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METHODS ARTICLE

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Circular life cycle sustainability assessment

An integrated framework

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Abstract

Robust monitoring and assessment methods are required to assess circular economy (CE) concepts in terms of their degree of circularity and their contribution to sustainability. This research aimed to develop an integrated framework for the CE context—considering both the technical circularity and the complexity of the three dimensions of sustainability (environment, economy, and social). Two existing methods were identified as an appropriate foundation: CE indicators and life cycle sustainability assessment (LCSA), combining life cycle assessment (LCA), life cycle costing (LCC), and social life cycle assessment (S-LCA). The developed circular life cycle sustainability assessment (C-LCSA) framework added circularity assessment (CA) as an additional dimension to LCSA (C-LCSA = LCA + LCC + S-LCA + CA). The abundance of CE indicators required a systematic selection process to identify the most appropriate indicators for the framework which was built on criteria levels, performance, loops, unit, dimension, and transversality. The material circularity indicator, product circularity indicator, and longevity indicator were identified as most suited for C-LCSA. Being developed for a single life cycle, the traditional life cycle approaches needed refinements for application to CE concepts, derived from discussions and proposed adaptions presented in the academic literature. The cut-off approach was identified as the most suitable end-of-life allocation method for C-LCSA, being in line with the technical system boundaries. C-LCSA can be used by LCA practitioners to identify trade-offs between an improved circularity and resulting impacts on the environmental, economic, and social pillars to provide a basis for decision making in industrial ecology.

KEYWORDS
circular economy, circularity assessment, framework, industrial ecology, life cycle sustainability assessment, sustainability

1 | INTRODUCTION

Severe resource depletion is one of the biggest challenges in today's society and industry. Circular economy (CE) emerged as an umbrella concept to counteract this trend by keeping resources in the loop as long as possible with an adapted design or by turning formerly associated wastes into valuable resources (Ellen MacArthur Foundation, 2013; Sassanelli et al., 2019). Steps toward a CE have been integrated in various policies around the world, including the Circular Economy Action Plan from the European Commission (2015, 2020), the *Recycling and Waste Reduction Act 2020* in Australia (Australian Government, No. 119, 2020), and the Sustainable Development Goals (SDG 12: Responsible consumption and production) from the United Nations (2015). To close and narrow material and energy loops, different CE strategies need to be implemented. Beginning with the letter "R," they are often referred to as R-principles that can be ranked in a hierarchy. Hereby, several authors referred to a different number of R-principles. An extensive list is given by Reike et al. (2018) who proposed to rank 10 Rs as follows: *refuse*, *reduce*, *resell/reuse*, *repair*, *refurbish*, *remanufacture*, *repurpose/rethink*, *recycle*, *recover*, and *remine*. CE concepts apply one or more of these R-principles. An early consideration of different R-principles in the design phase is important, as, for example, a design for recycling enhances the later recycling itself (Gehin et al., 2008). Focusing on a single R-principle can be detrimental to another. Thus, not all CE concepts are automatically more sustainable than linear ones, as trade-offs may occur (Anastasiades et al., 2020; García-Muiña et al., 2021; Geissdoerfer et al., 2017). Linking technical CE, referring to the implementation of R-principles and their contribution to CE (e.g., recycling/reuse rate or longevity), and environmental, economic, and social sustainability, thus is crucial for monitoring CE concepts to minimize burden shifting (Leipold et al., 2023; Peña et al., 2021). Leipold et al. (2023) emphasized the need for interdisciplinary links for holistic CE thinking and encouraged researchers to build on existing methods developed by sustainability scientists. Peña et al. (2021) encouraged researchers to link CE and life cycle approaches in the position paper of the Life Cycle Initiative. Moreover, the relevance of assessing circularity performance is given by the current development of ISO 59020 (ISO, 2023).

This research aimed to integrate technical circularity into life cycle sustainability assessment (LCSA) by developing a circular life cycle sustainability assessment (C-LCSA) framework. Therefore, circularity assessment (CA) was added as an additional dimension alongside life cycle assessment (LCA), life cycle costing (LCC), and social life cycle assessment (S-LCA) to the traditional LCSA framework.

CE indicators have the potential to transfer complex information into comparable numbers (Kristensen & Mosgaard, 2020; Saidani et al., 2019). However, the research on CE indicators is still in its infancies and has just intensified in recent years. The currently existing CE indicators are to some extend overlapping but many of them differ in their goals, scopes, and potential applications (Corona et al., 2019; Janik & Ryszko, 2019; Saidani et al., 2019). As the immature state of development, diversity, and oversupply of CE indicators make the assessment of CE concepts complex, an adequate indicator selection process is required as conducted in Section 2.2 (Pauliuk, 2018; Saidani et al., 2019).

LCSA was selected as the basis of the framework as it considers all sustainability dimensions by combining and applying in parallel LCA, LCC, and S-LCA to the same functional unit (FU) and equivalent system boundary (Finkbeiner et al., 2010; Kloepffer, 2008). LCSA was identified as relevant approach in the CE context by several authors and also the recent ISO 59020 draft (ISO, 2023) claims LCSA to be particularly valuable as a complementary assessment for CE (Larsen et al., 2022; Niero & Hauschild, 2017; Niero & Rivera, 2018; Pagotto et al., 2021; Stillitano et al., 2021). LCA is the most applied approach to assess the environmental performance of CE concepts while LCC and S-LCA studies currently are less commonly addressed (Kirchherr et al., 2017; Sassanelli et al., 2019). The traditional life cycle approaches were developed for a single life cycle. Challenges for the traditional LCSA approach in the CE context, for example, are end-of-life (EoL) allocations in LCA (needed for an assessment of multiple loops) or to consider finite and variable loops and their dependence on time related to less valued future financial flows (Civancik-Uslu et al., 2019; Corona et al., 2019; Schaubroeck et al., 2021). Hence, refinements of the traditional approaches for the application in parallel to CA were derived from literature, paying attention to avoid double counting (Sections 2.3–2.5). The C-LCSA framework developed in this paper can be described by adapting the traditional LCSA formula as follows: C-LCSA = LCA + LCC + S-LCA + CA.

C-LCSA is intended to be used by LC(S)A experts and will serve as a reference for future studies to achieve consensus in assessing CE concepts and ensure they are comparable. This will enhance the research on CE assessment. The framework will help LCSA assessors to consider the broad implications of their decisions and to identify improvement options as the framework allows the identification of trade-offs between an enhanced circularity and resulting impacts on sustainability performance.

2 | METHODS: FRAMEWORK DEVELOPMENT

The development steps of the framework are shown in Figure 1 and are further described in the following sections.

2.1 | Framework structure and coverage

The C-LCSA framework aims to integrate technical circularity into LCSA to provide a basis for a holistic assessment of products and services. Therefore, the traditional LCSA was enhanced and extended by a CA. C-LCSA follows the structure of LCSA including the four phases: goal and scope, inventory, impact assessment, and interpretation (UNEP, 2011). The framework aims to be used by LCSA experts, researchers, and industry practitioners. It is generally applicable across sectors for assessing products and services (micro level of CE). Applying C-LCSA is especially beneficial for assessments during the development of CE concepts as hotspots and trade-offs can be identified. At this early stage the design, material selection, and manufacturing process of a new product can be easily improved than at a later large-scale production.

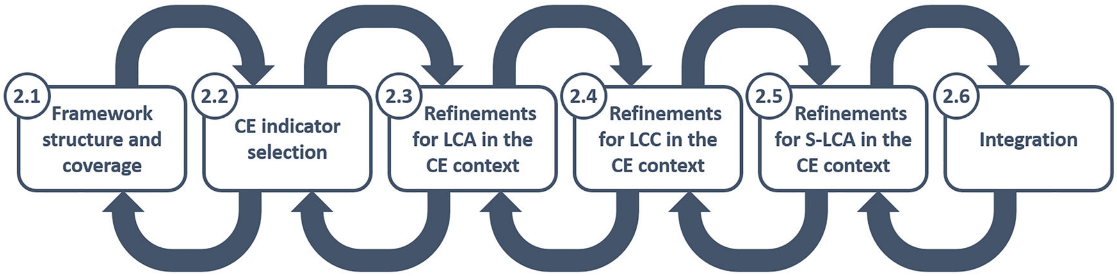

FIGURE 1 Development steps of the life cycle sustainability assessment framework. Due to interlinkages between the different assessment approaches, an iterative development process was required to consider interdependencies and to avoid double counting. The numbering follows the structure of the subsections.

2.2 | Circular economy indicator selection

The CE indicator selection process was built on previous studies that have identified CE indicators. Studies were sourced from Scopus using keywords such as "circular economy indicator" with variations (CE, circularity, and metric) and "review." The focus was on general CE indicators that included circularity aspects (e.g., recycling rate) but excluded indicators only focusing on sustainability impacts of CE (e.g., global warming potential or operational costs) and on specific sectors. Through snowballing, further reviews and studies were added. In total, 133 CE indicators and CE indicator sets were extracted from previous reviews (Corona et al., 2019; de Oliveira et al., 2021; de Pascale et al., 2021; Geng et al., 2012; Kristensen & Mosgaard, 2020; Moraga et al., 2019; Pauliuk, 2018; Saidani et al., 2019) and two recent studies (Bracquené et al., 2020; Brändström & Eriksson, 2022). The use of the term "indicator" varies between different authors. "Indicator" could not only refer to a single number resulting from a formula, but also to sets of single indicators (e.g., recycled content and reuse rate). The classification as indicator was adopted from the studies referred to above.

Not all of the identified CE indicators were suitable for the C-LCSA framework because of their foci and aims. Thus, a systematic indicator selection was conducted based on 6 out of 10 categories (levels, performance, loops, unit, dimension, and transversality) to classify CE indicators that were proposed by Saidani et al. (2019). The remaining criteria (perspective, usage, format, and sources) were not considered relevant for the CE indicator selection for the framework.

2.2.1 | Levels (micro, meso, macro)

CE can be linked to different levels which are the macro (cities, regions, and nations), meso (eco-industrial parks), and micro level (products, companies, and consumers) (Fang et al., 2007; Kirchherr et al., 2017; Saidani et al., 2019). As the CE assessment should take place in parallel to LCSA which commonly operates on the micro level, only CE indicators addressing the micro level were considered. This left 78 CE indicators to be further analyzed. Another two CE indicators were excluded as neither the original source nor a description of them could be found.

2.2.2 | Performance (intrinsic, impacts)

This criterion refers to whether a CE indicator measures the intrinsic circularity (such as, e.g., recirculation rate) or the sustainability of CE concepts (Saidani et al., 2019). As LCSA addresses the sustainability of CE concepts, CE indicators used in the framework must only address the technical and, consequently, the intrinsic performance to avoid double counting of potential impacts. Forty-one CE indicators were discarded in this step.

2.2.3 | Loops (R-principles)

Most of the numerous R-principles formulated in recent years can be linked to the four R-principles defined by the EU, which are reduce, reuse, recycle, and recover (Anastasiades et al., 2020; Reike et al., 2018). To ensure the inclusion of different CE strategies and to emphasize that CE goes beyond recycling by considering higher ranked R-principles, at least three of these R-principles must be addressed by the CE indicators to be included—in line with CE as an umbrella concept and avoiding the overweighting of single CE strategies. Twenty-six CE indicators did not meet this criterion.

2.2.4 | Units (quantitative, qualitative)

Units indicate the measurability and comparability of indicators. Indicators can be qualitative or quantitative and include, for example, mass, time, or intensity (Saidani et al., 2019). The CE indicators to be integrated into the framework must be calculated with real measurements/numbers as input data and result in a quantitative output to allow, as far as possible, an objective comparison to other CE concepts. Three CE indicators relied on subjective scoring or needed to be calculated in a tool and were removed.

2.2.5 | Dimension (single, multiple)

CE indicators can be calculated with a single formula only or have a higher dimensionality by combining a number of formulas. For the framework, a certain degree of transparency was required, which is mainly provided by a higher dimensionality. CE indicators were considered if transparent and if the individual components and their weighting were traceable. Two CE indicators were discarded.

2.2.6 | Transversality (generic, sector specific)

Transversality indicates whether a CE indicator applies to all sectors (generic) or only to a specific one (Saidani et al., 2019). As the framework, in this case, should be generally applicable, general CE indicators will be selected. A building-specific indicator was excluded in this step.

2.2.7 | Final selection

Four CE indicators (material circularity indicator [MCI], material efficiency metric [MEM], product circularity indicator [PCI], and longevity indicator [LI]) remained after the systematic analysis. Table 1 shows the stepwise CE indicator selection process, referring to the fulfillment of the above introduced criteria. The MCI was developed by Ellen MacArthur Foundation (EMF) and Granta Design (2015/2019). It assesses the flow of materials and how long and intensely a product is used in comparison to similar products. EMF and Granta Design (2015) highlighted the necessity to consider MCI together with a circular LCA, emphasizing the validity of using MCI for C-LCSA. Moreover, several studies have already combined LCA and MCI (Glogic et al., 2021; Lindgreen et al., 2021; Lonca et al., 2018, 2020; Niero & Kalbar, 2019; Rufí-Salís et al., 2021). MCI provides the circularity in the form of a score from 0 to 1 and is one of the most robust CE indicators (Stillitano et al., 2021). Bracquené et al. (2020) developed the product circularity indicator (PCI) for complex product supply chains by enhancing the MCI. It differs from the MCI, for example, considering material losses during feedstock and component production leading to higher benefits from reuse compared to recycling and is more complex in its application by adding variables and formulas to MCI. The MEM was developed by Brändström and Eriksson (2022) and focuses on material inputs and outputs, giving the results in kilogram. Without the comparison to another product, a result interpretation is not easily possible. Thus, MEM was not considered for the framework. The longevity indicator (LI), also known as resource duration indicator, was developed by Franklin-Johnson et al. (2016) and considers the initial lifetime, the lifetime contribution through refurbishment and reuse, and the lifetime contribution through recycling.

The authors considered the MCI as minimum requirement for C-LCSA as its application is straightforward and it already is widely applied in academia. Moreover, it considers the resource inflow and outflow indicators given as minimum requirement of CA in the ISO 59020 draft (ISO, 2023). For sensitivity analysis, the more complex and time intense PCI as well as LI might be considered. The extended CE indicator list including all levels of CE can be found in Supporting information S1.

2.3 | Life cycle assessment in the circular economy context

LCA was developed for a single cradle-to-grave life cycle (ISO 14040, 2006a). The shift to a cradle-to-cradle perspective with multiple loops requires a closer look at the methodology. No consensus is yet given in defining and selecting both FU and the system boundaries in the CE context (Xing et al., 2022). Another recent point of discussion is allocation methods for environmental burdens in multiple loops (Corona et al., 2019). The authors are aware that these methodological LCA discussions cannot be fully solved in this paper. However, the authors derived and justified the most suitable LCA specifications for applying the C-LCSA framework. The focus was on the FU, the system boundaries, and EoL allocations.

TABLE 1 Stepwise selection of relevant circular economy indicators at micro level according to the criteria proposed by Saidani et al. (2019). D, dimension; L, loops; P, performance; T, transversality; U, units. Indicators that do not meet the selection criteria are indicated with "–" and those meeting the criteria with "X."

Indicator	Acronym	Authors	P	L	U	D	T
Closed loop calculator	CLC	(Kingfisher, 2014)	Not accessible				
PRP Circular e-procurement tool and ReNtry®-module	PRP	(Rendemint, 2016)	Not accessible/language				
Assessment of CE strategies at the product level	APL	(Niero & Kalbar 2019)	–				
C2C indicators (incl. MRS)	C2C	(Cradle to Cradle Products Innovation Institute, 2013)	–				
Circular building assessment prototype	CBA	(BAMB, 2018)	–				
Circular business model set of indicators based on sustainability	CBM-IS	(Rossi et al., 2020)	–				
CE measurement scale	CEMS	(Núñez-Cacho et al., 2018)	–				
CE toolkit	CET	(Evans & Bocken, 2014)	–				
Circularity calculator	CC	(IDEAL&CO Explore B.V, 2017)	–				
Circularity measurement toolkit	CMT	(Garza-Reyes et al., 2019)	–				
Circularity potential indicator	CPI	(Saidani et al., 2017)	–				
Circularity transition indicators	CTI	(WBCD & Circular IQ, 2020)	–				
Circulytics	CYT	(EMF, 2020)	–				
Disassembly effort index	DIE	(Das et al., 2000)	–				
Eco-efficiency index	EEI (2)	(Laso et al., 2018)	–				
Economic–environmental indicators	EEI	(Fregonara et al., 2017)	–				
Eco-cost value ratio	EVR	(Scheepens et al., 2016)	–				
Economic–environmental remanufacturing	EER	(van Loon & van Wassenhove, 2018)	–				
EoL best practice indicators	BPI	(Jiménez-Rivero & García-Navarro, 2016)	–				
EoL of life indices	EoLi	(Favi et al., 2017)	–				
EoL index	EoL	(Lee et al., 2014)	–				
End-of-use product value recovery	EPVR	(Cong et al., 2019)	–				
Evaluation index system of CE for PCFs	CE-PCF	(Liang et al., 2018)	–				
Expended zero waste practice model	ZWP	(Veleva et al., 2017)	–				
Improved water circularity index	WCI	(Sartal et al., 2020)	–				
Input–output balance sheet	IOBS	(MarcoCapellini, 2017a)	–				
Material input per service delivered	MIPS	(Ritthof et al., 2002)	–				
Mathematical model to assess sustainable design and EoL options	SDEO	(Ameli et al., 2019)	–				
Mine site MFA indicator	MI	(Lèbre et al., 2017)	–				
Multi-criteria evaluation method of product-Level circularity strategies	MCEM-PLCS	(Alamerew et al., 2020)	–				
Multidimensional indicator set	MIS	(Nelen et al., 2014)	–				
Product recovery multi-criteria decision tool	PR-MCDT	(Alamerew & Brissaud, 2019)	–				
Product-level circularity metric	PCM	(Linder et al., 2017)	–				
Recycling benefit rate	RBR	(Huysman et al., 2015)	–				
Remanufacturing with the aid of the product profiles tool	REPRO	(Zwolinski et al., 2006)	–				
Resource efficiency assessment of products	REAPro	(Ardente & Mathieux, 2014)	–				
Set of indicators to assess sustainability	SIAS	(Golinska et al., 2015)	–				

(Continues)

TABLE 1 (Continued)

Indicator	Acronym	Authors	P	L	U	D	T
Sustainable circular index	SCI	(Azevedo et al., 2017)	–				
Systems indicators for circular economy dashboard	SICED	(Pauliuk, 2018)	–				
Typology for quality properties	TQP	(Iacovidou et al., 2019)	–				
Value-based resource efficiency indicator	VRE	(Di Maio et al., 2017)	–				
Circularity check	CC (2)	(Ecopreneur, 2019)	–				
CE benefit indicators	CEBI	(Huysveld et al., 2019)	X	–			
CE index	CEI	(Di Maio & Rem, 2015)	X	–			
CE performance indicator	CEPI	(Huysman et al., 2017)	X	–			
Circular gap	CG	(Circle Economy, 2018)	X	–			
Circularity index	CI	(Cullen, 2017)	X	–			
Circularity index Circ(T)	Circ(T)	(Pauliuk et al., 2017)	X	–			
Circularity of material quality	QC	(Steinmann et al., 2019)	X	–			
Ease of disassembly metric	eDiM	(Vanegas et al., 2018)	X	–			
Eco-efficient value ratio	EEVR	(MarcoCapellini, 2017b)	X	–			
Effective disassembly time	EDT	(Mandolini et al., 2018)	X	–			
Material reutilization score	MRS	(Cradle to Cradle Products Innovation Institute, 2013)	X	–			
EoL recycling rates	EoL-RRs	(Graedel et al., 2011)	X	–			
Environmental sustainability of food packaging indicators	FPI	(Pauer et al., 2019)	X	–			
Global resource indicator	GRI	(Adibi et al., 2017)	X	–			
Longevity and circularity	L&C	(Figge et al., 2018)	X	–			
Material efficiency in supply chains spreadsheets	MESCS	(Braun et al., 2018)	X	–			
Product circularity improvement program (material circularity score)	PCIP/MCS	(Circularity IQ & KPMG, 2021)	X	–			
Product recycling desirability index	PRDI	(Mohamed Sultan et al., 2017)	X	–			
Recycling indices for the CE	RIs	(Van Schaik & Reuter, 2016)	X	–			
Recycling rates	RRs	(Haupt & Zschokke, 2017)	X	–			
Total restored products	TRP	(Pauliuk, 2018)	X	–			
Reuse potential indicator	RPI	(Park & Chertow, 2014)	X	–			
CE value	CEV	(Fogarassy et al., 2017)	X	–			
Circular design guidelines	CDG	(Bovea & Pérez-Belis, 2018)	X	–			
Circularity assessment model	CAM	(Giacomelli et al., 2018)	X	–			
Sustainability performance indicators	SPI	(Mesa et al., 2018)	X	–			
CE indicator prototype	CEIP	(Cayzer et al., 2017)	X	X	–		
Circular pathfinder	CP	(van Dam et al., 2017)	X	X	–		
BIM-based whole-life performance estimator	BWPE	(Akanbi et al., 2018)	X	X	–		
Material and energy circularity indicators	MECI	(Zore et al., 2018)	X	X	X	–	
Eco-design indicators	EDI	(EEA, 2016)	X	X	X	–	
Building circularity indicators	BCI	(Verbene, 2016)	X	X	X	X	–
Material circularity indicator	MCI	(EMF & Granta Design, 2015/2019)	X	X	X	X	X
Product circularity indicator	PCI	(Bracquené et al., 2020)	X	X	X	X	X
Material efficiency metric	MEM	(Brändström & Eriksson, 2022)	X	X	X	X	X
Longevity indicator (or resource duration indicator)	LI	(Franklin-Johnson et al., 2016)	X	X	X	X	X

2.3.1 | Functional unit

The FU, a core element of LCA, defines the quantification of the product's functions and thus defines what is being studied. Analyses are conducted relative to the defined FU, enabling the comparison of different LCA studies (ISO 14040, 2006a). In the built environment, several LCA studies use the volume of demolition waste as FU. However, the composition of demolition waste usually differs from case to case (e.g., different building materials) and consequently also the quality of the resultant recycled material. Thus, a further specification of the FU is crucial (Lei et al., 2021). According to Lei et al. (2021), an option is to address durability by indicating a lifespan in the FU that tackles the CE aim of longevity (refuse and reduce). Niero and Olsen (2016) further proposed to include the function of the use in the following loops in the FU (e.g., an aluminum can carrying beverages and the function of scrap as secondary resource). However, predictions beyond the system boundaries of the studied life cycle (e.g., how much material actually will become secondary material for how many loops) are vague and come with considerable uncertainties (Antunes et al., 2021). The authors thus suggest to include the lifespan and the quality of the material in the FU. Related to Niero and Olsen (2016), this means that the alloys (which are relevant for aluminum recycling) might be directly given in the FU. In that case, no assumption needs to be made while possible future uses of the material (e.g., closed loop or downcycling) are indicated with the quality. This is in line with EMF and Granta Design (2015) emphasizing the need to consider failure rates and the ability to reuse or recycle when conducting LCA in the CE context.

2.3.2 | Addressing multiple loops: System boundary expansion and EoL allocations

In multiple loops, when a material flow with an economic value that is not classified as waste leaves the system, environmental benefits and burdens beyond the system boundaries become relevant (Allacker et al., 2017; Schaubroeck et al., 2021). One way to tackle this is to extend the system boundaries by including the additional functions related to the products in the previous and subsequent loops. However, a differentiation of the impact of the different loops would not be possible (Allacker et al., 2017). In the building context, Module D is the standardized approach to addresses environmental benefits or burdens resulting from reuse, recycling, and energy recovery beyond the system boundaries (DIN EN 15978, Deutsches Institut für Normung e. V., 2011). All environmental impacts from primary material production and recycling are assigned to the first life cycle. Previous or following life cycles are not covered with this approach (Eberhardt et al., 2020; Obrecht et al., 2021). The uncertainty of data has been identified as a major issue in considering Module D (Antunes et al., 2021).

Another option to address environmental benefits and burdens beyond the system boundaries are EoL allocations which are regularly discussed in the LCA community (Allacker et al., 2017; Civancik-Uslu et al., 2019; Corona et al., 2019). The cut-off approach (100:0) assumes a burden free input of waste (Allacker et al., 2017; Corona et al., 2019). The impacts of primary production are totally assigned to the first loop (Civancik-Uslu et al., 2019). The following loop receives the impacts from the recycling process 2017. When applying the EoL recycling approach (0:100), all impacts are assigned to the product life cycle that produces the recycled material while no burdens are allocated to the products using the recycled materials (Allacker et al., 2017). The primary loop obtains the impacts but is also rewarded with credits for the amount of virgin material avoided by recycled material use (Corona et al., 2019). The 100:100 approach allocates all impacts from recycling to both the upstream and downstream loops while the 50:50 approach spreads the impacts equally (Allacker et al., 2017; Corona et al., 2019). The latter can also be expanded to include primary production and final disposal (Corona et al., 2019). The circular footprint formula (CFF) allows the use of specific distribution coefficients, moreover including the quality of recycled material (Zampori et al., 2019). Table 2 provides an overview of advantages and disadvantages of the different approaches.

Solving the general discussion about burden allocations in multiple loops for LCA is beyond the scope of this paper. However, given the above information, in the context of the C-LCSA framework, the authors considered the use of the cut-off approach as most suitable. A reason for this is that the approach, contrary to the other EoL allocation approaches, follows the technical and business system boundaries (Corona et al., 2019). This means, for example, that a company that operates in an open loop economy only focuses on its own product system. Thus, also the data for the studied product system is usually available or realistic assumptions for the own system can be made. Assumptions for the next life cycle, especially for products with a long lifespan and in open loops, provide several uncertainties (Antunes et al., 2021). The cut-off approach removes the risk of minimizing a single loop's impacts by making overly favorable assumptions for reuse and recycling which could be the case with the EoL recycling approach, Module D, or CFF. Anyhow, the approach favors secondary material use over reduction and adequate design as higher efforts in material choices or a design that eases disassembly for a later recycling might imply higher environmental impacts that would still be fully assigned to the first loop (Corona et al., 2019; Eberhardt et al., 2020; Menegatti et al., 2022). These additional efforts, however, would be positively assessed in the CA part of the framework.

2.4 | Life cycle costing in the circular economy context

Developed as an economic counterpart to LCA, LCC can be an appropriate tool to assess the economic sustainability of CE concepts across different product systems (Kambanou & Sakao, 2020). In parallel to LCA, LCC should include goal and scope definition, information gathering (life cycle cost

TABLE 2 Advantages and disadvantages of the different end-of-life approaches.

EoL approach	Advantages	Disadvantages	Reference
Cut-off (100:0)	- Intuitive - Easy to communicate - Most robust approach - No double counting	- Beneficiary for secondary material use	(Corona et al., 2019; Eberhardt et al., 2020; Menegatti et al., 2022)
EoL recycling approach (0:100)	- No double counting	- Consideration of credits is based on assumptions	(Allacker et al., 2017; Corona et al., 2019)
50:50 approach	- Values of existing materials considered	- Data uncertainty - Does not display accurate distribution (greenwashing)	(Allacker et al., 2017; Corona et al., 2019; Eberhardt et al., 2020; Zimmermann et al., 2022)
100:100 approach	- All impacts shown for every loop	- Double counting	(Allacker et al., 2017)
CFF (PEF)	- Use of specific distribution coefficients - Quality considered - Market considered	- Assumptions for coefficients reduce comparability - Complexity of approach	(Eberhardt et al., 2020; Zampori et al., 2019)
Module D	- Design for reuse and recycling encouraged	- Previous loops not addressed - Assumed recycling potential in the assessment might not apply in the real world (green washing) - Uncertainty of data	(Antunes et al., 2021; Eberhardt et al., 2020; Obrecht et al., 2021).

inventory analysis), interpretation and identification of hotspots, and sensitivity analysis and discussion (life cycle costs assessment and interpretation). LCC summarizes all costs across a product's life cycle, involving different actors (Hunkeler et al., 2008; Swarr et al., 2011). In the CE context, LCC needs to consider the material supplier, the manufacturer, the consumer, and the EoL actor (Hunkeler & Rebitzer, 2003; Jansen et al., 2020). Moreover, it is important to note that the EoL actor of one loop can simultaneously be a material supplier for the next one (indicating revenues). For the C-LCSA framework, the above actors should be considered. Taking the product perspective, providing the results in the same perspective as LCA, intermediate money flows should not be considered to avoid double counting.

R-principles are likely to imply additional costs (e.g., through deinstallation), while reducing costs for primary materials. Hence, Jansen et al. (2020) proposed to add a variable to the traditional LCC for considering the R-principles, including the average percentage of parts. Value over time is crucial in terms of multiple loops that aim to keep resources in loops as long as possible. Future costs and cashflows should hence be discounted to consider the net present value (NPV) (ISO 15686-5, 2017; Jansen et al., 2020). Externalities (monetized environmental impacts) that could be included in an LCC should not be considered in C-LCSA to avoid double counting (Hunkeler et al., 2008; Swarr et al., 2011).

2.5 | Social life cycle assessment in the circular economy context

In a previous study, the authors focused on social impacts of CE and their assessment (Luthin et al., 2023). Forty papers were reviewed to assess the current consideration of social impacts in the literature. Conducting S-LCA according to the UNEP S-LCA guidelines (UNEP, 2020) considering the indicated stakeholder categories, subcategories, and social inventory indicators was found suitable for CE concepts. However, the need to focus on specific CE subcategories, some of them newly introduced, was highlighted. Examples of CE-specific subcategories are employment—including job creation resulting from new CE concepts but also the job losses in regions that were benefitting in a linear economy (e.g., mining in developing countries); training and education (for employees); and social acceptance (Luthin et al., 2023). A number of social circularity inventory indicators for CE concepts were derived in the previous study which were included as reference in the C-LCSA framework (Section 3.8).

2.6 | Integration

The integration of the different approaches was mainly based on the traditional LCSA framework—starting with an overall aim of the study. This is especially important as the individual approaches have different foci and goals (UNEP, 2011). Moreover, LCA, LCC, S-LCA, and CA should be conducted with a consistent system boundary and the results should refer to the same FU (Traverso et al., 2012). The assessments are not only conducted in parallel but the single steps in the C-LCSA framework build upon each other as described in the next section. As the FU and system boundaries in the CE context are a major point of discussion in LCA, the latter two will be defined in the LCA part of C-LCSA and will form the basis

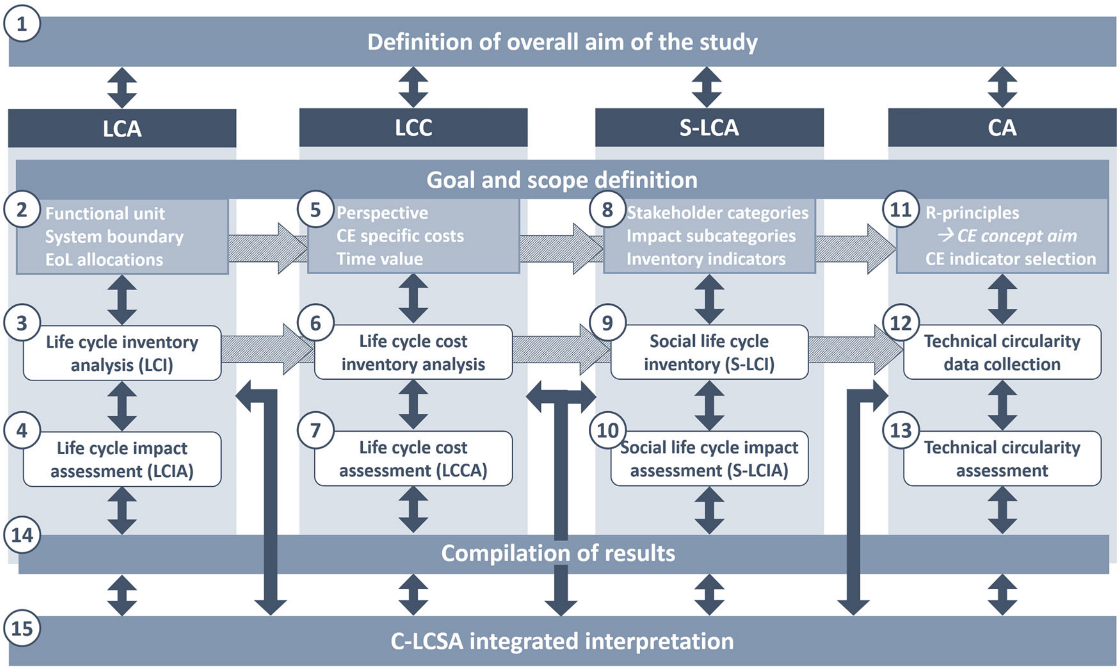

FIGURE 2 The circular life cycle sustainability framework and included conduction steps. The light grey arrows indicate the goal and scope for life cycle assessment forming the basis for the goal and scope of life cycle costing and, subsequently, for the other approaches. Thereby, in each step, approach related specifications are added. The same applies to the life cycle inventory forming the basis for the life cycle cost analysis and, again, subsequently for the data collection of the other approaches. The dark arrows indicate the iterative approach as given in the ISO 14040, 2006a.

for LCC, S-LCA, and CA. Also, the life cycle inventory (LCI) of the LCA will form the basis for the other approaches which will need to include further data such as costs, worked hours, social data, and technical circularity data.

A major benefit of an integrated assessment is the identification of trade-offs (UNEP, 2011). While the conversion into a single value would result in a loss of transparency, an appropriate visualization enables the identification of both positive and negative impacts of the studied product system. A combined presentation of results was encouraged by Finkbeiner et al. (2010) and UNEP (2011) and was also found relevant for C-LCSA to highlight the interlinkages of changes in the product system. It needs to be noted that the results of the different approaches come with different ranges. MCI is indicated within a range from 0 to 1 and S-LCA results might be given within a range (e.g., −2 to +2). LCA and LCC results, however, imply specific values. This issue will be tackled in Section 3.14.

3 | RESULTS: CIRCULAR LIFE CYCLE SUSTAINABILITY ASSESSMENT

In this section, the C-LCSA framework is presented as a guidance for conducting future studies. Figure 2 shows the iterative assessment approach. In total, 15 steps have been defined for conducting C-LCSA studies. Relevant equations are given in Table 3.

3.1 | Definition of overall aim of the study

Integrating the different approaches begins in the early stage of the study. Defining the overall aim of C-LCSA studies should include the subject of the study, the assessment approaches used, and the intended use of the study. If, due to complexity, only certain aspects of the approaches are considered (e.g., focus on carbon footprint and circularity), this should be stated here.

3.2 | Life cycle assessment: Goal and scope

The goal and scope defined in the LCA part of the study form the basis for the latter approaches. It is to follow ISO 14040/44, 2006a, 2006b with an extra focus on the FU and EoL allocations. In terms of the FU, the quality of the material (input and/or output) should be addressed, indicating qualitative potential for further use at the EoL.

TABLE 3 Relevant formulas for the application of the circular life cycle sustainability framework.

Description	Formula	Reference	Equation
Cut-off approach	$EI_C = (1 - R_1) \times E_V + R_1 \times E_{recycled} + (1 - R_2) \times E_D$ where EI_C = environmental impact (per impact category); R_1 = recycled content of material; E_v = emissions and resources for acquisition and pre-processing of virgin material; $E_{recycled}$ = emissions and resources for production process of recycled material; R_2 = recycled fraction of material; and E_D = emissions and resources for disposal of waste material	Allacker et al. (2017)	1
Total costs	$C_{total} = C_{supplier} + C_{manufacturer} + C_{consumer} + C_{EoL\ actor}$ where C = costs	Jansen et al. (2020)	2
Total revenues	$R_{total} = R_{supplier} + R_{manufacturer} + R_{consumer} + R_{EoL\ actor}$ where R = revenues	Jansen et al. (2020)	3
Net present value	$X_{NPV} = \sum (C_n \times q) = \sum_{n=1}^{P} \frac{c_n}{(1+d)^n}$ $\frac{U}{U_{av}}$ where C_n = costs in year n; q = discount factor; d = real expected annual discount; n = number of years; and P = assessment period.	ISO 15686-5:2017	4
Material circularity indicator*	$MCI = 1 - LFI \times F(X)$ where LFI $= \frac{V+M}{2M}$ and X $= \frac{L}{L_{av}} \times \frac{U}{U_{av}}$ where LFI = linear flow index; $F(X)$ = the utility factor; V = virgin material [kg]; M = mass of the product [kg]; L = average lifetime [years]; U = average number of functional units achieved; and av = industry-average product of the same type * for products consisting of a number of different components, please refer to the comprehensive approach given by EMF and Granta Design (2019).	EMF and Granta Design (2019) EMF and Granta Design (2019) EMF and Granta Design (2019)	5 6 7

The system boundary should include the studied life cycle, excluding burdens and credits assumed for previous and following life cycles. The use of the cut-off methodology when applying the C-LCSA framework is recommended.

3.3 | Life cycle inventory analysis

The LCI should be based on ISO 14040/44, 2006a, 2006b. It involves data collection and calculation procedures for input and output quantification. Data to include are material and energy inputs, products, co-products, waste, and emissions. Data can be obtained from manufacturers, official institutions, and literature.

3.4 | Life cycle impact assessment

The life cycle impact assessment is to be based on ISO 14040/44, 2006a, 2006b. In this step, the LCI results are classified and characterized to assess the potential environmental impacts. This can be done using LCA software that automatically calculates the environmental impacts from the LCI. Using the cut-off approach, Equation (1) (Table 3) should be applied.

3.5 | Life cycle costing: Goal and scope

The goal and scope for the LCC is the economic assessment of the FU defined in Step 2. Further specifications for the scope such as considered costs, time value, and perspective (e.g., manufacturer, EoL actor, product perspective) must be provided. Costs arising from the following actors should be addressed: material supplier, manufacturer, consumer, and the EoL actor. Attention should be drawn to CE-specific costs such as repair, dismantling, disassembly, and CE-specific revenues when former wastes become resources. To avoid double counting by including externalities, only real money flows should be considered. Costs should be referred to a reference year using, for example, the NPV.

TABLE 4 Non-exhaustive list of social circularity indicators for the different stakeholder categories according to Luthin et al. (2023).

Stakeholder category	Social circularity indicators
Worker	Number of accidents related to CE activities, employees involved in CE actions, CE related job adverts, and threats related to remanufacturing, existing initiatives to promote zero waste, minutes of CE training per employee per year
Local community	Number of jobs created that involve CE activities, job losses due to the end of mining activities, local initiatives promoting CE, CE related accidents/malfunctions leading to increased emissions, and campaigns to enhance social acceptance, evidence of NIMBY among percentage of residents, access to relevant technologies enhancing CE, green or circular government purchases for the region
Value chain actors	Number of CE educative workshops for suppliers, patents related to innovative technologies applied in CE, and CE related meetings with stakeholders, existing commitment to green supply chain management
Consumer	Number of participative CE workshops with clients, campaigns to enhance social acceptance, and relevant services including CE content/actions, existing marketing practices for green washing, clear information about EoL options, labels used to promote transparency for consumers
Society	Number of CE innovation meetings/workshops/brainstormings for innovation development, (R&D&I CE investment)/(total investment)
Children	Existence of CE trainings for students
Other	Number of top-management CE actions, share of secondary material imports from/exports to other countries design for reuse and recycling encouraged

3.6 | Life cycle cost inventory analysis

The life cycle cost analysis is based on the LCI (Step 3). Additional monetary values such as personnel costs are to be collected, for example, using internal information, market prices, cost data provided by industry or official organizations, or using secondary data from the literature.

3.7 | Life cycle cost assessment

Costs and revenues are to be based on real money flows, calculated in accordance with the chosen perspective. For the product perspective, the total costs and revenues can be calculated as per Equations (2) and (3) and the NPV, considering the value in time, as per Equation (4) (Table 3).

3.8 | Social life cycle assessment: Goal and scope

The FU and system boundaries of Step 2 are the basis for the S-LCA part of the assessment. Additionally, considered stakeholder categories (worker, local community, value chain actors, consumer, society, and children), subcategories, and inventory indicators must be defined. This should be based on the UNEP S-LCA guidelines (2020), the upcoming ISO 14075, and the recommendations of Luthin et al. (2023).

Additional subcategories to be considered in the CE context are:

- Training and education for employees (worker);
- Job losses in the linear economy (society); and
- Social acceptance (local community and consumer) (Luthin et al., 2023).

Social circularity indicators for the CE context according to Luthin et al. (2023) are given in Table 4.

3.9 | Social life cycle inventory

This step is to be based on the UNEP S-LCA guidelines (2020). Besides data collection (site specific/generic), this step includes the prioritization of data to be collected. The prioritization can be based on identified key social issues, hotspots, or most intensive processes of the product system (UNEP, 2020).

3.10 | Social life cycle impact assessment

This step is to be based on the UNEP S-LCA guidelines (2020), referring to the reference scale approach (Type I). It includes the calculation and evaluation of potential social impacts in the product system based on specific reference points. The reference scale approach (Type I) that aims to assess the social performance or social risk is currently the most used approach in S-LCA. The collected data is assessed against a defined reference scale (e.g., targets and average sector/country performance), typically using a −2 to +2 scale (UNEP, 2021). It is encouraged to use this approach for C-LCSA.

3.11 | Technical circularity assessment: Goal and scope

The circularity goals should be specified and boundaries be set (ISO 59020 draft, ISO, 2023) based on the defined FU and system boundaries of Step 2. The technical CA should at least include the MCI that was identified as most suitable for C-LCSA, being in line with LCA and CE as an umbrella concept. For sensitivity analysis, considering more indicators (such as the LI and PCI) or sector-specific indicators, might be beneficial. In the latter case, an individual CE indicator selection should be conducted using the approach described in Section 2.2.

3.12 | Technical circularity data collection

The technical circularity data collection is based on the LCI (Step 3). Additional data may include the actual average lifetime of a product and an industry-average product of the same type. Recycling rates should be based on real scenarios rather than ideal scenarios (EMF & Granta Design, 2019).

3.13 | Technical circularity assessment

The MCI mainly combines the extent of the linear and restorative flows and the longevity of a product. It is calculated using Equations (5)–(7) (Table 3). The intermediate calculation steps can be obtained from EMF and Granta Design (2019).

3.14 | Compilation of results

The results of the different methods are to be compiled. An appropriate and integrated results presentation is encouraged. This might be challenging as the results of the four dimensions are not given within the same ranges or even with absolute numbers rather than within a defined scale. The MCI indicates the circularity within a range from 0 to 1. The optimum here is given as 1. Social impacts are usually given on a scale (e.g., −2 to +2). The performance could be easily transferred into a range from 0 to 1, where the optimum of +2 is set as 1. For LCA and LCC, results are given in actual numbers for environmental emissions and costs. Here, a normalization is needed that is to be documented transparently. The best performance from a similar product with the same function could be set as the optimum (1) and the worst performance as 0. Figure 3 shows a possible visualization of C-LCSA results, keeping in mind the different scales of the methods.

3.15 | C-LCSA integrated interpretation

Interpreting the results together enables to suggest improvements based on interlinkages and trade-offs. To identify these, the same scenario variations should be applied for each method for the sensitivity analysis. Optimal case-specific actions to improve a CE concept can be taken based on the assessment. It is important to consider all four dimensions (environmental, economic, social, and circularity) and their interlinkages together to ensure holistic decision making and avoid burden shifting.

4 | DISCUSSION AND CONCLUSION

As CE indicators alone are not able to identify the most sustainable CE concepts, the combination of CE indicators and LCA as well as the development of further CE frameworks became subject of several studies. Lonca et al. (2018) quantified trade-offs between circularity and environmental impacts in the tire industry using LCA and MCI while Niero and Kalbar (2019) coupled MCI and MRS with indicators such as GWP or AP for a

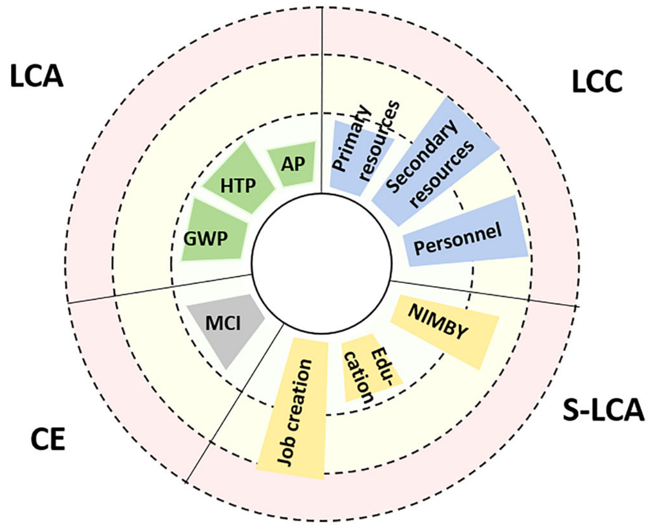

FIGURE 3 Possible visualization of circular life cycle sustainability assessment results. The central line indicates the optimum (1) while the outer line indicates the worst case (0). By adding a color code, favorable performances can be found in the green circle, medium performances in the yellow circle, and worst performances that need improvement can be found in the red circle. AP, acidification potential; GWP, global warming potential; HTP, human toxicity potential.

case study of beer packaging. To assess a Mediterranean rooftop greenhouse and different CE strategies, Rufí-Salís et al. (2021) used LCA and the MCI. Lindgreen et al. (2021) applied LCA and different CE indicators. While benefits for a parallel application for LCA and CE indicators have been identified in these studies, the economic and social pillars have been excluded. Related to CE framework development, Thakker and Bakshi (2021) introduced a computational assessment framework for circular systems combining LCA with optimization-based approaches for process synthesis and network representation. For the construction sector, Abadi and Sammuneh (2020) presented a *life cycle "circularity" assessment framework*, aligning 12 CE indicators with the different project life cycle stages (e.g., design and construction). Droege et al. (2021) developed a CE assessment framework focusing on 35 CE assessment elements, going beyond the environmental perspective (e.g., including operations and social activities). The latter two frameworks were not based on life cycle methodologies. C-LCSA contributes to academia by providing an assessment framework that is based on established life cycle methodologies but goes beyond LCA. Current challenges in the application of LCSA in the CE context were identified and addressed to bring consensus in the application.

Even though several authors agreed that an integration of LCA and CE indicators is relevant for robust studies, these assessments are complex (Rigamonti & Mancini, 2021). Moreover, the use of different indicators, allocation methods, or assumptions highly influences the outcomes of CA and LCA (Bracquené et al., 2020; Menegatti et al., 2022). C-LCSA is even more complex. Hence, a guidance was introduced to simplify and harmonize future C-LCSA studies that can be used by both, academics and industry practitioners. Still, applying C-LCSA requires a large amount of data and time which can be stated as a limitation of the framework. Challenges also appear as the expertise for the different dimensions might lay by different experts, requiring a close collaboration. Moreover, a high amount of data needed in the CE context provides uncertainties for CA and LCSA as assumptions about the future need to be made (Antunes et al., 2021). This might hinder the comparability of studies. The framework and data used thus are to be handled transparently to allow future adjustments. This also allows an interdisciplinary application of the approach along different scholars or departments within the company. Focusing on certain aspects of the approach related to set industry aims might simplify the initial application (e.g., a social risk assessment instead of a full S-LCA). For sector-specific studies, a focus on sector-specific CE indicators might be beneficial (Khadim et al., 2022).

The need for an integrated assessment for CE and sustainability performance has been emphasized in recent position papers (Leipold et al., 2023; Peña et al., 2021). The C-LCSA framework developed in this research aims to lay the foundation for a holistic assessment in terms of the technical circularity and sustainability performance of products and services. The proposed C-LCSA framework may serve as a reference for future studies to achieve consensus in assessing CE concepts and ensure they are comparable. It may help scientists and decision makers to consider the broader impacts of their decisions that can further be adapted by policy makers.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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