For many product groups, the technical lifetime is seldom exhausted, and many products are replaced long before. This relates not only to the often-named examples of "up-to-date products" such as smartphones, but can be also seen for so-called workhorses like washing machines and coolers (Wieser et al. 2015; Jaeger-Erben and Hipp 2018; Prakash et al. 2016; Cox et al. 2013). Additionally, studies show that product use time varies significantly between regions and countries (Thiebaud-Müller et al. 2018), indicating that the technical lifetime is not the single reference to assume the active use time of a device. Durability as an anti-obsolescence measure would lead in these cases not to a longer use but to a potential unnecessary input of resources.

Therefore, it is necessary to analyse the specific obsolescence conditions for the products under study. For ICT products, for instance, functionality-related aspects and technological progress often lead to product replacement as new products have improved functions and additional features. Upgradable and expandable product designs are for such cases a more focussed measure to prolong use time than durability and repairability (Proske and Jaeger-Erben 2019). To define the reference flow for such products, periods for product upgrades and product cycles need to be defined and possible rebound effects through e.g. faster replacement of modules compared to whole products or "over-stocking" with add-ons (Proske and Jaeger-Erben 2019; Schischke et al. 2016) should be considered (and possibly addressed via scenarios). "Service life prediction", meaning the "general process of estimating material and system maintenance, repair, and replacement" over the lifetime—as it is common in building LCAs (Grant et al. 2014)—would be also helpful to define the service life of such repairable and/or upgradable products.

Symbolic reasons, trends and changing user behaviour over time are further reasons for premature product replacement, which additionally vary significantly across user types, age and regions. The difficulty these cases have in common is that reduced use time due to these effects is far more difficult to measure compared to a technical lifetime. So it is likely that rough assumptions have to be made to determine a realistic use time and thereby the reference flow. Taking into account behavioural science—as suggested by Polizzi di Sorrentino et al. (2016)—would be helpful.

If defining how many users would actually make use of increased durability is difficult, an additional strategy would be to calculate the "additional burden" for the changed design and, based on this, how many users have to make use of that ability to make it pay off from an environmental standpoint. An upgradable design makes that aspect even more difficult as it requires a definition how many upgrades will be used, linking to the so-called service life prediction (Grant et al. 2014).

To increase the informative value and significance of the analysis, it would be useful to work with different scenarios here, e.g. how would an optimal/intended use time look like compared to an "average" or even "fast-paced" usage. Where would the break-even point be in terms of use time for the material investment of the new product design, in order to pay off in environmental terms or even lead to a negative effect due to accelerated upgrades.

Example: For smartphones as "lifestyle" products, replacement reasons are connected to functional (fast technology development), symbolic (appreciation of newness) and contextual (duration of service contracts) conditions. They are rarely used until the end of their technical lifetime (Wieser et al. 2015; Jaeger-Erben and Hipp 2018). Therefore, use time is far more relevant to define the reference flow.

Washing machines, on the other hand, are "workhorses" (Cox et al. 2013) and are more often used until broken; nevertheless, contextual obsolescence plays an important role (e.g. moving to a new apartment) (Jaeger-Erben and Hipp 2018). Thereby, technical lifetime is still a good approximation for the realized use time and quality differences regarding the durability lead to actual differences in the use time.

For clothing, major replacement reasons are wear and tear, fit and size, and fashion, varying significantly between user types and types of garments (Laitala 2014). Therefore, it has to be decided based on the specific target product and group how the use time should be defined.

So summarizing that, a reasonable use time needs to take into account realistic and device-specific technical lifetimes, common use time and group-specific replacement reasons. Based on this use time, the reference flow can be defined.

According to Cooper (2003), the reference flow should use only "full products". This would mean to compare two products with 2 versus 3 years of use, there would be two options: for a functional unit of 1 year of performance, either one product each would be used as reference flow or the functional unit would need to be extended to 6 years of performance and 3 versus 2 products as reference flow. The first option would make it impossible to address the aspects of longevity, the latter could redirect the focus towards questions regarding technology progress and the design and efficiency of future product generations (regarding the product as well as the manufacturing). From our point of view, with the focus of comparing the effects of lifetime and obsolescence, scaling a functional unit to 1 year of performance and working with reference flows such as 1/2 or 1/3 of a product can be appropriate if no significant efficiency gains are expected for future product generations. This would also be in line with ETSI ES 203199, according to which results should be presented per year of use. This is a helpful and easy-to-understand way to present results when different use-time scenarios are analysed and compared.

3.2.2 Durability versus resilience—how to include accidents and harsh use

High quality and longevity are often connected with "durable" devices that can be used in the long-run with only minimal wear and tear. However—depending on the product—durability alone is not sufficient. Resilience, i.e. resistance against harsh use and accidents, can be equally important.

Typically, LCA does not cover accidents and unintended use of a device and focuses on "normal" use. However, in the context of obsolescence and the display of real-life scenarios, excluding accidents and harsh use per se can take a too-narrow view.

Example: Dropping and/or scratching of mobile products happens quite frequently during intended use although, of course, the dropping itself is not intended. Under lifetime aspects to reduce obsolescence, resilience against such (frequent) accidents should be taken into account when defining a functional unit. This does not include all forms of incorrect use, and careful consideration is necessary to estimate and define which accidents lead to "acceptable" damages. Thereby, the view differs according to products but also between stakeholders. Manufacturers—for understandable reasons—exclude all forms of unintended use from warranty. For users, though, although they might accept the warranty exclusions, not all kinds of damages are "acceptable". As most stakeholders "accept" that dropping a notebook on the floor leads to a broken display, a broken display due to a single drop is "not acceptable" for many smartphone users, whereas it is seen as unintended use by manufacturers.

Thereby, resilience can also relate to technical measures to avoid unintended use in the first place.

Example: There are washing machines which can detect overload and warn the user to avoid premature wear and bearing failure. So, although the device is technically not more robust, it is still likely to experience less unintended use.

So if resilience is relevant for the analysed product group and there are technical differences in the resilience between the analysed products, these should be reflected in the functional unit either directly or via additional scenarios in connection to the goal of the study. This could be checked e.g. by using failure statistics of how many products break through unintended use/accidents and if this leads to environmentally significant reduction of the use time, similar to the approach suggested by Frischknecht et al. (2007) for capital goods.

3.2.3 Use pattern and frequency of use

When looking at the lifetime of products in the context of the functional unit, three main different "ageing" models can be defined:

[1] Lifetime depends on time (e.g. a fence).
[2] Lifetime depends on the number of use cycles (e.g. hinge of the fence door).
[3] Lifetime depends on use intensity (number of use cycles within a certain time) (e.g. electronics of the automatically operated fence door).

So, the functional unit should take into account which "lifetime model" is prevalent to properly reflect the main lifetime limiting factor for the analysed product:

[1] FU should focus on duration of delivered function (e.g. function is provided for 2 years).
[2] FU defines the number of delivered use cycles.
[3] FU defines the specific use pattern (e.g. professional versus private use, single use versus shared product) needs to be defined.

Example: Clothes refer to the age model [2] as the lifetime depends mainly on the number of wearing and washing cycles, but often, a functional unit per time is applied (Laitala et al. 2017). Thereby, the number of washing cycles impacts the wear out of clothes at least as much as wearing those (McLaren et al. 2015). In the context of obsolescence, changing the fibre of the garment to increase durability might also require changes in the use phase, as e.g. *wool garments are worn twice as long as cotton garments before washing (Laitala et al. 2017), adding an additional lifetime aspect. A smartphone on the other hand is used more or less continuously; the functional unit can therefore realistically refer to the duration of use [age model 1].*

In real life, lifetime always depends on all three aspects, and the predominant aspect is for most products the dependence on provided use cycles. The functional unit is therefore often defined as a number of provided use cycles. However, in specific cases, a heavy use might lead to increases in wear [3], so that the use pattern becomes important.

Example: Special cases can also be battery-powered devices with rare use such as e-book readers and cameras. Besides the ageing with time, deep discharge of the batteries in no-use phases can harm the battery permanently and decrease the lifetime of the device significantly when batteries are not changeable (Clemm et al. 2018).

Additionally, if we extend that aspect on use time as discussed above, the use time might also depend on the technical progress for new products. So a rare use and a low number of use cycles might not lead to a longer overall use time as the product is replaced for performance reasons. In that context, heavy usage (e.g. through sharing) with a short use time in number of years might still exhaust a device's durability to its full capacity.

Example: For clothes, this could be related to the fact that replacement for style reasons is quite common (Day et al. 2015). A low number of garments with resulting high frequency of wearing and washing cycles could lead to the fact they might actually deliver more "service cycles" before being replaced due to being out of style. It therefore affects the overall life cycle impact significantly whether a "one season" use with wearing once a week or once a month is assumed.

Such scenarios should be taken into account when defining the functional unit, pointing out again the necessity to understand the relevant obsolescence conditions for the product system under study.

3.3 System boundaries

Setting relevant system boundaries covering all relevant processes is necessary and must be equivalent for the compared alternatives.

In the context of anti-obsolescence measures such as repairable, upgradable or otherwise changeable product designs, a service-life prediction is necessary to define the number of spare parts and upgrade modules, which will be needed throughout the use time of the product. Thereby, not only the necessary repair and (re)distribution processes should be covered by the system boundaries. For products with a short time in market per product model, it also needs to be taken into account that these service parts might be pre-produced without knowing the specific number of needed service parts often leading to overproduction (Ostertag 2008). How to address that specifically depends on the product group, legal conditions and the goal and scope definition. If there are legal requirements on e.g. the availability of spare parts, similar assumptions can be made for the compared product systems. However, if no legal requirements apply and longer use time is assigned based on business models with guaranteed availability of spare parts, possible pre-production has to be defined in this context, if it does not fall under the defined cut-off criteria.

System boundaries should also cover additional support systems which are needed to fulfil the functional unit—either from technical or from business model perspective—if they differ between the compared alternatives.

Example: LCAs for smartphones only seldom cover the related data transmission processes and the mobile networks as such. In general product comparisons with comparable product use in context of data volumes, this seems reasonable as the network impact does not differ between the products and the effort for the LCA decreases significantly. However, in the context of "always available" networks and high data transfer rates, there are ideas to reduce the need for internal memory—and even computing power—through cloud storage and mobile cloud computing. This could be seen also as an option to reduce obsolescence as the need for newer, better equipped devices might decrease. To reflect that in a fair manner, system boundaries need to cover data transmission as well as external data storage and computing in data centres.

3.4 Types and sources of data

As obtaining primary data is often difficult, a clear definition where manufacturer-specific data is needed and where not helps to reduce the effort. Therefore, defining types and sources of data is already part of the goal and scope definition. Regarding obsolescence, if a more durable design is achieved through a different product design (e.g. different material choice, more material, different construction), this can be reflected with similar assumptions and data sources regarding the manufacturing process. However, depending on the product/part, higher quality can also be achieved through higher-quality manufacturing:

- Different e.g. more precise tools with different energy consumption
- Different manufacturing processes for the same resulting part: Thereby, the environmental impact does not need to scale with the increase in the quality (as e.g. shown by Higgs et al. (2010) for high-purity gases).
- Lower yield by applying strict quality assurance, low tolerance range and more testing. Thereby, changes in the yield can influence the results significantly (Boyd et al. 2010) and, depending on the product group, testing can cause significant amounts of manufacturing energy.
- Additional production steps

  Example: Longevity of clothes can be increased by decreasing pilling which not only is impacted by the choice of yarn (quality) but can also be achieved by certain textile finishers as an additional step in manufacturing (Cooper et al. 2017).

This correlates with the aspect called “[l]ocal technical uniqueness” by Reap et al. (2008). In these cases, using manufacturer/technology-specific production data and a realistic yield is necessary, but hard to obtain for third parties.

Example: In this context, the product group can make a significant difference. For electric products such as white goods, quality is often achieved through “sturdy” design (metals instead of plastics, material thickness, etc.), so the manufacturing process can be reflected in a fair way based on generic data. For electronics such as smartphones on the other hand, strict control of manufacturing parameters (e.g. clean room classes) is necessary to ensure reliable electronic components (Bajenescu and Bazu 2012), resulting in the need for company- or process-specific data.

For other aspects, though, using local technical data can be misleading. In the context of PEF, the location of manufacturing can influence the overall impact more strongly than the efficiency of the production if national electricity mixes are used (Lehmann et al. 2016). This does also relate to questions of obsolescence. If existing product designs and qualities should be compared regarding their ability to reduce the environmental impact through obsolescence, similar assumptions regarding place of location and electricity mixes should be made, if they cannot be argued with global portioning of the market.

Example: If two different product designs—repairable and not repairable—are manufactured by SMEs in Poland and France (to stick to the example of Lehmann et al. 2016), the same grid mix should be used to assess the product design. On the other hand, if a long-life washing machine with predictive maintenance is manufactured in China where the predictive maintenance is achieved through more electronic parts (e.g. WiFi ability, bigger display with touch functionality) compared to a repairable design developed in Europe, using different grid mixes can be argued by the accumulated electronics manufacturing in Asia.

3.5 Allocation

In the context of obsolescence, a specific allocation problem can be discussed related to quality tests of products and rejections which might be sold as manufacturing seconds with lower quality standards. In many cases, failing a quality test at the end of production results in discard or reworking of the product. However, such rejected products are also brought to market as B-grade products, i.e. products with an assigned lower quality and/or lifetime class. From an environmental perspective, using a less-qualitative component instead of disposing it right after production can be positive and negative—positive, because the impacts of production are not “useless”; the yield of the production process increases; negative, if a less qualitative component leads to the production of final products with a lower lifetime, hence increasing the problem of obsolescence.

Example: Many brands sell clothes with small mistakes such as weaving faults and colour deviations as B-grade products instead of discarding them. In the context of lifetime, this could relate to batches with lower yarn quality resulting in quicker pilling (Claxton et al. 2017).

Regarding allocation, the question is how emissions from such a production process are assigned: physical units such as mass and volume might be very similar for A- and B-grade products and therefore cannot lead to a sensible distinction. The price of the component can be a meaningful indicator to “summarize[s] complex attributes of product or service quality” (Ardente and Cellura 2011) and thereby the preferable allocation method.

3.6 Allocation procedures for reuse and recycling

“Anti-obsolescence” strategies such as modular structure for enabling repairability can also lead to better recyclability in theory e.g. through better disassembly. In real life, though, the recycling rate might not increase as e.g. there are not enough products on the market for recyclers to change their procedures or there is no business case. Hence, for LCA, real-life recycling options should be considered; other options can be addressed via scenarios.

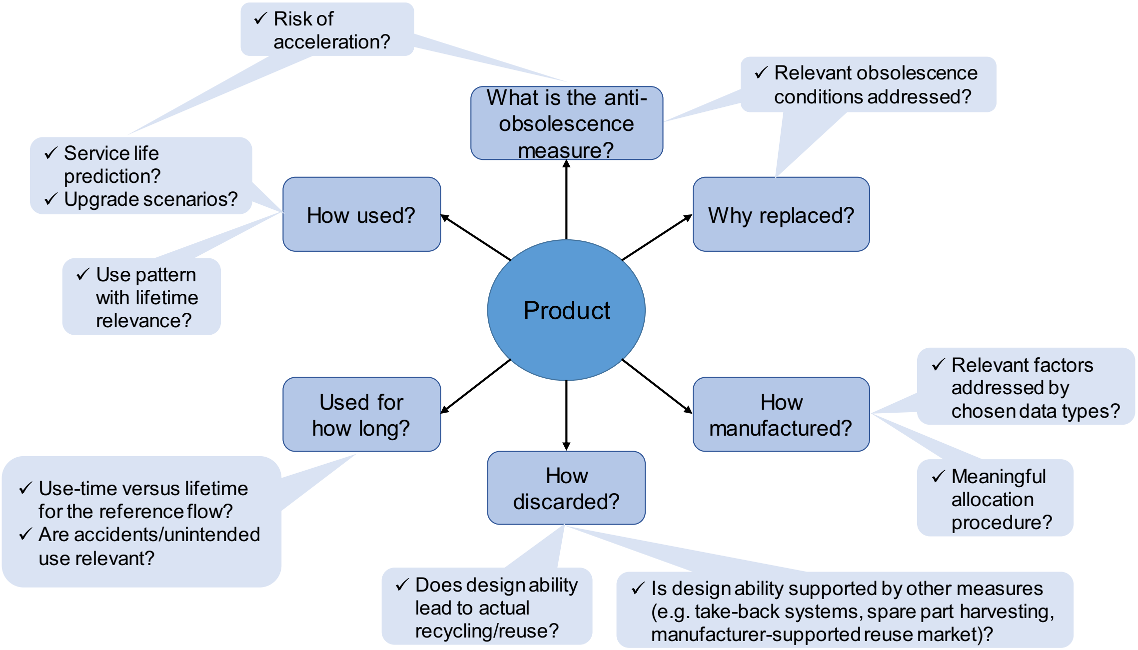


Fig. 3 Summarizing key question from product perspective

However, by combining the recyclable design with business models and manufacturer strategies (e.g. takeback systems, dedicated contracts with recyclers), the real-life conditions can be changed based on a given product design and should then be reflected in LCA. Similar aspects apply to reuse: potential reuse is difficult to address without a market. If a manufacturer offers and cares for a reuse market itself or uses e.g. products from a takeback system as spare parts, this can and should be reflected.

Example: For washing machines which enter a regular recycling stream quite often (Jaeger-Erben and Hipp 2018), a recyclable can "pay off" more or less directly. Smartphones, in comparison, are stored at home after use or discarded with general household waste a lot more often (Manhart et al. 2016; Jaeger-Erben and Hipp 2018) due to the size of the product; a recyclable design does not become effective directly. Supporting the collection of devices by product deposits and incentives when buying new products as done by some manufacturers does increase the number of products which are actually used for spare parts harvesting and to enter a correct recycling stream.

For both reuse and recycling, different allocation methods exist and are heavily discussed (among others Allacker et al. 2017; Schrijvers et al. 2016) and tested on product examples (e.g. van der Hart et al. 2016). As Schrijvers et al. (2016) point out, a "one-formula-fits-all" approach is very difficult, and the allocation method should always take into account the goal and scope.

In general, with more recycling/reuse credits assigned to the product's current life cycle (compared to preceding or following life cycles), the relative impact of manufacturing decreases, making use-time extension and thereby the general problem of obsolescence less relevant in the calculation. However, this cannot be connected to a specific formula alone, but depends also on possible downgrades of material, regional recycling rates, etc. (as shown by van der Hart et al. 2016).

4 Summary and conclusions

The aim of this paper is to show not only the necessity but also the possibility to evaluate the effects of obsolescence in LCA as obsolescence and product lifetime are important topics. To reflect that, ISO 14040/44 as a baseline methodology can cover all important aspects by goal and scope defined methodological choices as long as the practitioner is aware of the critical requirements. Figure 3 summarizes the main critical aspects as discussed in this paper, but also key questions from a product perspective, which should be raised when addressing obsolescence in LCA.

The aspects discussed here not only are valid for discussions around obsolescence but also cover many aspects concerning the circular economy, PSS and in general product lifetime and "quality". It is shown that to reflect the specific impacts of durability and longer lifetimes, basic lifetime and use pattern assumptions per product group are not helpful. Depending on the specific goals, the scope and specifically the functional unit and its reference flow has to be chosen carefully—finding a balance between showing the potential of using a "durable" product and not overloading the technical design with unrealistic long use times. Sticking to the example of the smartphone as is often used in this paper, with the current speed of technological progress, a "durable" smartphone without upgrade functionalities will not be used for 10 years even if the technical lifetime would allow for that. However, a more resilient screen might impact the statistical use time significantly.

Special attention should be paid to methodologies and PCRs which focus on comparability across studies. This can be difficult when they limit individual choices. Nevertheless, they can be formulated in a way to address and include the product-specific obsolescence conditions. They even have the potential to analyse the usage specifics of a product group and, building on this, to define specific rules for use-time assumptions.

It is crucial for all these aspects to understand the relevant obsolescence conditions for the product system under study and how these may differ across the market segment or user types. This paper argues for the necessity to analyse the obsolescence conditions, contributes to understanding the critical methodological requirements and shows clear and applicable examples of how obsolescence can be integrated in LCA.

Acknowledgements Marina Proske is a member of the interdisciplinary researcher group "Obsolescence as a challenge for sustainability" (Obsoleszenz als Herausforderung für Nachhaltigkeit—OHA) which is being funded from July 2016 to June 2021 by the German Federal Ministry of Education and Research in the context of the Research for Sustainability programme.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

Allacker K, Mathieux F, Pennington D, Pant R (2017) The search for an appropriate end-of-life formula for the purpose of the European Commission Environmental Footprint initiative. Int J Life Cycle Assess 22:1441–1458

Andrae A, Vaija MS (2017) Precision of a streamlined life cycle assessment approach used in eco-rating of mobile phones. Challenges 8(2):21

Ardente F, Cellura M (2011) Economic allocation in life cycle assessment - the state of the art and discussion of examples. J Ind Ecol 16(3): 387–398

Ardente F, Mathieux F (2014) Environmental assessment of the durability of energy-using products: method and application. J Clean Prod 74: 62–73

Bajenescu TI, Bazu MI (2012) Reliability of electronic components: a practical guide to electronic systems manufacturing. Media, Springer Science & Business

Bakker C, den Hollander M, van Hinte E, Zljlstra I (2014a) Products that last – product design for circular business models. TU Delft

Bakker C, Wang F, Huisman J, den Hollander M (2014b) Products that go round: exploring product life extension through design. J Clean Prod 69:10–16

Behrendt S, Göll E (2018) Produkte länger nutzen, Project Evolution2Green – Transformationspfade zu einer Green Economy

Bertling J, Hiebel M, Pflaum H, Nühlen J (2014) Arten und Entstehungstypen frühzeitiger Produktalterung – Entwicklung eines Obsoleszenz-Portfolios. UmweltMagazin, pp:3–2014

Bobba S, Ardente F, Mathieux F (2015) Technical support for environmental footprinting, material efficiency in product policy and the European platform on LCA – durability assessment of vacuum cleaners. JRC. https://doi.org/10.2788/563222

Boyd SB, Horvath A, Dornfeld DA (2010) Life-cycle assessment of computational logic produced from 1995 through 2010. Environ Res Lett 5:1

Claxton S, Cooper T, Goworek H, Hill H, McLaren A, Oxborrow L (2017) Pilling in knitwear: a clothing longevity problem beyond design. In: Product lifetimes and the environment. conference proceedings, 8–10 November, Delft, NL, https://doi.org/10.3233/978-1-61499-820-4-89

Clemm C, Winzer J, Dethlefs N, Proske M, Hofmann F, Reichgardt L, Lang K-D (2018) Stärkere Verankerung der Ressourceneffizienz und Abfallvermeidung in produktpolitischen Instrumenten, Umweltbundesamt

Cooper JS (2003) Specifying functional units and reference flows for comparable alternatives. Int J Life Cycle Assess 8:337

Cooper T (2005) Slower consumption – reflections on product life spans and the "throwaway society". J Ind Ecol 9:1–2

Cooper DR, Gutowski TG (2015) The environmental impacts of reuse – a review. J Ind Ecol 21(1):38–56

Cooper T, Oxborrow L, Claxton S, Goworek H, Hill H, McLaren A (2017) New product development and testing strategies for clothing longevity: an overview of UK research study. In: Product lifetimes and the environment, conference proceedings, 8–10 November, Delft, https://doi.org/10.3233/978-1-61499-820-4-94

Cox J, Griffith S, Giorgi S, King G (2013) Consumer understanding of product lifetimes. Resour Concerv Recy 79:21–29

Day C, Beverley K, Lee A (2015) Fast fashion, quality and longevity: a complex relationship. In: Product lifetimes and the environment, conference proceedings. June, Nottingham, pp 17–19

Ellen MacArthur Foundation (2013) Towards the Circular Economy – Economic and business rationale for an accelerated transition, Volume 1

ETSI ES 203 199 V1.3.1 (2015–02) Environmental engineering (EE); methodology for environmental life cycle assessment (LCA) of Information and Communication Technology (ICT) goods, networks and services

ETSI TR 103 476 V1.1.2 (2018–02) Environmental engineering (EE); circular economy (CE) in information and communication technology (ICT); definition of approaches, concepts and metrics

Finkbeiner M (2014) Product environmental footprint—breakthrough or breakdown for policy implementation of life cycle assessment. Int J Life Cycle Assess 19:266–271

Finkbeiner M, Inaba A, Tan R, Christiansen K, Klüppel H-J (2006) The new international standards for life cycle assessment: ISO 14040 and ISO 14044. Int J Life Cycle Assess 11:80–85

Frischknecht R, Althaus H-J, Bauer C, Doka G, Heck T, Jungbluth N, Kellenberger D, Nemecek T (2007) The environmental relevance of capital goods in life cycle assessments of products and services. Int J Life Cycle Assess. https://doi.org/10.1065/lca2007.02.309

Grant A, Ries R, Kibert C (2014) Life cycle assessment and service life prediction – a case study of building envelope materials. J Ind Ecol 18(2):187–200

Günther A, Langowski HC (1997) Life cycle assessment study on resilient floor coverings. Int J Life Cycle Assess 2(2):73–80

Gutowski TG (2018) A critique of life cycle assessment; where are the people? Procedia CIRP 69:11–15

Hankammer S, Jiang R, Kleer R, Schymanietz M (2017) Are modular and customizable smartphones the future, or doomed to fail? A case study on the introduction of sustainable consumer electronics. CIRP Journal of Manufacturing Science and Technology. https://doi.org/10.1016/j.cirpj.2017.11.001

Higgs T, Cullen M, Yao M, Stewart S (2010) Review of LCA methods for ICT products and the impact of high purity and high cost materials. Proceedings of the 2010 IEEE International Symposium on Sustainable Systems and Technology, https://doi.org/10.1109/ISSST.2010.5507691

ISO 14040:2006 (2006) Environmental management – life cycle assessment – Principles and framework

ISO 14044:2006 (2006) Environmental management – life cycle assessment – Requirements and guidelines

ISO/TR 14049:2012 (2012) Environmental management — life cycle assessment — illustrative examples on how to apply ISO 14044 to goal and scope definition and inventory analysis

Jaeger-Erben M, Hipp T (2018) All the rage or take it easy – expectations and experiences in the context of longevity in electronic devices. Descriptive analysis of a representative online survey in Germany Obsolescence Research Group (ed) OHA texts 1/2018

JRC (2010) International reference life cycle data system (ILCD) handbook - general guide for life cycle assessment - detailed guidance. First edition, European Commission - Joint Research Centre - Institute for Environment and Sustainability. Luxembourg

Kjaer LL, Pigosso DCA, McAloone TC, Birkved M (2018) Guidelines for evaluating the environmental performance of product/service-systems through life cycle assessment. J Clean Prod 190:666–678

Laitala K (2014) Consumers' clothing disposal behaviour – a synthesis of research results. Int J Consumer Studies 38:444–457

Laitala K, Klepp IG, Henry B (2017) Use phase of wool apparel: a literature review for improving LCA. In: Product lifetimes and the environment, conference proceedings. November, Delft, pp 8–10. https://doi.org/10.3233/978-1-61499-820-4-202

Lehmann A, Bach V, Finkbeiner M (2016) EU product environmental footprint—mid-term review of the pilot phase. Sustainability 8:92

Makov T, Fishmen T, Chertow MR, Blass V (2019) What affects the secondhand value of smartphones – evidence from eBay. J Ind Ecol 23(3):549–559

Manhart A, Blepp M, Fischer C, Graulich K, Prakash S, Priess R, Schleicher T, Tür M (2016) Resource efficiency in the ICT sector. Final Report, Öko-Institut

McLaren A, Oxborrow L, Cooper T, Hill H, Goworek H (2015) Clothing longevity perspectives: exploring consumer expectations, consumption and use. In: Product lifetimes and the environment, conference proceedings. June, Nottingham, pp 17–19

Middendorf A, Benecke S, Nissen NF, Wittler O, Lang K-D (2015) Establishing EcoReliability of electronic devices in manufacturing environments. Procedia CIRP 26:436–442. https://doi.org/10.1016/j.procir.2014.07.063

Ostertag R (2008) Supply-Chain-Koordination im Auslauf in der Automobilindustrie: Koordinationsmodell auf Basis von Fortschrittszahlen zur dezentralen Planung bei zentraler Informationsbereitstellung, Springer

PEF (2013) COMMISSION RECOMMENDATION of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations (Text with EEA relevance) (2013/179/EU)

Polizzi di Sorrentino E, Woelbert E, Sala S (2016) Consumers and their behavior: state of the art in behavioural science supporting use phase modeling in LCA and eco-design. Int J Life Cycle Assess 21:237–251

Prakash S, Dehoust G, Gsell M, Schleicher T (2016) Einfluss der Nutzungsdauer von Produkten auf ihre Umweltwirkung: Schaffung einer Informationsgrundlage und Entwicklung von Strategien gegen „Obsoleszenz", Umweltbundesamt

Proske M, Jaeger-Erben M (2019) Decreasing obsolescence with modular smartphones? - an interdisciplinary perspective on lifecycles. J Clean Prod 223:57–66

Proske M, Clemm C, Richter N (2016) Life cycle assessment of the Fairphone 2, Berlin

Reap J, Roman F, Duncan S, Bras B (2008) A survey of unresolved problems in life cycle assessment – part 1: goal and scope and inventory analysis. Int J Life Cycle Assess 13:290

Richter JL, Dalhammar C, Tähkämö L (2017) Considering optimal lifetimes for LED lamps: a mixed approach and policy implications. In: In product lifetimes and the environment, conference proceedings, 8–10 November, Delft, https://doi.org/10.3233/978-1-61499-820-4-353

Schischke K, Proske M, Nissen NF, Lang K-D (2016) Modular products: smartphone design from a circular economy perspective, EGG2016+. Berlin. https://doi.org/10.1109/EGG.2016.7829810

Schrijvers DL, Loubet P, Sonnemann G (2016) Critical review of guidelines against a systematic framework with regard to consistency on allocation procedures for recycling in LCA. Int J Life Cycle Assess 21:994–1008

Thiébaud-Müller E, Hilty LM, Schluep M, Widmer R, Faulstich M (2018) Service lifetime, storage time, and disposal pathways of electronic equipment: a Swiss case study. J Ind Ecol 22:1

Van der Hart E, Potting J, Kroeze C (2016) Comparison of different methods to include recycling in LCAs of aluminium cans and disposable polystyrene cups. Waste Manag 48:565–583

van Nes N, Cramer J (2005) Influencing product lifetime through product design. Bus Stateg Environ 14:286–299

Wieser H, Tröger N, Hübner R (2015) Die Nutzungsdauer und Obsoleszenz von Gebrauchsgütern im Zeitalter der Beschleunigung. Eine empirische Untersuchung in österreichischen Haushalten, AK Wien, Vienna