THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Repair or replace? Guidance from indicators and life cycle assessment on circular economy strategies for energy-using products

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Cover:
The machine which produces sea ice is broken. The penguins must choose: repair the current machine and extend its use, or replace it with a new one? As they are concerned for their changing environment, one penguin decides to carry out an assessment. But using indicators or life cycle assessment? Or both? This thesis aims to help him make his decision. For instance, the tools of the penguin in charge of the repair and the resources to build the electric pylon in the background might play an important role in the assessment.

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Abstract

Various circular economy (CE) strategies, such as use extension with repair or reuse, have been suggested as a means for addressing the increasing resource and environmental footprint of society. To identify effective CE strategies, companies or policy makers seek guidance from the evaluation of resource use and environmental impact of alternatives that introduce different CE strategies to product systems. CE indicators and life cycle assessment (LCA) have been used for that purpose. However, a clear description of the differences between these two assessment methods as well as of the aspects accounted for by CE indicators is still missing. Therefore, the aim of this licentiate thesis is to advance the description of CE indicators and LCA in order to provide recommendations for practitioners to select the appropriate assessment method for their specific assessment goal.

To this end, LCA and CE indicators are compared by considering the type of results generated and the modelling specifications. Specific attention is given to the assessment of use extension of energy using products (EuP). This comparison builds on two studies: a review and analysis of CE indicators which identify the flows and processes that indicators account for and how indicators' and LCA results differ, and an LCA of the repair of a long-lived and energy intensive product which identifies what aspects are important to consider in the assessment of this overlooked product category.

The comparison shows that the two assessment methods provide different types of results. CE indicators inform on variations of resource use and especially on variations that are relative to other flows in the product system. LCA provides information on the environmental impacts and thus makes it possible to identify trade-offs between different types of environmental impacts. Besides, LCA allows a greater flexibility than CE indicators in capturing flows and processes but requires an extensive data collection. In comparison, CE indicators, and especially indicators focusing on one CE strategy at a time, have the advantage of being more time-efficient and of providing a detailed description of variations in resource use.

For assessing the reuse or repair of EuP, CE indicators are more limited than LCA with regards to ensuring that important changes in resource use are not missed. No indicator accounts for resource use in the use phase, and thus for changes in energy efficiency by design or with repair and for resources in energy production and transmission. These have however been found to be key aspects in the environmental performance of the repair of an energy intensive EuP.

Therefore, to decide on a repair or replacement, the selection of CE indicators and LCA as assessment methods depends on the type of impacts that a practitioner wants to base its decision on (e.g., environmental impact and/or resource use) and on the important modelling specifications for the product system (e.g., resources in energy production and transmission for the repair of an energy intensive EuP). Further research could focus on understanding the needs from practitioners in specific contexts to develop the practicability of these recommendations and on exploring other central modelling aspects for use extension such as the product's lifetime.

Keywords: Circular economy, environmental assessment, use extension, indicator, life cycle assessment

List of appended papers

Paper I

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

Paper II

Jerome, A., Ljunggren, M., Janssen, M., 2022. Is repair of energy using products environmentally beneficial? The case of HV motors. (manuscript submitted to a scientific journal)

Other related papers

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

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

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To my parents and little sister, thank you for bearing my absence while I keep wanting to stay up north in the cold. And Rémi, I would not be who I am without you. Thank you for being supportive in whatever I do. After all, everything will eventually work out…

Table of Contents

1 Introduction

Natural resources such as energy, materials, land, or water, are fundamental for the functioning of human societies. Driven by an increasing population and economic development, the extraction of natural resources has grown and continues to grow (Ekins et al., 2017), leading to an extensive change in natural ecosystems. The extraction and processing of resources are responsible for more than 90% of biodiversity loss, water stress and around half of global climate change impact (Oberle et al., 2019). Increased resource efficiency can reduce material use and thus limit the impacts on human health and on the environment.

As a means for addressing this issue, the concept of circular economy (CE) has received growing attention in the literature and from political bodies (Geissdoerfer et al., 2017). CE is defined as "an industrial system that is restorative or regenerative by intention and design" (Ellen MacArthur Foundation, 2013), achieved by, e.g., product design strategies, new business models, and closed-loop supply chains. Various strategies are suggested to extend resource life by narrowing, slowing and closing resource loops (Bocken et al., 2016) with the aim of improving the environmental footprint of society (Kirchherr et al., 2017). At a product-level, the suggested strategies are targeting all product life cycle phases (Böckin et al., 2020), including production (e.g., reduction of energy or material losses during production), use (by using effectively, i.e., delivering not more function than the user's need, or using efficiently, e.g., improving the energy efficiency of a product), and post use (e.g., material recycling) (Figure 1). Additionally, several strategies for extending the use of products or components have been suggested, including increasing the technical lifetime by design and strategies occurring after use of the product such as maintenance, reuse, repair, or remanufacturing.

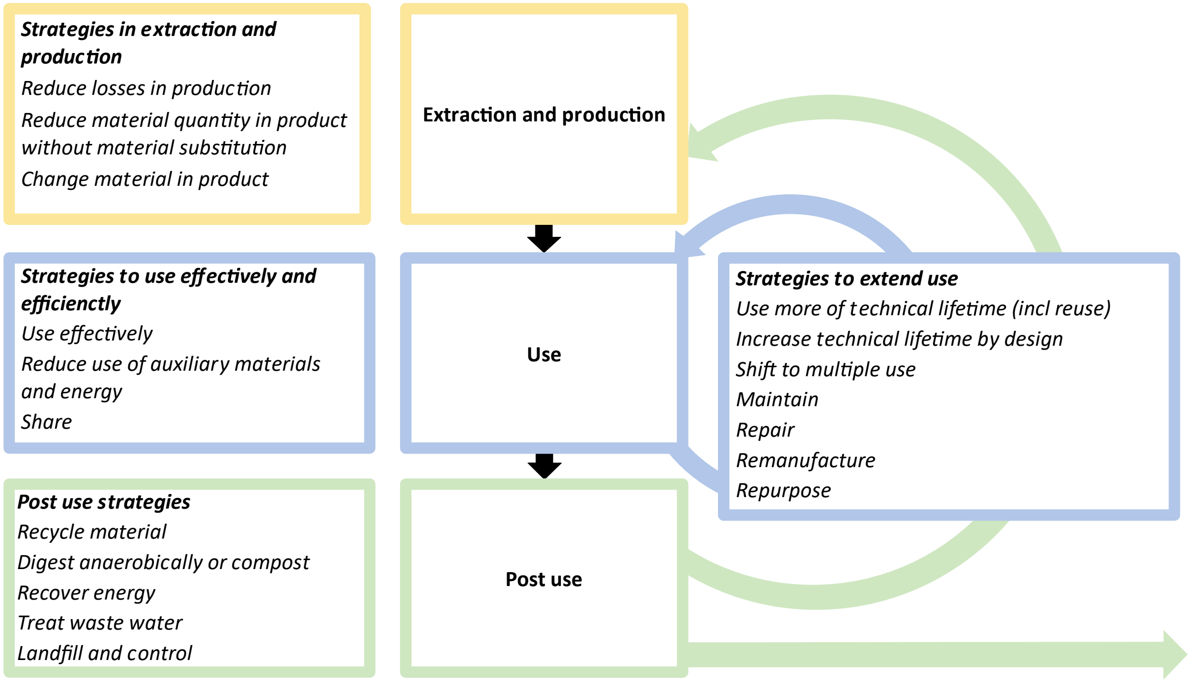


Figure 1. Physical CE strategies for products from Böckin et al. (2020).

Given this variety of CE strategies, it is challenging to select the strategies that would be effective to improve resource efficiency and to reduce the environmental impacts of a product. Simplified rankings of strategies such as the waste hierarchy adopted by the European Commission (European Commission, 2008) or as the different R-frameworks (e.g., Reduce-Reuse-Recycle) (Kirchherr et al., 2017) were suggested to set priorities between different CE strategies. But previous assessments pointed out that such simplified rankings are not relevant for all products (Böckin et al., 2020; Ljunggren Söderman & André, 2019). Introducing CE strategies in a product system may lead to burden shifting and trade-offs between impact categories, and different CE strategies are effective for different types of products (Böckin et al., 2020). Consequently, product and process development can be supported by quantitative assessments for selecting the most effective and efficient strategies by, e.g., evaluating alternatives that introduce different CE strategies to a product system. For instance, this evaluation of alternatives can support product designers in companies for selecting potential solutions, policy makers for developing effective requirements on product designs, or researchers for choosing case studies or for recommending CE strategies on specific products.

Many methods have been used for assessing changes due to CE strategies in resource flows and in their associated environmental impacts (Harris et al., 2021; Walzberg et al., 2021). These existing methods vary in terms of scope and thus in terms of the questions that can be addressed (Walzberg et al., 2021). But, when the goal of the assessment is decided, there is a lack of information supporting the choice of which method (or methods) to use and how to use them (e.g., adaptations to be made to specific cases, consecutive or complementary use of different methods). Especially, recommendations for the selection of established assessment methods (e.g., life cycle assessment (LCA), material flow analysis) for assessing CE strategies have been developed (Walzberg et al., 2021), but they do not include indicators that have been specifically developed to assess CE. This lack of clarity in the choice of methods may hinder practitioners and, e.g., companies to carry out an assessment of the effects of CE strategies (Roos Lindgreen et al., 2022).

Therefore, the aim of this licentiate thesis is to advance the description of methods for assessing the effects of CE strategies on resource use and environmental impact in order to provide recommendations for the selection and use of these assessment methods. The methods in focus are indicators and LCA. In addition, the use of these methods for assessing use extension strategies of energy-using products (EuP) is specifically addressed. EuP have been estimated to represent two thirds of the global household’s energy footprint and to drive the increase of this energy footprint (Vita et al., 2021). Besides, these products have been in focus in European policies since the introduction of the Ecodesign directive (European Commission, 2009), and are in focus again in the new European CE action plan (European Commission, 2020).

2 Theoretical background and literature review

2.1 Resource availability and environmental impact

This work focuses on the assessment of resource use and environmental impact. The two notions are important to distinguish, starting with a clear definition of what “resources” encompass.

Natural resources are assets occurring in nature that are deemed useful for human purposes. They encompass metals, non-metallic minerals, fossil fuel and biomass (Oberle et al., 2019), as well as renewable energy sources, air components, water, soil, and land and water surface (Sonderegger et al., 2017). Raw materials and energy carriers (e.g., coal, fuel or electricity) are the result of a transformation of natural resources through, e.g., mining and refining, agricultural or manufacturing activities. But the boundary between natural and other resources is somewhat arbitrary as most resources require some processing before being used (Sonderegger et al., 2017). Raw materials and energy carriers can originate from nature, called primary sources, or from discarded materials, called secondary sources. Viewing waste as a resource through, e.g., recycling or urban mining, has been key in the development of the CE concept (Blomsma & Brennan, 2017). In this licentiate thesis, “resource” encompasses natural resources, primary and secondary raw materials and energy carriers. Within resources, a distinction between “materials” (expressed in mass unit) and “energy” (expressed in energy unit) is also used as a convenient distinction for measuring and reporting resource use at the level of product systems.

Different categorisations of resources are possible, depending on the purpose and grounds of the categorisation (Tillman et al., 2020). For instance, resources can be categorised based on their renewability, i.e., they can be renewed by natural cycles relative to human timescale, and exhaustibility, i.e., they can be used up if the extraction rate is significant. Non-renewable resources are stock resources such as fossil fuels, minerals, and metals, and are also exhaustible. Renewable resources include fund resources (e.g., flora and fauna) that are exhaustible, and flow resources (e.g., wind and solar radiation) that are not exhaustible (Sonderegger et al., 2017; Tillman et al., 2020).

The availability of these different categories of resources are subject to different issues. The availability of non-renewable resources concerns either the depletion of their stock or the dissipation of the resource which limits their extraction. Fund resources may be overused, and flow resources are subject to variations in availability with time. Other issues related to resources are the competition for land or water surface, and the degradation of soil quality (Oberle et al., 2019; Sonderegger et al., 2017).

In contrast to resource availability, an environmental impact is an effect on the environment caused by an environmental load (e.g., the emission of a pollutant). The cause-impact pathway is long and complex, with one effect contributing to several other secondary effects and with feed-back mechanisms (Baumann & Tillman, 2004). The definition of what is considered as the environment differs between frameworks, especially on what part of human societies could be considered as part of the environment. For instance, metal resource depletion is not integrated in the planetary boundary framework (Steffen et al., 2015), as the extraction of these resources does not change the Earth system. In the LCA framework, resource availability is considered as one of the three areas of protection.

Different LCA environmental impact assessment methods related to resource availability were developed. Methods for area of land use, water use, and impacts related to water quality (e.g., eutrophication or acidification) are available and are part of the two other areas of protection, human health and ecosystem quality (Huijbregts et al., 2016). For resource availability, developed impact assessment methods are mostly focused on non-metallic mineral, metal and fossil resource depletion and dissipation (Sonderegger et al., 2017), but the choice of impact mechanism (e.g., reduction of stock, future efforts to extract a resource) is still debated (André, 2020; Arvidsson et al., 2020; Sonderegger et al., 2020).

Resource use may not have the same meaning in a context of a mapping of resource flows in a product system or in the context of assessing environmental impacts of the same. In the former, the amount of material and energy, expressed in mass or energy units, are studied. In the latter, the amount of material or energy is translated into an impact unit, based on the contribution of specific resources to the impact. In this licentiate thesis, “resource use” refers to the first context described above, and “resource depletion impact”, included in “environmental impact”, refers to the second context. For instance, for a product made of steel, copper and plastics, the resource use for resources in the product is the sum of material quantities without differentiation of the different materials. The resource depletion impact accounts for the contribution of each material relative to a given material (e.g., impact expressed in kilogram of silicon equivalent).

2.2 Life cycle assessment

2.2.1 Method description

Life cycle assessment (LCA) is an assessment method which estimates the potential environmental impact of a product system, and which has been formalised in international standards (ISO, 2006a, 2006b). This method takes a life cycle perspective, i.e., covers a product system from the extraction of raw materials to the end-of-life treatment. The assessment is based on the study of resource flows from technical activities and their effects on the environment.

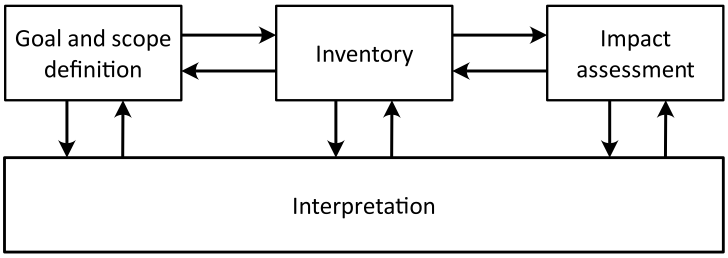


Figure 2. Representation of the LCA procedure (ISO, 2006a).

An LCA is carried out in four steps (Figure 2) (Baumann & Tillman, 2004; ISO, 2006a).

1) First, the goal and scope are defined. The purpose of the study and methodological choices that derive from it are described. The system boundaries, the different alternatives to be studied and the functional unit are defined. The functional unit reflects the function of the system under study and sets the basis of comparison between the studied alternatives but also with other products fulfilling the same function. Additionally, the environmental impact categories to be examined are selected. The selection could be large with various impact categories or limited to key indicators, and could include midpoint indicators (i.e., located somewhere along the cause-impact pathway such as global warming, mineral resource depletion or freshwater eutrophication) and/or endpoint indicators (i.e., reflecting one of the three areas of protection, which are human health, resource availability and damage to ecosystems, and thus combining several midpoint impacts into one value).
2) Then, the inventory analysis is done by collecting data about all activities and flows in the system. The flows include material and energy inputs and outputs, products, emissions, wastes, other physical inputs such as land use.
3) In the step of the impact assessment, each flow is characterised regarding its contribution for each selected impact category. The potential environmental impact of the product system is calculated as the sum of the relevant contributions to an impact category.
4) Finally, the interpretation step is the analysis of the results in relation to the goal and methodological choices for the study.

The learnings from all steps inform the choices made along the assessment. For instance, the analysis of initial results could lead to additional data collection for highly contributing activities or to implement a sensitivity analysis for selected input parameters. The assessment is thus done in an iterative way.

Conclusions from an LCA can be used to support decision-making for product design and development of public policy, by identifying improvement possibilities and hot spots in the life cycle or by comparing alternatives with the same product function (Baumann & Tillman, 2004).

2.2.2 LCA for assessing CE strategies

For assessing the effects of product-level CE strategies on environmental performance, LCA has often been used by researchers (Böckin et al., 2020; Corona et al., 2019; Harris et al., 2021) and by companies (Roos Lindgreen et al., 2022; Sassanelli et al., 2019). It has been recommended for its comprehensiveness in terms of potential impacts (Elia et al., 2017) and for its holistic approach of describing the product system (Corona et al., 2019). Several limitations of the use of LCA to assess CE strategies for products have been raised as well. First, the extensive data collection required and the difficulty to communicate the results to a non-expert audience are practical barriers for implementation (Elia et al., 2017). Second, methodological aspects for the allocation of recycling between the upstream and downstream products is still debated (Corona et al., 2019), with concerns about the accountability for the burden of the treatment (Baumann & Tillman, 2004), the possible displacement of virgin material production (Zink et al., 2016) and the material quality losses (Schrijvers et al., 2016). And third, LCA only addresses the environmental consequences of a modelled product system and leaves out other sustainability aspects such as social and economic consequences (Baumann & Tillman, 2004). Socio-technical dynamics are also not possible to study, and thus side effects of CE strategies such as rebound effects are not possible to identify (Niero et al., 2021).

2.3 Product-level CE indicators

2.3.1 Sustainability indicators

Sustainability indicators are variables that provide relevant information for decision-making (Gallopín, 1996; Moraga et al., 2019). Compared to other pieces of information, indicators are tools of change (Meadows, 1998) and are given an importance through interpretation, which is specific to the decision-making process (Bakkes et al., 1994). They are used to provide information for comparing situations, to assess current conditions and trends (sometimes in relation to a target for performance indicators), to provide early warning information and to anticipate future conditions and trends (Gallopín, 1996).

Indicators are expected to be a simplified but accurate description of a complex reality, based on models that were developed to make sense of the world (Meadows, 1998). Many characteristics define good indicators including, among others, consistency, relevance, time-efficiency, and clear and easy understanding (Meadows, 1998).

With the emergence of plans of actions for sustainable development, indicators have been pointed out as necessary to set ambitions, monitor changes and to ensure that no aspect is left behind (UN, 1993, 2015). More than 700 initiatives on sustainable development indicators have been reported by Pintér & Hansen (2008). Various indicator frameworks at the global, regional, national levels and for companies have been developed (Lundqvist, 2000; Palme, 2007). A framework is a set of indicators and is based on a model to develop indicators and to organise them into categories or along a causal chain (Lundqvist, 2000). Thus, a framework reduces the risk of an ad hoc choice of indicators and an unclear understanding of the issues addressed.

Results from LCA can be considered as a set of indicators informing on several environmental impact categories (Lundqvist, 2000). But in the context of this thesis, the term “indicator” refers to variables that are less time and resource consuming to compute in comparison to data-intensive assessment frameworks such as LCA.

2.3.2 Product-level indicators in the context of CE

Like sustainable development indicators, indicators for the CE, henceforth referred to as CE indicators or indicators, were developed for various implementation levels with examples of indicators at a regional (e.g., the CE monitoring framework from the European Commission (2018)), national, and company level (de Pascale et al., 2021). Additionally, as companies are regarded as an essential driver in the transition to a more circular economy (Lieder & Rashid, 2016), many product-level CE indicators were developed (Elia et al., 2017; Helander et al., 2019; Moraga et al., 2019; Parchomenko et al., 2019;

Saidani et al., 2019). They are expected to support companies in understanding the situation (e.g., benchmarking, monitoring progress), communicating internally or externally, or in decision-making (e.g., assess alternatives) (Saidani et al., 2019).

Reviews of product-level CE indicators have been carried out to compare them, focusing on a classification of indicators based on the CE strategies (Moraga et al., 2019; Parchomenko et al., 2019; Saidani et al., 2019), sustainability aspects (Corona et al., 2019; Kristensen & Mosgaard, 2020) or life cycle phases (Helander et al., 2019) addressed. These reviews showed that most indicators are limited in these regards. Using one indicator is then not sufficient to identify eventual burden shifting in the product system. Therefore, using multiple complementary CE indicators have been suggested (Corona et al., 2019; Moraga et al., 2019).

However, the complementarity between indicators is unclear (Parchomenko et al., 2019; Saidani et al., 2019), hindering the identification of relevant indicator frameworks for products. It could partly be explained by a lack of testing the indicators in case studies. Testing indicators is an essential step in the understanding of their application and abilities, and in development of new assessment frameworks (Meadows, 1998). However, previous reviews are built on a classification of indicators based on analyses of the indicators' methodology description. Only one study applied a limited range of CE indicators to a case (Saidani et al., 2017) to conclude that the three indicators tested are unable to grasp all CE strategies and thus to be used for assessing any product alternative. Therefore, a clear description of what is specifically quantified by indicators is missing.

Besides, a clear identification of complementarities with other assessment methods such as LCA is lacking (Corona et al., 2019; Harris et al., 2021; Helander et al., 2019). Some indicators were used in combination with LCA (Niero & Kalbar, 2019; Walker et al., 2018). Furthermore, three studies focused on comparing the results from one indicator, different for each study, to LCA results (Bracquené et al., 2020; Linder et al., 2020; Lonca et al., 2018). These studies highlighted a difference in the preferred CE strategy for a product identified by CE indicators and LCA results (Walker et al., 2018), but they did not explain what is captured by the tested indicators in comparison to LCA and the range of tested CE indicators was limited. Therefore, a comparison of CE indicators and LCA to identify their relationship and appropriateness to address the goal of one's assessment remains to be developed.

2.4 Assessment of use extension of energy-using products

Energy using products (EuP) are products requiring energy input for their functioning during the operational phase. In the European Union, EuP have been targeted by the Ecodesign Directive (European Commission, 2009) to reduce their energy consumption. Initiated by the CE Action Plan (European Commission, 2020), an update of the Ecodesign Directive is currently developed with the aim of enabling CE strategies through the design of EuP. The new requirements would promote use extension of products by promoting products that are more durable, reusable, reparable, easier to maintain and to refurbish (European Commission, 2022).

Use extension by reuse, design, maintenance, repair, remanufacturing, and repurposing have been suggested as relevant CE strategies for resource use and environmental impact of EuP (Böckin et al., 2020). But the application of these strategies does not always lead to positive outcomes. For instance, a trade-off between use extension and energy efficiency improvement by replacement with newer technologies has been identified (Böckin et al., 2020; Keoleian, 2013). Previous studies assessing the effects of use extension on the environmental performance and resource use of EuP used LCA. By summarising their conclusions (Table 1), a number of aspects have been identified as important for the outcome of EuP use extension. These aspects are related to the product (e.g., annual energy consumption, impact of production, speed of technological development), the use extension itself (e.g., impact from preparation for use extension, duration of additional use provided), and background system (e.g., choice of electricity mix). The outcome of use extension also changes with the impact category as some aspects, such as the share of the impact of production, preparation for use extension or from the production of a given electricity mix, vary with the impact category considered. For instance, the production was found to be dominant in the impact of washing machines for mineral resource depletion but not for global warming, which explains why use extension was identified as always beneficial for mineral resource depletion but not necessarily for global warming (Tecchio et al., 2016). Therefore, the potential benefit of use extension depends on the product, use extension strategy implemented and environmental impact category considered.

However, only a limited range of EuP have been studied so far. Case studies have so far focused on household appliances, laptops or smartphones (Table 1). More long-lived and more energy intensive products have not yet been studied with regards to the effects of use extension on resource use and environmental impacts. This shortcoming limits the identification of important aspects for the performance of energy intensive EuP and the effects of use extension on resource use and environmental impacts.

Table 1. Characteristics of studies on the effects of use extension on the environmental performance of EuP.

	Product											Impact categories	Use extension strategies						Important aspects for the outcome of use extension							
	Large household appliances				Small household appliances			Other EEE			Other															
Reference of the study	refrigerator	washing machine	dishwasher	oven (electric)	vacuum cleaner	toaster	other	mobile/smartphone	laptop/computer	other EEE	other		By design	Reuse	Maintain	Repair	Remanufacture	Repurpose	Degradation of efficiency with use	Impact of production	Speed of technology development	Impact of prepa. for use extension	Additional use duration	Initial use duration	Electricity mix	Use pattern
(Ardente & Mathieux, 2014)		x										GW, AD, TE				x				x	x	x	x			
(Ardente et al., 2018)										x[4]		(ILCD)					x			x	x	x				
(Bakker et al., 2014)	x								x			ReCiPe	x								x					
(Baxter, 2019)	x											GW, OD, PO, Ac, Eu, CED					x				x	x	x	x	x	
(Biswas et al., 2013)										x[5]		GW				x	x					x	x			
(Bobba et al., 2016)					x							(ILCD)				x				x			x	x		
(Boldoczki et al., 2020)	x	x							x	x[6]		CED, (ReCiPe)		x						x	x			x	x	x
(Boustani et al., 2010)	x	x	x									CED					x				x					
(Bovea et al., 2020)					x	x	x[1]					GW, AD, Ac, Eu, OD, PO, HT, ReCiPe				x						x	x			
(Chen & Lu, 2017)											x[8]	GW, AD, Ac, HT, EPS, ReCiPe			x		x			x				x		
(Cheung et al., 2018)							x[2]					GW, MD, PED		x							x				x	x
(Devoldere et al., 2009)		x										EI99		x							x			x		
(Downes et al., 2011)		x				x	x[3]	x	x			GW*	x							x						
(Güvendik, 2014)								x				GW, MD, HT		x			x									
(Hummen & Wege, 2021)											x[9]	GW, ReCiPe					x				x					
(Iraldo et al., 2017)	x			x								(ILCD)	x								x			x		
(Lindahl et al., 2014)											x[10]	GW, EI99	x				x							x		
(O'Connell et al., 2013)		x										CED		x							x		x	x		x
(Pérez-Belis et al., 2017)					x							ReCiPe				x						x		x		x
(Pini et al., 2019)	x	x							x	x[7]		IMPACT2002+					x					x				
(Prakash et al., 2017)									x			GW	x							x				x		
(Proske et al., 2020)								x				GW, AD, HT, TE		x			x					x				
(Quariguasi-Frota-Neto & Bloemhof, 2012)								x	x			CED					x				x		x	x		
(Rüdenauer et al., 2005)		x										GW, CED		x							x			x		
(Schau et al., 2012)											x[11]	PED					x					x			x	x
(Schischke et al., 2003)								x				(CML)		x							x					x
(Spielmann & Althaus, 2007)											x[12]	EI99		x							x					
(Tecchio et al., 2016)		x	x									GW, AD, FE		x		x					x		x			
(Zink et al., 2014)								x				GW, Ac, HT, OD, PO					x	x								x

Other products assessed: [1] hand blender, coffee maker, heater, juicer, kettle, iron, sandwich maker, hair dryer, [2] video projector, [3] printer, [4] server, [5] compressor (for refrigerators or air conditioning), [6] printer, monitor, [7] LCD, fluorescent lamp, [8] truck fleet, [9] circulation pump, [10] soil compactor, [11] alternator (car component), [12] car.

Impact categories: in parenthesis are the name of sets of indicators, ReCiPe midpoint indicators from Huijbregts et al. (2016), ILCD from JRC) (2011) and CML from Guinée (2002). Midpoint impact categories: Ac: acidification, AD: abiotic depletion, CED: cumulative energy demand, Eu: eutrophication, FE: freshwater eutrophication, GW: global warming, HT: human toxicity, MD: metal depletion, OD: ozone layer depletion, PO: photochemical oxidation, PED: primary energy demand, TE: terrestrial ecotoxicity. Endpoint impact categories: EI99: Eco-indicator99, EPS, IMPACT2002+, ReCiPe.

* The study also considers “resource depletion” and “water use” but the method is unclear.

3 Aim of the licentiate thesis

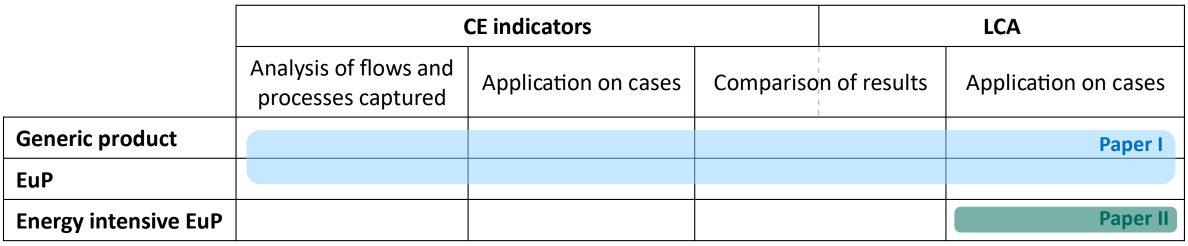
In section 2, two research needs were identified regarding the knowledge of methods for assessing the effects of CE strategies on resource use and environmental impact. First, a clear description of what is accounted for by CE indicators is missing, hindering an informed selection of indicators as an assessment method or as part of the assessment together with LCA. Besides this description, the selection of indicators would be informed by the important aspects in the modelling of the product system to be assessed in order to avoid missing important variations in resource use and environmental impacts. Specifically for use extension of EuP, the range of products that have been studied is focused on small- and medium-sized EuP, limiting the range of identified aspects that need to be accounted for in assessments of use extension of EuP. Hence, the second identified research need is the study of the effects of use extension of long-lived and energy intensive EuP on resource use and environmental impacts.

This licentiate thesis seeks to advance the description of methods for assessing the effects of CE strategies on resource use and environmental impact, and specifically the description of CE indicators compared to LCA in the context of the assessment of the use extension of EuP, including energy intensive EuP. This work then aims to provide recommendations for the selection and use of these assessment methods.

4 Method

4.1 Research design

The work presented in this thesis builds on two appended papers that address the research needs identified in section 2, and on a comparison of CE indicators and LCA to combine the conclusions from the two papers into recommendations for selecting and using these assessment methods. The first paper focuses on CE indicators and their testing on cases compared to LCA. The second one is more specific to energy intensive EuP and to LCA (Figure 3).



	CE indicators			**LCA**
	Analysis of flows and processes captured	Application on cases	Comparison of results	Application on cases
Generic product				**Paper I**
EuP				
Energy intensive EuP				**Paper II**

Figure 3. Overview of the scope of the two papers appended to this licentiate thesis.

In the first study, a systematic literature review was performed to identify existing product-level and resource-based CE indicators (Paper I). They are mapped on a generic product-system flowchart, tested on seven case studies and compared to LCA results of the same case studies. The following specific research questions are answered: What resource flows and processes are captured in CE indicators and what limitations can be identified? And, do conclusions drawn from CE indicators differ from those from LCA? Recommendations on assessment with CE indicators derived from the work in Paper I are useful for, but not limited to, use extension or EuP.

For the study in Paper II, an LCA for a case of repair of high-voltage (HV) electric motors was carried out. HV motors are big and stationary motors used in the industry. The motors studied are used for at least 20 years and deliver 16 MW full time for 50 weeks per year. Two motor designs with different energy efficiency and their repair were studied to answer the following specific research question: what are the effects of repair and improved energy efficiency by design on the environmental performance of HV motors?

In this licentiate thesis, the learnings from the two studies are combined to develop a broader description of assessment methods for CE strategies by comparing CE indicators and LCA. In particular, the following research questions are addressed:

(1) What differences exist between indicators and LCA when assessing the effects of CE strategies on resource use and environmental impact?

And more specifically for the use extension of EuP:

(2) What are the implications of those differences when assessing the effects of use extension for EuP on resource use and environmental impact?

The comparison of the two assessment methods does not aim to propose a framework for method comparison such as done by (Tillman et al., 1997), or to be a comprehensive comparison on all the relevant aspects that need to be taken into consideration when choosing an assessment method such as methodological aspects and situation of use (Baumann & Cowell, 1999; Finnveden & Moberg, 2005; Tillman et al., 1997). Instead, the conclusions from the two papers presented above are combined and structured into a method comparison.

From the comparison, recommendations for the selection and use of assessment methods for comparing product system alternatives which introduce different CE strategies are drawn. The recommendations do not aim to prescribe an assessment method or to develop a new method based on the identified limitations and complementarities of CE indicators and LCA. These recommendations aim to shed light on some aspects that are important to consider when either product designers, policy makers or researchers decide on the appropriate assessment methods for their specific assessment goal. Indeed, product design processes differ with, e.g., the design approach, the availability of data, and the complexity of the product system (Keoleian, 1993). Furthermore, the choice of assessment methods and how the methods are used differ with the decision context (Finnveden & Moberg, 2005), so one generic assessment method cannot be recommended.

4.2 Method for the comparison

The comparison of CE indicators and LCA was developed by, first, identifying the elements of comparison for guiding the selection of assessment methods for CE strategies and, second, by evaluating and comparing product-level CE indicators and LCA against these elements.

4.2.1 Elements of comparison

Due to choices in the selection of CE indicators to be studied (see Paper I for the list of criteria), the CE indicators in focus in this work and LCA share several general methodological and contextual aspects that were considered important for selecting methods in previous comparisons (Baumann & Cowell, 1999; Finnveden & Moberg, 2005; Tillman et al., 1997). For instance, the object of study is a product system, and input data are quantitative and describe physical systems (as opposed to social and economic systems).

Both Paper I and II are based on the application of the methods on cases. Additionally, an analysis of the flows and processes captured by CE indicators was performed in Paper I. Therefore, the combined conclusions of the two studies inform on the comparison of CE indicators and LCA with regards to the practical use of the two methods. Two main types of elements of comparison have been selected to inform practitioners on the selection of assessment method: the type of results and various modelling specifications. The first type informs on what would be learned with the assessment method for the comparison of alternative product systems and is thus related to the aim of the assessment. Modelling specifications provide information on the elements of the physical product systems that are modelled.

Types of assessment results

The type of results is further distinguished into the type of impacts and the basis for comparison. The types of impacts are limited to environmental impacts, including resource depletion impacts, and resource use, as the focus of this work is the assessment of these two types of impact. Besides, the choice of the basis of comparison is an essential element for comparing alternatives.

Modelling specifications

Modelling specifications are further subdivided into four categories: 1) the system modelled, 2) the modelling of the product, 3) the use extension strategy and 4) the background system focusing on energy production and transmission. These four categories follow the steps in the thinking process for developing the assessment in Paper II. The category on the system modelled focuses on the processes and type of flows that are covered by the assessment and thus on knowledge for the definition of the system boundary. The three remaining categories encompass modelling specifications that are related to, respectively, the product to be assessed irrespective of the use extension strategy, then the use extension strategy based on the alternatives that are decided for the product, and finally to a more careful attention to the background system for an eventual sensitivity analysis. The aspects included in those categories are based on relevant aspects for the analysis of CE indicators and their comparison with LCA that were identified in Paper I. Aspects that are more specific to the use extension of EuP were gathered from previous assessments (see Table 1). Finally, additional aspects for energy intensive EuP were identified in Paper II with the LCA of the repairs of HV motors.

4.2.2 Evaluation against the elements of comparison

The evaluation CE indicators and LCA against the elements of comparison was based both on 1) a mapping and analysis of what is captured by CE indicators (Paper I) and on 2) applications of the two assessment methods on cases (Paper I and II).

The mapping and analysis address a knowledge gap on what exactly each CE indicator captures in terms of flows and processes in a product system. This was based on an in-depth analysis of their data requirements and calculation method (Paper I). The visualisation of the captured flows and processes was done on a generic flowchart of a product system. This flowchart was developed over the course of the analysis to include only the flows and processes that are captured by indicators. This way, the limitations in terms of processes and flows not yet addressed were also made visible in the analysis. Then, missing processes and flows that are related to the list of CE strategies from Böckin et al. (2020) were added to create an extended flowchart. Besides, CE indicators were further analysed on four aspects (Paper I): 1) CE strategies that CE indicator’s methodology has in focus, 2) the life cycle phases that are accounted for, 3) the requirement of additional data besides physical resource data (e.g., temporal data such as the product lifetime, product function, energy use), and 4) whether the indicator makes a distinction between renewable and non-renewable energy or resources.

This analysis was completed by applying the two assessment methods on the seven cases (Paper I). The cases were based on three published studies:

- The more resource efficient production and use of incontinence products (Willskytt & Tillman, 2019) which encompasses four cases: recycling production wastes back into production, changing material composition to more bio-based materials, shifting to multiple use of one component, and the effective use of the products by tailoring the size to its user,

- The use extension of laptops (André et al., 2019) for which a resale company sorts laptops that are deemed reusable and suitable laptops are used a second time. However, the case focuses on the laptop without the battery and thus excludes energy use in the use phase,
- The weight reduction of truck engines with 3D-printing (Böckin & Tillman, 2019) which encompasses two cases: one with the regular 3D-printing technology and one with an advanced 3D-printing technology. For both, changes are made in the composition and design of the engines, which leads to a reduction of the weight of the engine.

For each case, CE indicators and LCA were used to assess the alternative with enhanced CE and to a business-as-usual alternative, i.e., representing the then existing situation. More information about the description of the cases and their alternatives is available in Table 1 of Paper I. The results were expressed as the relative difference between the CE alternative and its business-as-usual alternative. The interpretation of the results from CE indicators and LCA were compared and gave insights on the type of results provided by the two assessment methods.

Finally, LCA was applied on the repair of high-voltage (HV) electric motors for LCA (Paper II). The case was chosen to extend the range of EuP studied to energy intensive ones in assessments of the effects from use extension on environmental impacts and resource use. The study focused on the effects of improved energy efficiency and the effects of use extension with two comparisons: 1) between two HV motor designs with varying energy efficiency and 2) between motors with and without extended use with repair (Paper II).

5 Results

5.1 Types of assessment results

The application of CE indicators and LCA on the same cases in Paper I showed that the type of results is different for the two assessment methods. LCA informs on environmental impacts, while CE indicators inform on resource use, i.e., the variations of material and sometimes energy resource flows. Specifically, variations in production efficiency, i.e., the material quantity in the final product compared to the quantity in input of the production, and in recycling efficiency are possible to identify with CE indicators. For instance, for the case of 3D-printed engine with advanced technology (Figure 4), CE indicators point to a reduction of recycled content (indicators in MC) and a lower recovery rate (indicators in Rec) from metal recycling due to changes in the material content induced by 3D-printing. Additionally, an increased energy use and a reduced waste generation during production with 3D-printing are pointed out (indicators in RL). In comparison, the reduction of material recovery rate at end-of-life and improved production efficiency is not clearly visible in the LCA results. But the results point to a reduction of global warming and fossil resource depletion impacts, explained by a lower fuel consumption during use resulting from the light-weighting of the engine, and higher ionizing radiation. The latter is explained by a higher energy use during the 3D-printing, provided with an average Swedish electricity mix with a high share of nuclear energy. LCA results then point to consequences of the emissions from energy sources on different environmental impact categories.

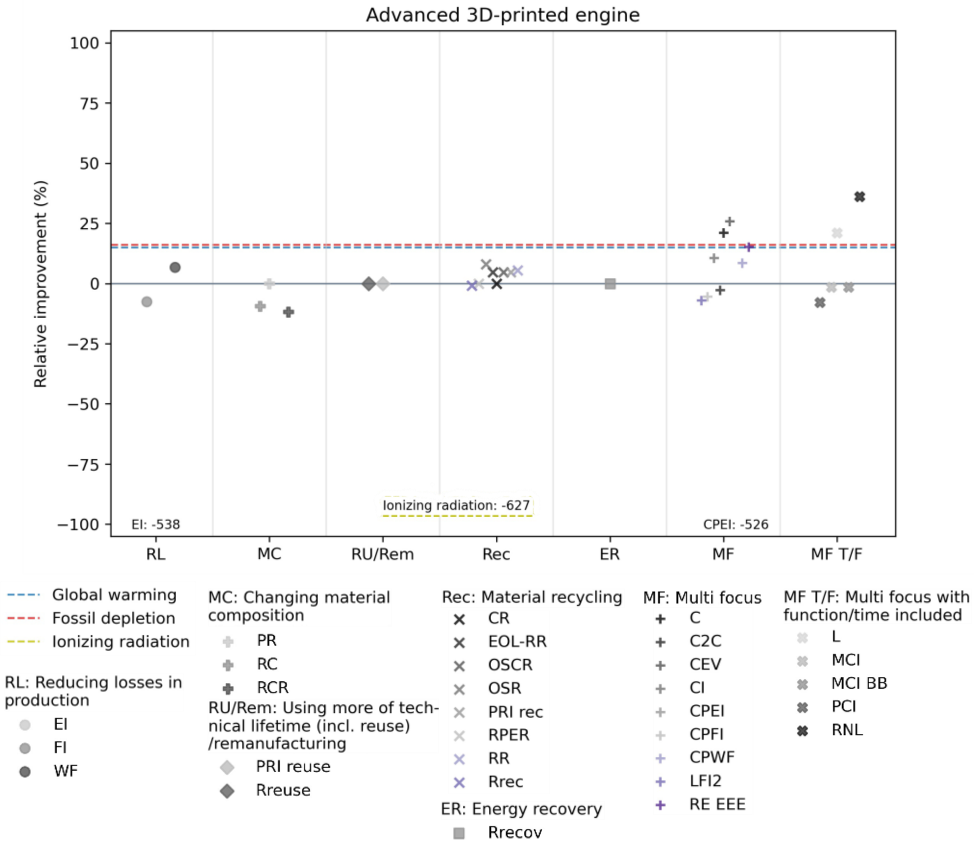


Figure 4. Relative improvement for the 31 tested indicators and the selected LCA impact categories on the case of the 3D-printed engine with advanced technology. Results for the six other cases are available in Figure 4 in Paper II.

From the results of CE indicators for the different cases (Paper I), it was also concluded that absolute variations of material flows were visible with only one indicator. All other indicators express mass flows as relative to other mass flows within the same system. For instance, for the assessment of cases on incontinence products, the packaging box is the only component with a high rate of renewable materials, and which is recycled and not incinerated at end-of-life. Thus, a heavier packaging contributes positively to CE indicators that reward renewable materials and high recycling rates. However, it is questionable if having more packaging and thus a higher resource use for the delivery of the same function should be rewarded. With LCA, a heavier packaging for the same product function resulted in increased global warming, fossil resource depletion and land use. This observation was partly explained by a different basis for comparison (Paper I). Expressing the impact per functional unit is a foundational feature in LCA. Thus, a heavier product with all other variables (e.g., product composition, waste rates) unchanged, and for the same product function, requires additional material extraction and production, which contribute to a higher environmental impact per functional unit. For CE indicators, except for one indicator which is expressed per product function, results are expressed for one product and as a fraction of flows within the product system. The same heavier product as above then results in the same value for these CE indicators.

Therefore, the comparison of the type of results has led to a distinction of CE indicators and LCA on two aspects (see Table 2 for a summary of the comparison). CE indicators essentially inform on variations of resource flows for one product, and absolute variations of resource use are visible with only the indicator expressed per product function. LCA provides information on environmental impacts per product function. It can be noted that quantitative data on resource use and pollutant emissions are possible outputs from the inventory in LCA (Tillman et al., 1997), although this type of results is not commonly reported in LCA studies.

5.2 Modelling specifications

5.2.1 System modelled

For the system modelled, the comparison focuses on the processes and type of flows included in the assessment, based on the flowchart mapping of CE indicators and the application of both assessment methods on cases.

Processes captured

The flowchart mapping highlighted that no indicator accounts for the whole product system (Paper I). Indicators cover different CE strategies and life cycles as already pointed out in previous reviews (Corona et al., 2019; Helander et al., 2019; Moraga et al., 2019). However, the flowchart mapping adds by specifically showing differences in the flows and processes covered for indicators focusing on the same CE strategies (see supplementary information of Paper I). For instance, the flowchart tool is useful for identifying if pre-consumer recycling is included or not in indicators focusing on recycling.

The analysis of what CE strategies are in focus in the methodology and how they are calculated revealed that that most of them (21 out of 36) focus only on one CE strategy (see Table 2 in Paper I).

These are hereafter referred to as *single-focus indicators*. The CE strategies in focus are mostly related to the product end-of-life with 11 indicators focusing on recycling and one on energy recovery. The next most important strategies in focus are strategies related to the production phase with the reduction of losses in production (four indicators) and changing material composition (three indicators). Finally, only two indicators focus on use-related strategies and especially use extension by using more of the technical lifetime (including reuse) and by remanufacturing. The mapping of the flows and processes captured by single-focus indicators showed a limited coverage of the product system, with often only one or two life cycle phases included in the assessment.

The indicators focusing on more than one CE strategy were labelled *multi-focus indicators*. Compared to single-focus indicators, they account for more processes and flows in the product system as well as more life cycle phases, thus being more comprehensive. However, a single indicator cannot cover all flows and processes that were mapped in the generic flowchart.

The extended flowchart developed in Paper I showed processes for CE strategies that are not accounted for by any indicator. Two processes were identified as not accounted for by any indicator: maintenance and repurposing (Figure 5) which are both use extension strategies.

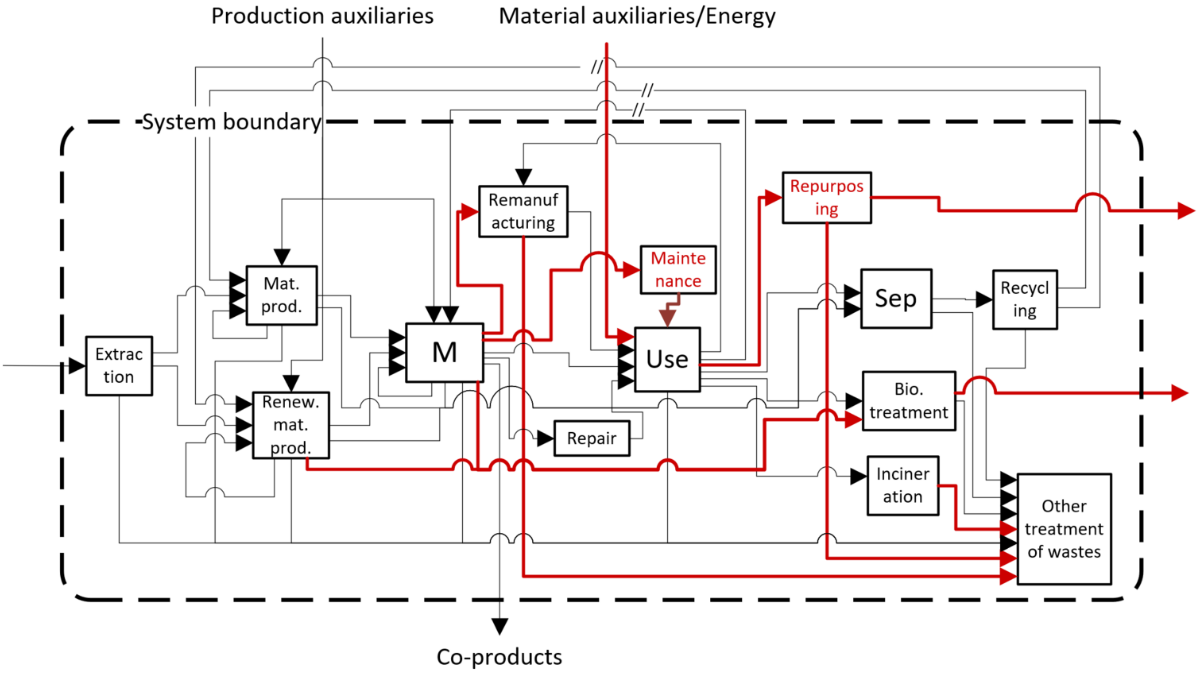


Figure 5. Extended flowchart from the review of CE indicators (Paper I) illustrating flows along the product system that are captured by CE indicators (black) and flows currently not captured (red). Abbreviations: Mat. prod., non-renewable material production; Renew. mat. prod., renewable material production; M, component production and product assembly; Sep, pre-treatment and separation; Bio. Treatment, biological treatment.

Additionally, the application of CE indicators and LCA to the case of the reused laptop showed that studying product systems with multiple use cycles was not possible with all CE indicators (Paper I). The reused laptops go through two use cycles: 1) the production and initial use of the product and 2) the preparation for reuse and second use of the product. For seven out of the 31 tested CE indicators, only the second cycle was accounted for. It left out from the assessment the flow of laptops not suited for reuse and the original production phase which are important aspects for the product's resource performance.

For LCA, the processes included in the assessment is decided by the practitioner in the steps of the scope definition and the inventory. This is influenced more by how the assessment method is used than by choosing LCA as an assessment method.

Type of flows included

The analysis of indicators showed that most indicators (28 indicators out of 36) focus on material flows. Some indicators also include energy flows (Table 2 in Paper I). The energy flows are related to energy use in production processes and for end-of-life treatments.

In an LCA, material and energy flows are inventoried for most processes, as well as emissions and land use. These additional types of flows are necessary in the estimation of environmental impacts. For instance, a higher bio-based material content in incontinence products resulted in a higher land use, an effect that cannot be identified by the resource-based CE indicators (Paper I).

5.2.2 Modelling of the product

The modelling specifications related to the product include product properties such as its material composition, function and energy efficiency, and aspects related to how the product is used such as the duration of the product's initial use and the use of resources in the use phase.

The variations in the **material composition of the product** are included in both assessment methods but with different approaches. The CE indicators which focus on changes in the material composition address either the recycled content or the content from renewable sources (Paper I). They focus on rewarding a greater use of secondary or renewable materials but do not distinguish further the product composition. In an LCA, the bill of material of the product, or at least the main materials, can be used in the modelling of the product system and changes in the product content influence the results. This influence may be analysed with a contribution analysis of the different materials in the product. For instance, a contribution analysis of the cradle-to-gate impact of two designs of HV motors showed that the reason for a lower global warming and higher resource depletion for the more energy-efficient design is a lower steel content and higher copper content compared to the less energy-efficient design (Paper II). Thus, a distinction between the different metals in HV motors is reflected in the LCA results.

For EuP, the **use of resources in the use phase**, including the use of both material and energy, might play a significant role in the product's performance. For instance, the environmental impact for the 3D-printed engine (Paper I) is dominated by fuel consumption during use for fossil resource depletion impact (Böckin & Tillman, 2019), and, for HV motors, the impact of energy losses during use is dominant for all impact categories (Paper II). The quantity of resources used is influenced by the energy efficiency and the use pattern of products. For instance, the more efficient HV motor design results in lower energy losses during use, which results in lower environmental impact than the less efficient one for all impact categories. However, the flow of energy and material during use is not captured by any CE indicators. This limitation is highlighted in the extended flowchart (Figure 5) and by the results of CE indicators on the 3D-printed engine. 3D-printing allows a production of lighter engines, which reduces the fuel consumption during use, but none of the indicators includes this variation in resource use.

The share of the use phase in the life cycle of EuP is influenced by the **duration of its initial use**. For the study of HV motors (Paper II), the possibility of early failure or early retirement has not been considered. But in studies on the early replacement of EuP, the choice to repair instead of replacing with a new product is affected by the initial use duration (Bovea et al., 2020). In LCA, the use duration can be an input parameter for quantifying the use of resources in the use phase and might also be included in the functional unit. Six CE indicators account for the product lifetime (see Table 2 in Paper I). One of these indicators is expressed as the time a material resource is maintained in a product system and therefore uses the initial product lifetime as a central element in the indicator calculation.

The other five indicators accounting for the product lifetime also include the **product function**. Product lifetime is then used in the assessment of the product function (e.g., one year of motor use to provide 16 MW over 50 weeks full time for the HV motors in Paper II). The latter is used either as a benchmark of the product to an industry average for four indicators, or as a basis for comparison between the alternatives studied for one indicator. As described in section 5.1, the choice of the product function as basis for comparison allows absolute mass variations for the delivery of the same function to be identified. In LCA, the functional unit, and thus the product function, is a foundational feature as basis for comparison.

Finally, in the case of use extension of EuP, the **difference in energy efficiency between the product in use and the new product for replacement** has also been identified as an important parameter for the outcome of the assessment (Table 1). This difference might be explained by the speed of energy efficiency improvement for the studied technology (Baxter, 2019; Devoldere et al., 2009), the choice of the performance of the new product considered for replacement (Ardente & Mathieux, 2014; Iraldo et al., 2017), and the deterioration of the performance of the product with use (Kiatkittipong et al., 2008). The difference in energy efficiency can be accounted for in LCA modelling with the quantification of resource flows during the use phase. For instance, for HV motors, there has been no significant improvement of the energy efficiency of HV motors for the last 20 years and currently no technological breakthrough is expected to happen in the next 15-20 years. Thus, no improvement of energy efficiency over time was studied. Besides, no significant evolution of energy efficiency due to wear has been reported. Therefore, the motor after repair causes the same energy losses as the motor without repair. In contrast, the average electricity consumption for refrigerators decreased by 60% between 1980 and 2012, but the speed of efficiency improvement has lately been decreasing (Bakker et al., 2014). As a consequence, extending their use compared to the replacement with a new one is not necessarily beneficial after a certain use duration, and this use duration increased from 8 years for refrigerators bought in 1980 to 20 years for those bought in 2011 (Bakker et al., 2014). CE indicators do not account for the difference in energy efficiency between products as flows of energy and materials in use are not accounted for.

5.2.3 Modelling of use extension strategy

In previous assessments of use extension of EuP, the **use of resources in maintenance, preparation for reuse, repair or remanufacturing process** compared to the resources involved in the life cycle of the product has been identified as affecting the outcome. The impact of the use extension process is linked to the amount of energy and the extent of component replacement required. With CE indicators, two single-focus indicators and five multi-focus indicators have use extension strategies in focus (Table 2 in Paper I). They account for flows of products or materials collected for use extension or going back into use. The material flow from new components or materials required in repair is accounted for by one indicator. But no indicator accounts for the flows of new components or materials required for maintenance (Figure 5) and the energy use during those processes. With LCA, the impact of use extension processes can be accounted for. For the case of HV motors (Paper II), the production of the new copper windings to be changed as well as the end-of-life treatment of the old windings are accounted for. And as the repair results in lower environmental impact than the production of a new motor, some scenarios of repaired HV motors with sufficient additional use result in lower impact than motors without repair.

The potential benefit of use extension depends on the **additional use duration** provided, as shown in the LCA results for the HV motors (Paper II). For the motors' environmental performance per year of use, several years of additional use are necessary for the repair to be beneficial. The repair process requires less material than motor production but several years of use are still required to pay-off the resource investment needed for restoring the motor. Like the initial use duration, the additional use duration can be accounted for in LCA modelling, and six CE indicators include it in their calculation. For the latter, the additional use duration of the product is combined with the initial use duration as the total lifetime of the product, except for the indicator expressed as the time a material resource is maintained in a product system.

Finally, the **quality of the repair or remanufacturing** in terms of deteriorated energy efficiency might also influence the benefits of repair. For HV motors, a small efficiency reduction leads to the repair to worsen the environmental impacts of HV motors (Paper II) because the impact from the additional losses during the additional use offsets the benefits from repair. Like the difference in energy efficiency between product in use and new product for replacement, LCA can account for the effects of the quality of repair or remanufacturing by including the material and energy flows involved in the use phase in the assessment, and CE indicators do not.

5.2.4 Modelling of the background system

The **differentiation energy source** influences the impact of products, and especially products with a high energy consumption or with an energy intensive production. When accounting for energy flows, CE indicators do not allow a differentiation of the energy source except for one indicator which distinguishes between energy from renewable and non-renewable sources (Table 2 in Paper I). This distinction influences the results for one indicator for which the use of renewable energy is rewarded. In LCA, the effects of the differentiation of energy source can be identified. For instance, three different electricity mixes during use have studied for the HV motors (Paper II): an average Swedish electricity mix with a high share of nuclear and renewable energy, hydroelectricity only and oil-based production. Less greenhouse gas is emitted during hydroelectricity production than with the average Swedish electricity production and the fossil-based production and it is reflected in the motors' environmental impact for global warming which decreases with a cleaner electricity mix.

Additionally, **resources for electricity production and transmission**, both materials and energy, have been found to influence the impact of energy intensive products. For HV motors (Paper II), the energy losses in the use phase dominate resource depletion impact for any tested electricity mix. It is due to uranium and coal from nuclear and fossil electricity production as well as copper and other co-mined minerals from transmission network. Their contribution is even more important than minerals in the motors. In LCA, the background system can be included in the modelling, but so far little attention has been paid to resources in electricity production and transmission in LCAs. For instance, the same quantity of transmission line production is allocated to electricity markets for all countries in the datasets available in ecoinvent (Itten et al., 2014), a database for LCA inventory data frequently used in LCA studies, and no study challenging this allocation factor with, e.g., a sensitivity analysis, has been found in the literature. In CE indicators, no consideration for the background system is given. The resource flows accounted for are inputs of materials or energy and outputs of waste that are related to processes that are related to the product under study such as manufacturing, use or recycling. Materials or energy used in the production and transmission of electricity are thus not accounted for by CE indicators. In sum, attention to resources for electricity production and transmission is lacking in both LCA and indicators, with the difference that they are not considered in indicators whereas data are too general in LCAs.

5.3 Summary of the comparison

The elements of comparison and the results from the comparison of LCA and product-level CE indicators are synthetised in Table 2.

Table 2. Comparison of CE indicators and LCA for assessing the effects of CE strategies on resource use and environmental impact.

			CE indicators	LCA
Type of assessment results	Type of impacts	Resource use	Yes (variations in material and sometimes energy flows)	Yes (variations of material and energy flows from the life cycle inventory analysis)
		Environmental impact including resource depletion impact	-	Yes
	Basis for comparison	Per functional unit	With one indicator	Yes
		Per product	With all except one indicator	-
Modelling specification	System modelled	Processes captured: ● In a product system	● Selection of processes fixed by the choice of indicators (multi-focus indicators more comprehensive than single-focus indicators) Not captured by any indicator: repurposing, maintenance	●All processes selected with the system boundary definition, which is fixed by the practitioner
		● Possibility to study multiple use cycles	● Yes with 29 indicators out of 36	● Yes
		Type of flows captured	Materials, and energy for some indicators	Materials, energy, emissions, land use
	Modelling of the product	Material composition of the product	Distinction of recycled content and renewable content	Distinction of several materials in the product
		Use of resources in the use phase	-	Yes, energy and material use
		Duration of initial use	Yes with 6 indicators out of 36	Yes

		Function of the product	Yes with 5 indicators out of 36	Yes
		Difference in energy efficiency between product in use and new product for replacement	-	Yes
	Modelling of use extension strategy	Use of resources in maintenance/repair/ remanufacturing/ preparation for reuse	Yes for material use in repair with one indicator out of 36	Yes
		Duration of additional use	Yes with 6 indicators out of 36	Yes
		Quality of repair/ remanufacturing	-	Yes
	Modelling of the background system	Differentiation of energy sources	No. For one indicator, distinction between renewable/non-renewable energy	Yes
		Resources for electricity production and transmission	-	Yes, but no regional variability available in available datasets

6 Analysis

6.1 Differences between LCA and CE indicators

6.1.1 Knowledge on resource use and environmental impacts

The two studied assessment methods provide results on different types of impacts with indicators capturing changes in resource use, and LCA providing environmental impacts thereof, including resource depletion impacts. With the latter, trade-offs between different environmental impact categories can be identified. For instance, a trade-off between global warming, due to a lower use of fuel from the lower weight of the engine, and ionising radiation, due to high use of electricity from nuclear sources for the 3D-printing process, was possible to detect in the case of the 3D-printed engine (Paper I). This is partly due to the ability of LCA to account for a differentiation of energy sources and their related emissions.

Moreover, the difference in the type of impact is explained by the ability to differentiate resources in resource flows with LCA. The calculation of CE indicators seldom requires a differentiation of the type of resources. Several indicators allow a differentiation between renewable and non-renewable materials (see Table 2 in Paper I), implying that an increasing use of renewable materials is positive. Otherwise, no distinction in terms of, e.g., toxicity or availability is made. In LCA, the different resources in each flow are differentiated and characterised based on their potential impact on various environmental impact categories. For instance, a higher bio-based material content in incontinence products results in a higher land use, and this effect is not identified by any CE indicators. This characterisation is an essential step for LCA to calculate the environmental impacts related to the variations of resource flows. Therefore, an assessment based on only CE indicators cannot substitute an environmental assessment with LCA.

6.1.2 Comprehensiveness and data intensity

To not miss any important consequences or burden shifting along the life cycle, an assessment framework needs to cover sufficiently the product system and the implemented CE strategies. The comparison of the system modelled in the two studied assessment methods (section 5.2.1) shows that CE indicators can account for less processes and types of flows than LCA. Among CE indicators, multi-focus indicators are more comprehensive than single-focus indicators. There is less risk of missing important resource flow changes when using one of the multi-focus indicators. To cover a sufficient range of life cycle phases and flows with single-focus indicators, a set of complementary indicators could be selected with the help of the developed flowchart tool in Paper I.

Moreover, a comprehensive understanding of consequences from CE strategies requires the system boundaries of the assessment to include all use-cycles. Seven of the 31 tested CE indicators focus on the scope of one use-cycle only and this leaves out of the assessment important parameters for the product’s resource performance. For instance, for the case of the reused laptop in Paper I, such important parameters are the success rate of the reuse process or possible changes in the design to facilitate reuse. The inclusion of several use-cycles is possible with LCA. But methodological challenges have to be faced when the function of the product does not remain the same over the several uses, for example in the case of repurposing. The handling of multi-functionality challenges the choice of functional unit and allocation methods for which no unified method exists yet (Schulz et al., 2020).

A disadvantage of comprehensiveness is the requirement of a more extensive data collection. For instance, a limitation of LCA is its data intensity (Elia et al., 2017) as it requires the inventory of material, energy, emission, and waste flows required for processes in the product system. In comparison, the studied indicators are more time-efficient to assess, and, among CE indicators, multi-focus indicators require more extensive data than single-focus indicators. Therefore, the choice of an assessment method faces the inherent tension between comprehensiveness and extensive data collection but should ensure that the product system is still sufficiently covered for the intended use of the method.

6.1.3 Detailed understanding of a system and easy conclusion from the assessment

Real cases of CE application often involve the combination of CE strategies (Blomsma & Brennan, 2017), e.g., use extension and recycling in the same product system. Thus, one aggregated value, such as the result from multi-focus indicators, might be difficult to interpret. The testing of CE indicators highlighted the difficulty to understand changes in the product system when expected benefits from CE strategies are offset by other consequences (Paper I). For instance, for the case of the 3D-printing engine, it was not possible to identify the prevailing variations that leads to results from some multi-focus indicators. Results from single-focus indicators were easier to interpret as they focus on only one aspect. These indicators showed that 3D-printing is more energy intensive but generates less scrap than the conventional engine production, and that materials used in the printing have lower recovery rates and lower recycled content than traditional materials in engines. Thus, using several single-focus indicators provides a more detailed understanding of the product system and of the potential trade-offs.

However, a more straightforward conclusion based on the comparison of alternatives is possible with multi-focus indicators as a broader range of aspects is summarised into one value. This observation is similar to the choice of studying a set of midpoint impact categories and endpoint impact categories. The latter combines several midpoint impact categories into one value and provides a clear conclusion but trade-offs between impact categories are more difficult to identify than with an assessment of midpoint environmental impact categories.

Nevertheless, further analysis of the cradle-to-grave LCA results needs to be performed to identify detailed variations in the product system with, e.g., contribution analysis of different processes or elementary flows. And variations of some aspects are still difficult to identify. The comparison between LCA and CE indicators showed for instance that process efficiencies for production and recycling are more clearly emphasized by CE indicators. This suggests that some CE indicators might be relevant to use to support the interpretation of LCA results.

6.2 Important elements of comparison for use extension of EuP

Among the modelling specifications studied in the comparison of LCA and CE indicators, several are especially relevant for the implementation of use extension:

- the use of resources in the process to extend the use,
- the duration of initial use,
- the duration of additional use.

Previous studies showed that use extension processes with a high impact compared to the initial production, or a short additional use compared to the initial lifetime do not necessarily lead to an improvement of the product environmental performance (Bovea et al., 2020). Additionally, a short initial use duration may increase the benefit of extending the use (Baxter, 2019).

CE indicators are more limited than LCA to account for all these aspects (Table 2). Several indicators consider use duration, and one indicator accounts for the use of resources in the use extension process. Two processes related to use extension, i.e., repurposing and maintenance, are not accounted for by any indicator. Repurposing has been identified as promising for reducing resource use (Shirvanimoghaddam et al., 2020) and maintenance might be particularly relevant for durable products which require considerable component replacement to reach their expected lifetime (Kaddoura et al., 2019). Therefore, it might be important to account for these strategies with other indicators or assessment methods.

For the assessment of cases for EuP, additional modelling specifications were identified to be specifically relevant:

- the use of resources in the use phase,
- the differentiation of energy sources,
- the resources for electricity production and transmission.

The use of material and energy in the use phase is responsible for most of the impact of some EuP, such as the use of fuel during the use of the 3D-printed engine (Paper I). Due to this dominance, variation of energy and material use during the use phase has a role in determining the potential benefits of CE strategies for those products. The reduction of material quantity for the 3D-printed engine thanks to 3D-printing leads to fuel consumption reduction which is significant enough to counterbalance the higher global warming impact from the novel production process (Böckin & Tillman, 2019). For energy intensive EuP, the impact of the use phase is dominant due to high energy requirement, high operating time and long lifetime. In the case of HV motors, energy losses in use are dominant in the environmental impacts of motors, even for resource depletion impacts (Paper II). As a result, the use extension by repair for HV motors leads to very little benefit from the avoided production of a new motor since production does not represent a high share of the environmental impact compared to the use phase. Moreover, energy efficiency is a key parameter in the environmental performance of HV motors. The more efficient design resulted in a lower impact than the less efficient design for all impact categories due to the lower losses during use. It showed that accounting for resource flows in the use phase are especially important.

Also due to the dominance of the use of energy in the use phase for some EuP, the energy source influences their resource use and environmental performance. For instance, hydroelectricity during the use of HV motors decreases their impact by 99% for global warming and by 93% for resource depletion compared to the use of oil-based electricity production (Paper II). Additionally, materials and energy that are involved in the energy production and transmission in the use phase appears to matter significantly for the resource depletion impact of EuP with intensive use. For HV motors (Paper II), the energy losses in the use phase are dominant for resource depletion. It is due to uranium and coal from nuclear and fossil electricity production as well as copper and other co-mined minerals from transmission network construction. Their contribution is more important than minerals in the motors. This highlights that background system modelling matters for the results of energy intensive EuP.

The comparison of the two assessment methods showed that the reviewed CE indicators do not include those aspects. They are thus especially limited for identifying important variations in the resource use and environmental impact of EuP, and especially energy intensive EuP.

For use extension of EuP specifically, two additional modelling specifications were identified as important:

- the difference in energy efficiency between product in use and new product for replacement,
- and the quality of repair or remanufacturing.

They are related to the resource use during the use phase of EuP. Previous studies for EuP with a significant technological evolution for energy efficiency or with a discrepancy between the average energy efficiency of the products in use and the most efficient product on the market showed that extending the use of a product with low energy efficiency might not be preferable compared to its replacement with a more efficient one (Ardente & Mathieux, 2014; Bovea et al., 2020).

The quality of repair or remanufacturing has been identified as a key parameter for energy intensive EuP (Paper II). Due to the dominance of the use phase due to the high energy requirement and high operating time, a small efficiency reduction after repair results in higher impact for repaired motors than motors without use extension. It is explained by the higher losses from the additional use which offset the benefits from repair. The eventual decrease of efficiency during repair is therefore important to be accounted for in assessments of use extension of energy intensive EuP.

LCA accounts for these two aspects but CE indicators do not (Table 2). Besides the limitations stated above for use extension and for EuP, the studied CE indicators appear to be more limited than LCA to account for important effects of use extension on EuP.

6.3 Recommendations on the selection and the use of assessment methods

From the comparison of CE indicators and LCA, several recommendations for practitioners to select and to use these methods for assessing the effects of CE strategies on resource use and environmental impacts can be drawn.

First, the choice of the method depends on the type of results sought. Resource-based CE indicators and LCA provide different types of results. The former focuses on variations in resource use and thus how efficiently resources are used in a product system. The results are expressed for one product for all indicators except one, and thus inform on absolute mass variations. LCA results are expressed per functional unit and provide information on the effects of the variations of resource flows on various environmental impact categories. Trade-offs between environmental impact categories can be identified. This difference of type of results is explained by a differentiation and characterisation of the different materials and energy sources in the resource flows. These steps are performed by LCA and are not by CE indicators. Therefore, the selection of a method (or methods) would come after the definition of the aim of the assessment and especially the type of impacts that is sought.

Then, an understanding of what is accounted for and left out of the assessment is important. For instance, CE indicators with the same CE strategy in focus but with different accounted flows may provide different results. It sometimes leads to contradictory conclusions such as with the two indicators focusing on use extension assessed on the case of the multiple use of incontinence products (Paper I). In this case, instead of disposable diapers, a disposable absorbing pad is combined with pants that can be washed and used several times. One indicator focusing on reuse shows a positive evolution due to the shift to reusable pants and the other indicator shows no evolution as non-commercial reuse is not part of its scope. This diversity of results stresses the importance of the choice of indicators in an assessment framework. This choice can be supported by the flowchart mapping of the flows and processes accounted for by each indicator (supplementary information of Paper I). It is important to ensure that the product system and CE strategies are comprehensively covered to avoid missing any important changes generated by applying CE strategies. These important changes differ with the product system and the CE strategies applied, so one generic indicator selection cannot be recommended. For LCA, the thinking of what is important to be accounted for would guide the practitioner in its definition of system boundaries and choices in the modelling.

Specifically for the use extension of EuP, the comparison of CE indicators and LCA showed that some important modelling specifications are not accounted for by CE indicators such as the use of resources in the use phase. Besides, some modelling specifications have received little attention in the product system modelling such as the resources for electricity production and transmission in LCA. The identification of the important modelling specifications for this type of CE strategies and this type of product was based on the application of both methods on cases. It suggests that a preliminary understanding of the product system and of the effects of CE strategies is useful to select the assessment method and to identify the modelling specifications that should be specifically accounted for.

7 Discussion and future research

The analysis of which flows and processes are accounted for by CE indicators (Paper I), and the application of CE indicators and LCA on cases (Paper I) and specifically on the repair of an energy intensive EuP (Paper II) contributed to advance the description of the studied assessment methods. This description is more practical than general classifications based on an analysis of the methodology description as done in previous indicator reviews (Corona et al., 2019; de Pascale et al., 2021; Elia et al., 2017; Saidani et al., 2019). The flowchart mapping of CE indicators in Paper I was for instance developed as a visual tool to select indicators. And the application of the methods on cases put the emphasis on the result of the assessment. The method comparison in this licentiate thesis structured the knowledge gained in the two papers for practitioners to select and use an assessment method according to their assessment goal. The focus on use extension of EuP highlighted some limitations for both CE indicators and LCA.

The research work is limited in three main aspects. First, the study of methods for assessing the effects of CE strategies is limited to two methods. Other methods such as material flow analysis (MFA) or input output analysis have also already been used for the same purpose (Corona et al., 2019; Das et al., 2022; Harris et al., 2021; Sassanelli et al., 2019). Extending the work presented here to these other methods would provide more comprehensive recommendations on the selection of methods as well as the identification of additional limitations of the two methods analysed here.

Second, the comparison is limited to the types of results and modelling specifications. Other methodological aspects might influence the selection of assessment methods such as the geographical system boundaries (Baumann & Cowell, 1999) or time modelling (e.g., snapshot view or longer periods of time, prospective/retrospective) (Baumann & Cowell, 1999; Saidani et al., 2019; Tillman et al., 1997). Furthermore, contextual aspects such as the type of decision maker (Baumann & Cowell, 1999; Tillman et al., 1997) or the purpose of the assessment (Baumann & Cowell, 1999; Saidani et al., 2019) are also key for a practitioner to decide on the methods to use. The application of CE indicators on cases has been tested in Paper I, but this testing was performed in only one context (an analysis of CE indicators). Other contexts, e.g., adapted to the needs of different practitioners in different situations have not been evaluated, limiting the possibility to provide recommendations on the suitability of the methods in different contexts. Additionally, further research is needed about how the methods can be combined with each other and with other assessment methods to provide a more comprehensive approach for assessing CE strategies as suggested by Walzberg et al. (2021).

Third, the modelling specifications included as elements for the comparison were developed based on the conclusions from Paper I and II but not as an exhaustive list of modelling aspects to consider. Thus, the comparison is limited to modelling specifications that were highlighted as important for the study of EuP. Other types of products or EuP with different characteristics may introduce other important aspects, like the study of a long-lived and energy intensive product highlighted the importance of resources for electricity production and transmission (Paper II). Additionally, the modelling in the two papers did not focus on aspects that are central to CE strategies and that might also highlight important modelling specifications.

For instance, product lifetime is central in use extension and thus circular economy: the focus is on increasing the lifetime of products and materials to slow resource use. The work presented in the two papers is limited to cases where the product is used for its full lifetime before being repaired or replaced by a new product. However, the decision to end the use of a product is taken by the user, for various reasons. For instance, it could occur after the full technical lifetime of the product (i.e., after a failure occurs or the delivered function is not sufficient for a given application), after a shorter use period due to the user preference (e.g., based on fashion trends) or the technological lifetime, i.e., technological development and/or policies making a product obsolete (Diener, 2017). The choice of use extension strategy might differ depending on the decision from the user. For instance, being discarded before the full technical lifetime or with a partial function of the product remaining are characteristics that influence the range of relevant use extension strategies (Böckin et al., 2020). Besides, the relevance of use extension has also been found to be influenced by the extent of the initial use of products. If the product fails early due to a malfunction for instance, it might be beneficial to repair it as a lot of resources have been invested in production for little use time (Hummen & Desing, 2021). Use extension also becomes beneficial after a minimum additional use provided, as shown in Paper II. Studying the effects of variations in use scenarios would then be a possible future research direction to identify the influence of users in improving the resource use and environmental performances of products. Including more accurate considerations of products' lifetime is challenging due to a lack of data (Cooper, 2008). This potential research direction would expand the understanding of cases of use extension for EuP and of the important modelling specifications for assessing those cases.

Another example of a modelling aspect not studied in detail in this work but with implications for the assessment of use extension of EuP is the modelling of products involved in more than two use cycles. Such complex cases, e.g., with the repurposing of a product or component with remaining function after additional use with repair, are still little studied. This is visible in the analysis of developed CE indicators as repurposing is not accounted for by any indicator and as 22% of the tested indicators do not allow the assessment of more than one use cycle. Moreover, only a single study looked at the repurposing of EuP (Table 1). Other studies on the repurposing of electric vehicles' batteries have been carried out (Bobba et al., 2018; Schulz-Mönninghoff et al., 2021; Wilson et al., 2021) in response to the concern for a growing stock of used batteries due to transport electrification, also showing that different use cycles might be developed for different components of a product. Modelling such system is still a challenge, e.g., in LCA, with questions related to the allocation of the impact to the different use cycles, especially when the function of the product changes or is degraded over its different uses. This research topic would have implications on the assessment of use extension with guidance on the modelling specifications that are important to be included.

8 Conclusions

This licentiate thesis aims to advance the description of methods for assessing the effects of CE strategies on resource use and environmental impact in order to provide recommendations for the selection and use of these assessment methods. In particular, it focuses on the differences between CE indicators and LCA as well as their implications when assessing the effects of use extension for EuP.

One of the main differences between CE indicators and LCA lies in the type of results provided. Indicators focus on the variations of resource use while LCA informs on the environmental impacts thereof (Paper I). This is partly explained by a differentiation of materials in resource flows in LCA depending on their contribution to various potential environmental impacts, and by accounting for emissions to air, water and land and for land use in addition to resource and energy flows.

Furthermore, LCA requires an extensive data collection. In comparison, CE indicators are more time-efficient to assess variations in resource use. Some single-focus indicators also have the advantage of providing a detailed understanding of these variations such as process efficiencies for manufacturing and recycling. The identification of those variations might be difficult in LCA results, and thus could be supported by CE indicators.

Additional differences in modelling specifications of the two methods have implications for assessing the use extension of EuP. CE indicators are more limited than LCA with regards to ensuring that important changes in the resource use are not missed. No CE indicator accounts for energy or material use during the use phase although it represents a significant share of the resource use for some EuP and especially energy intensive EuP. Neither the consideration of the energy efficiency of those products, e.g., between the product in use and a new product for replacement or the product after repair, nor a differentiation of energy sources and their related resource use in production and electricity transmission are possible. Both have been found in LCA studies to be key aspects in the environmental performance of an energy intensive EuP (Paper II). Additionally, the assessment of product systems with several use cycles, and accounting for product use duration or the impact of the use extension process (e.g., repair, remanufacturing, or preparation for reuse) require a careful selection of CE indicators as these aspects are missing in some of them (Table 2).

So, repair or replace? An important starting point is for practitioners to decide on a more specific question to be answered, including the selection of the type (or types) of impacts to be considered. This selection influences the choice between CE indicators (information on the variations of resource use) and LCA (information on environmental impacts), but also between these methods and other assessment methods that have not been studied here. Then, the specificities of the product system to be studied, including the type of product and CE strategies involved, have to be understood to develop its modelling for the assessment. For the use extension of EuP, it is recommended to account for specific modelling aspects that are related to the product (e.g., duration of use, difference of energy efficiency between product in use and new product), to the use extension strategy (e.g., impact of repair, duration of additional lifetime and quality of repair), and to the background system (e.g., differentiation of energy sources, resources involved in electricity production and distribution) as they might be decisive for the use extension to be beneficial. Other contextual aspects such as the time and data available for the assessment or the type of practitioners would also influence the choice of the assessment method and the modelling of the system to be studied. Thus, further research on the practical situations in which these assessment methods are used is needed to understand when and how the guidance from CE indicators and LCA would be appropriate for different types of practitioners.

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