University of Messina

Methods and tools to measure sustainability and circular economy (CE) at the company level

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Economics, Management and Statistics, Cycle XXXIV

Cresting WP 5.2: Measuring the impact of circularity

Sector of scientific discipline (SSD): SECS-P/13 Commodity Science

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List of figures

List of tables

List of abbreviations

BSI	British Standards Institution
CE	Circular Economy
CTI	Circular Transition Indicators
EA	Environmental Accounting
E-LCA	Environmental Life Cycle Assessment
EMF	Ellen Macarthur Foundation
EPR	Extended Producer Responsibility
ESR	Early Stage Researcher
EU	European Union
FE	Freshwater Eutrophication
FEcotox	Freshwater Ecotoxicity
FPMF	Fine Particulate Matter Formation
FRS	Fossil Resource Scarcity
GHG	Greenhouse Gas
GRI	Global Reporting Initative
GWP	Global Warming Potential
GWP	Global Warming Potential
HCTox	Human Carcinogenic Toxicity
HDPE	High-density polyethylene
HnCTox	Human non-Carcinogenic Toxicity
IR	Ionizing Radiation
ISO	International Standardization Organization
KPI	Key Performance Indicator
kWh	Kilowatt-hours
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCC	Life Cycle Costing
LCT	Life Cycle Thinking
LLDPE	Linear low density polyethylene
LU	Land Use

MA	Materiality Assessment
MCDA	Multi Criteria Decision Analysis
MCI	Material Circularity Indicator
MD	Material durability
ME	Marine Eutrophication
MEcotox	Marine Ecotoxicity
MFA	Material Flow Analysis
MFA	Material Flow Analysis
MFCA	Material Flow Cost Accounting
MRS	Mineral Resource Scarcity
NRG	Non-returnable glass
OF-HH	Ozone Formation, Human Health
OF-TE	Ozone Formation Terrestrial Ecosystems
PE	Polyethylene
PEF	Product Environmental Footprint
PEF	Product Environmental Footprint
PET	Polyethylene terephthalate
PP	Polypropylene
PSS	Product-Service Systems
PV	Photovoltaic
RC	Recycled content
RG	Returnable glass
rPET	Recycled polyethylene terephthalate
RR	Recycling Rate
SCEIA	Strategic Circular Economy Impact Assessment
SD	Sustainable Development
SDGs	Sustainable Development Goals
S-LCA	Social Life Cycle Assessment
S-LCA	Social Life Cycle Assessment
SME	Small and medium enterprises
SOD	Stratospheric Ozone Depletion

SSCM	Sustainable Supply Chain Management
ST	Stakeholder Theory
TA	Terrestrial Acidification
TCEI	Tailormade circularity indicators
TD	Transdisciplinarity
TEcotox	Terrestrial Ecotoxicity
TfD	Time for disassembly
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
TSI	Tailormade sustainability indicators
UNEP	United Nations Environmental Program
VNRRne	Volume of non-renewable resources not extracted
VVMp	Volume of virgin material production prevented
VWdl	Volume of waste diverted from landfill
WBCSD	World Business Council for Sustainable Development
WC	Water Consumption
WF	Water Footprint
WP	Work Package

Chapter 1. Introduction

1.1. Introduction of circular economy (CE) assessment at company level

The popularity of the idea of establishing a circular economy (CE) instead of today's linear economic model has grown remarkably in recent years (Calisto Friant et al., 2021). The multifaceted concept has a rich historical background and draws from various fields and previously established concepts related to sustainability (Blomsma & Brennan, 2017). CE is interpreted differently by different people, and there are many definitions available in academic literature (Kirchherr et al., 2017). One of the primary goals of establishing a CE is to decouple global economic development from finite resource consumption, leading to reduced environmental degradation while facilitating economic growth (Cullen, 2017; Ellen MacArthur Foundation, 2015). Although contested by some whether practically conceivable, the goal of establishing a CE is often considered to contribute to the global Sustainable Development Goals (SDGs) (Schöggl et al., 2020). The concept of closing resource loops and increasing resource efficiency plays a central role in CE (Amato, 2021; Merli et al., 2018).

CE has been rapidly propagated following the consensus on the detrimental impact of human consumption and production on environmental quality, social equity and long-term economic stability (Millar et al., 2019). The world's current global economic model relies heavily on extraction, transformation, use and subsequent disposal of resources, and has been described as an 'extract-produce-use-dump' model (Korhonen et al., 2018); it is considered unsustainable since some decades (Daly, 1990). CE, in its many forms, has gained popularity as an alternative model for navigating towards a more sustainable future (Pla-julián & Guevara, 2019).

Thus far, outside of academia, the concept has particularly gained attraction among both national policy makers as well as in the private sector (Flynn & Hacking, 2019). Both types of actors have used CE as a guideline, toolbox, framework, umbrella concept or philosophy to develop strategies to reduce resource dependency and environmental degradation while boosting economic competitiveness (Brown et al., 2019; Calisto Friant et al., 2021). In the European context, European Commission policy actively promotes private sector initiatives as an important driver for the CE transition, and the diversity of CE business models is growing (European Commision, 2015; Henry et al., 2020; Santa-Maria et al., 2021).

While the specific roles and responsibilities of companies have not yet necessarily been formalized in CE literature, various academic authors also emphasize the role of private sector uptake as a driver for CE implementation (Stewart & Niero, 2018). This is directly related to industry activities related to causing and determining flows of materials and energy through the global economy (Azapagic & Perdan, 2000). In addition, many of the earlier influential writings on CE, in particular by institutions outside of academia such as the Ellen MacArthur Foundation, clearly focus on promises of various (financial) benefits to industry by implementation of innovative CE business models (Ellen MacArthur Foundation, 2013). Though investigations on the uptake of CE principles by the private sector organizations remain somewhat limited, some reports signal an increase in CE initiatives in various countries (see e.g. PBL Netherlands Environmental Assessment Agency, 2019).

In academic literature, CE is increasingly characterized by a corporate and technocentric perspective, aligning CE with paradigms such as innovation and green growth (Friant et al., 2020; Schöggl et al., 2020). Perceived company benefits from implementing CE are related to lowering environmental impacts, realizing social improvements and economic benefits, such as cost savings and developments of new markets - or growing existing ones (Korhonen et al., 2018; Laubscher & Marinelli, 2014). Therefore, the alleged promise of CE practices lies in reducing negative sustainability impacts without jeopardizing growth and prosperity (Ferasso et al., 2020).

Given this central role of companies in transitioning to a CE, recent literature has described a need for CE indicators, metrics, tools and measurement methods to assist companies in managing and measuring their progress related to the implementation of their CE measures, and their attainment of the aforementioned company benefits (Kristensen & Alberg Mosgaard, 2020). Various papers and reports describe the absence of adequate standardized indicators as a barrier for companies to the CE transition: Tecchio et al. (2017) for example note that “the absence of adequate metrics and standards has been a key barrier to the inclusion of resource efficiency requirements” (2017). This also highlighted in Saidani et al. (2019), in which the authors describe how it is commonly acknowledged that the introduction of monitoring and evaluation tools has become essential to promote CE implementation. This assessment is essential because for many CE solutions and business models available to companies, it is unclear whether - or to what extent - they actually lead to more sustainable outcomes (Blum et al., 2020; Harris et al., 2021). Well-intended CE strategies might actually lead to unintended sustainability impacts and burden shifting (Corona et al., 2019; Lonca et al., 2018; Walzberg et al., 2021).

With respect to this terminology of “tools, metrics, and indicators”, academic literature has used different phrasings for managing units of information related to CE and sustainability, such as metric, variable, indicator, methodology, or index, etc. (Saidani et al., 2019, Sala et al., 2013; Veleva & Ellenbecker, 2001). No consensus or categorization on the structure or objective of these different phrasings exists (Saidani et al., 2019). Throughout this thesis, the term “assessment approaches” is used with the aim to capture this wide variety of understandings. Relating such “assessment approaches” back to the level of companies, in sustainability literature, the process of assessment usually refers to obtaining data on the sustainability performance of any system (product- or company level), allowing for its effective management (Beloff et al., 2004). The objectives of such assessment are diverse: the outcome could be used for purposes such as monitoring and evaluating company performance towards SD goals, but also for external purposes such as communication to clients, reporting or compliance with legislation (Bae & Smardon, 2011).

Central to this thesis is the design and validation of a new CE assessment framework SCEIA (Strategic Circular Economy Impact Assessmet): a modular framework to be used by companies motivated to assess the sustainability impacts of their CE strategies. The following sections of this introduction chapter provide more detail on the research gaps relevant to CE assessment at company level, and show how this thesis aims to address those gaps. The chapter addresses how the project’s research objectives and their associated scientific methodologies then lead to the design and validation of the SCEIA framework. First, the context of the research project is described in section 1.2. This is followed by an overview of the underlying research philosophies in chapter 1.3. Then, section 1.4. presents the research objectives as set in the project’s grant agreement and the overall scientific structure of this thesis. For each of the elements in this structure, the identified research gaps, research questions, hypotheses, applied methods and a brief summary of the scientific contribution (i.e. results) are presented. The final section 1.5 then lists the deliverables that have resulted from the research project, followed by the chapter's references.

1.2. Context

This research project is undertaken in the context of the transnational project Circular Economy: Sustainability Implications and Guiding Progress (Cresting). The project received funding from the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement number 765198. The funding allows 15 early stage researchers (ESRs) to critically analyze various CE aspects as interrelated social, technical, environmental and geographical phenomena. The multi-disciplinary team currently consists of 15 ESRs with different academic- and professional backgrounds, 10 supervisors from different European universities, 2 external co-supervisors from the University of Ibadan and Nanjing University, and 1 project manager. The following Universities are involved: the University of Hull (UK), Universidade NOVA and Universidade Aberta (both Portugal), Universiteit Utrecht (Netherlands), Universitaet Graz (Austria), Universite de Technologie de Troyes (France), Universita degli Studi di Messina and Universita degli Studi Gabriele d'Annunzio di Chieti-Pescara (both Italy).

Work Package 5, or WP5, is led by professor Andrea Raggi, D'Annunzio University of Chieti–Pescara, and comprises three ESRs and their supervisors (see table 1). WP 5.2 within the Cresting project focuses on methods and tools to evaluate sustainability and CE at company level. The ESR (PhD researcher) was based in Messina, Italy during the project. He worked from the University of Messina, Department of Economics, where he was enrolled in the PhD program 'Economics, Management and Statistics'. He has been supervised by professor Roberta Salomone, working at the department of Economics, who specializes in, among other topics, quality management and environmental management, LCA and sustainability assessment tools, and industrial ecology and eco-industrial parks. His second supervisor is associate professor Tatiana Reyes from the University of

Technology of Troyes (UTT), who focuses on eco-design and design for sustainability, sustainability assessment methods, and sustainable values decision making in corporate environments.

Table 1: Composition of Cresting Work Package 5 ('Measuring the impacts of circularity').

Work package	WP 5.1: Measuring CE sustainability: methodological and practical issues.
ESR	Anna Walker, based in Pescara, D'Annunzio University of Chieti–Pescara.
Supervisor	prof. Andrea Raggi, D'Annunzio University of Chieti–Pescara.
Co-supervisor	Prof. Walter Vermeulen, Utrecht University.
Work package	WP 5.2: Methods and tools to measure sustainability and CE at company level.
ESR	Erik Roos Lindgreen, based in Messina, University of Messina.
Supervisor	prof. Roberta Salomone, University of Messina.
Co-supervisor	prof. Tatiana Reyes, University of Technology of Troyes.
Work package	WP 5.3: Development of a sustainability indicator system to assess and communicate CE practices at company level.
ESR	Katelin Opferkuch, based in Lisbon, Portugal, Universidade Aberta.
Supervisor	prof. Sandra Caeiro, Universidade Aberta.
Co-supervisor	prof. Roberta Salomone, University of Messina.

1.3. Research philosophies

This section presents the underlying research philosophies of the three-year PhD research project. While the project's structure consists of a sequence of research phases with different research methods, these phases are connected through a research philosophy that is applied to the entirety of the Cresting project (transdisciplinary research) and a research philosophy that provides a foundation to WP 5.2 (stakeholder theory). Both are described in this subchapter.

1.3.1. Transdisciplinary research (TD)

The overarching research strategy of the CRESTING project is transdisciplinary research (TD). TD acknowledges that sustainability issues need innovative ways of knowledge production and decision making (Lang et al., 2012). The scientific principle is based on new knowledge creation aimed at meaningful outcomes for practice and science. It is a reflexive, impact-oriented, inclusive approach, aimed at solving societal and scientific problems synchronously by differentiating and integrating knowledge from various fields and stakeholders (Lang et al., 2012). It has scientific connections to the participatory methods from action research in (industrial) design, however focuses less on dilemmas of the situation in which practitioners find themselves, and more on solving broader societal challenges (Swann, 2002).

The paper by Daniel Lang and colleagues (2012) from which the above definition is extracted does only substantiate why TD is particularly relevant to sustainability-related problems, it also proposes principles of how to *do* transdisciplinary sustainability. Its ‘design principles for transdisciplinary research in sustainability science’ have largely been embedded throughout this research project. However, it is important to clarify that not all design principles are represented equally over the various phases of the project. The overall problem formulation and project design have not been established in close cooperation with (CE) practitioners, for example. The project can therefore not be considered a ‘transdisciplinary co-production’ (Polk, 2015).

The interpretation of TD that is more suitable to this project is that of Wickson et al. (2006) who present a more fluid definition of the concept. Their work describes three general characteristics of TD: ‘problem focus’, ‘evolving methodology’, and ‘collaboration’. ‘Problem focus’ refers to the origin of the to-be-solved problem at hand: this should be a real-world problem, instead of a problem that originates purely from academic interest. The ‘evolving methodology’ implies that the methodology evolves in an iterative relationship with the research. It “(…) continues to develop over the course of the project in response to the research context and the learning and changing perspectives of stakeholders in the research” (Wickson, 2006). Lastly, according to this interpretation of TD, close cooperation with practitioners, especially in the problem formulation phase, appears not to be essential. Instead, the authors describe ‘collaboration with the community’ as a distinguishing feature of TD. They formulate this characteristic as providing a type of ‘reality check’ for research processes and outcomes: by engaging with communities in a practical sense, the real-world boundaries and opportunities of social and material contexts are more likely to become part of the core of the research. In addition, and not unimportantly, collaborating with communities enables lone researchers to adopt TD approaches.

1.3.2. Stakeholder theory (ST)

This project largely revolves around the links between CE and corporate sustainability: the capacity of a firm to continue operating over a longer period of time. The latter strongly depends on the organization's sustainability of it stakeholder relationships (Perrini & Tencati, 2006). While the links between CE and the 'stakeholder view of the firm' or stakeholder theory (ST) have not been explicitly described in management literature, the concepts are compatible and can be said to be interlinked. This section will briefly describe the foundations of ST and its applicability as a relevant research philosophy of this project. In practice, the concept assists in understanding the role of a firm, and offers support in understanding the links between corporate sustainability, CE, and supply chain management.

ST can be interpreted as a 'framework', i.e. a set of ideas from which a number of theories can be derived, or even a 'genre of theories'. According to Parmar et al., ST is a narrative that allows to "understand and remedy three interconnected business problems – the problem of how value is created and traded, the problem of ethics and capitalism, and the problem of helping managers think about management such that the first two problems are addressed" (Parmar et al., 2010). ST suggests to address these problems by adopting the relationships between a business and the entities that are affected by it (groups or individuals) as a unit of analysis. Businesses can be viewed as a set of relationships among groups that have a stake in the activities that make up the business (Freeman et al., 2010). ST is then about these diverse groups and individuals interact to jointly create and trade value. Two additional important components of ST are the notion that managing stakeholder relationships is a moral endeavor and that creating, maintaining and aligning stakeholder relationships "better equips practitioners to create value and avoid moral failures" (Parmar et al., 2010).

When browsing academic literature on ST, many links with CE emerge. We here focus on two elements that are borrowed from academic literature on ST, and are used later in the critical evaluation of available CE assessment approaches and proposal of a newly designed assessment framework (paper 1 and chapter 4 of the thesis). First, we make use of the concept of providing a normative justification of the concept of CE and its associated activities (Parmar et al., 2010). This normative core is described as developing arguments to show that a given idea can be defended using normative reasons – notions of what *should* be the case. Second, ST is linked to the sustainable use of natural resources and supply chain management. These connections are well-described in Perrini & Tencati (2006), describing sustainability-oriented companies are described as organizations in which "financial and competitive success, social legitimacy and efficient use of natural resources are intertwined according to a synergetic and circular view of the company's aims". The efficient use of natural resources is clearly linked to some of the basic conceptual foundations of CE, and the other aims show that the overall approach to corporate sustainability is holistic. Next, the sustainability of a firm is said to be dependent on the sustainability of its stakeholder relationships. Among these are not only employees, communities, and civil society, among others, but also the organization's suppliers and other supply chain actors. Again, we observe a connection to the life-cycle perspective of CE and its focus on supply chain management, as investigated by e.g. Genovese et al. (2017). The authors explicate the connection to the development of systems that allow companies to measure "their own behavior". The integrated output, consisting of more than traditional financial information, can then be used to respond to stakeholder concerns, to communicate and demonstrate their performance, and to assist in decision-making processes. In the design of such systems, which is one of the primary tasks of this research project, the application- and assessment of CE, the concept of corporate sustainability and the stakeholder perspective to sustainability management come together.

1.4. Scientific structure: gaps, objectives, methods

This thesis builds on a set of interlinked research gaps related to the assessment of CE and sustainability by companies. The foundation of the thesis consists of the research objectives as formulated for Cresting WP 5.2 in the project's grant agreement. They are presented in table 2. In the next subchapters, the resulting scientific structure of the thesis is presented, synthesizing the identified research gaps that led to the thesis' research questions, hypotheses and its methodological steps.

Table 2. Cresting WP 5.2 project objectives.

Objective #	Description in the CRESTING project's grant agreement.
Objective 1	Provide systematic analysis of key experiences of measurement of sustainability and CE at company level, identifying the implemented methods and tools for different industry sectors, company dimension, sustainability perspective (environmental, economic, social), key waste streams and any other variable influencing these experiences.
Objective 2	Determine success factors and limitations of these measurement experiences in order to design best practices for accelerating the implementation of circularity at company level, identifying key strategies of universal implementation, reporting on proper methods, data quality requirements, organizational change, etc.
Objective 3	Determine the improvement potential of CE of specific selected industry case studies (specific waste streams, characteristics of related markets for recycled materials, potentiality for symbiotic exchanges, etc.)
Objective 4	Measure the sustainability and CE in the selected industry case studies that are following these best practices.

1.4.1. Overall scientific structure of thesis

The overall scientific structure of the thesis is presented in figure 1. This figure shows the previously described research philosophies, the three primary research gaps that are addressed, their hypotheses, methods of validation, and how the thesis activities contributed to the advancement of the science on these specific topics. The three research gaps lead to three research domains within the thesis, described hereafter: *State-of-the-art of CE assessment (1.4.2.), Company engagement with CE assessment* (1.4.3.) and *Design and validation of CE assessment framework* (1.4.4.) These domains and their outputs– and therefore, the structure of this thesis – are presented in the following subsections.

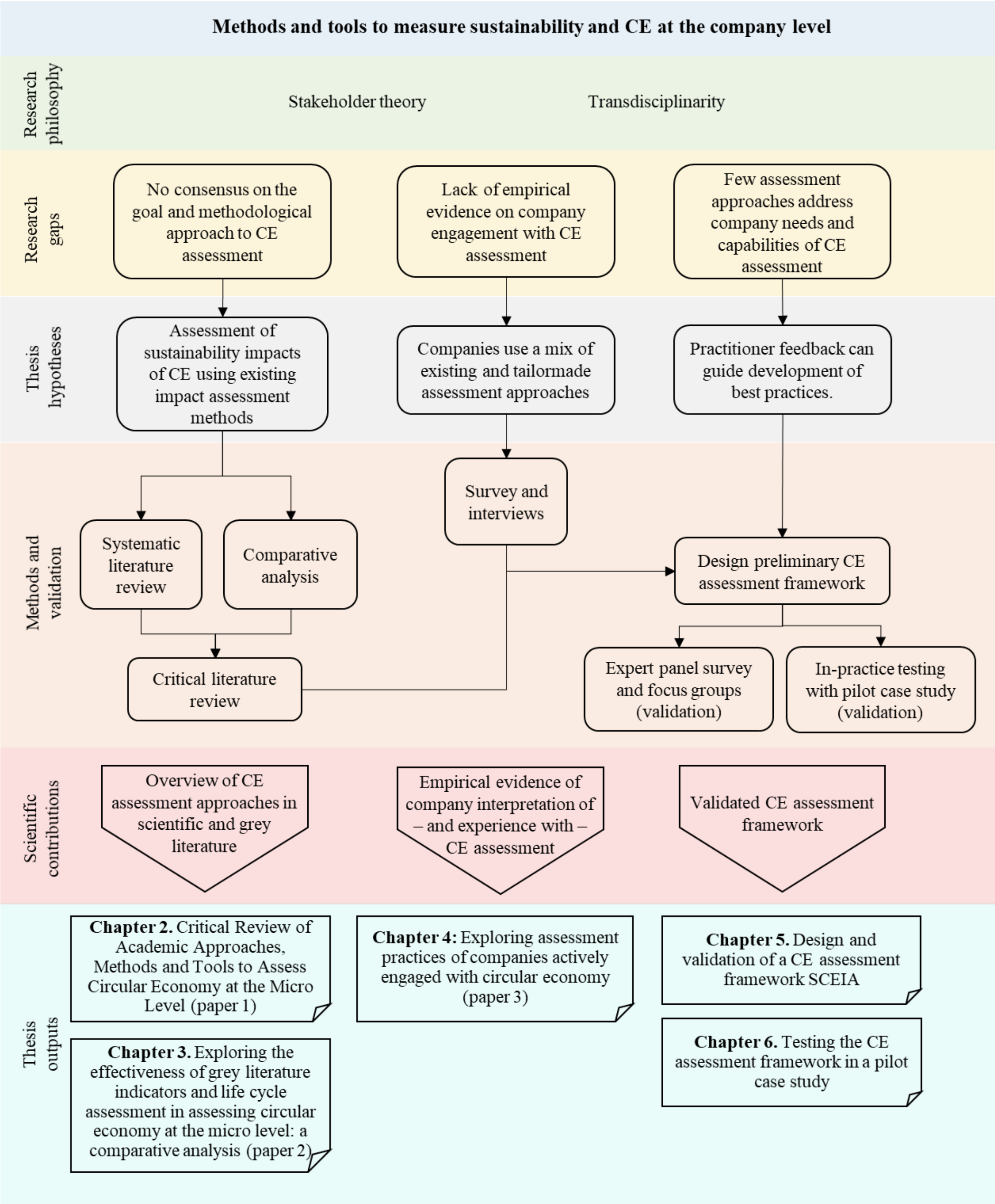

Figure 1. Scientific structure of thesis.

1.4.2. State-of-the-art of CE assessment

1.4.2.1 Research gap and hypothesis

A proliferation of academic- and grey literature proposing CE assessment approaches has occurred over the past few years (Vinante et al., 2020). These assessment approaches aim to assist companies with a variety of activities: from facilitating information exchange, monitoring progress to reaching sustainability goals and informing decision-making, to improving circular business investment decisions (Bae & Smardon, 2011; Corona et al., 2019). Simultaneously, the field of assessing CE at micro (products, firms) level can be said to be characterized by a low level of maturity, and, while evidence is still scarce but has grown in the past years, the level of implementation of CE assessment approaches by organizations appears to be limited (Das et al., 2021; Niero & Kalbar, 2019; Stumpf et al., 2019; WBCSD, 2018). This low uptake of CE assessment has been said to form a barrier to CE implementation, and to ensuring that implemented CE strategies result in the intended sustainability impacts (Kristensen & Alberg Mosgaard, 2020; Tecchio et al., 2017).

However, the reasons for this low uptake of assessment approaches, a central topic in this thesis, have not yet been investigated in detail in academic literature. While barriers to CE implementation are increasingly becoming clear – including quality issues in secondary materials, supply chain complexities, and high start-up/ investment costs – barriers to the assessment of CE specifically are less well-understood (Guldmann & Huulgaard, 2020; Jaeger & Upadhyay, 2020). Some authors consider the conceptual unclarity of CE and its relation with sustainability to play a role, which has resulted in a wide and diverse variety of CE metrics (Corona et al., 2019; Moraga et al., 2019).

To start the investigation into the low uptake of CE assessment approaches, an overview of available approaches relevant to companies, both in academic and grey literature, is needed. Previous reviews described CE assessment approaches to be heterogenous in terms of the sustainability dimensions included, their applied scope and their intended use (Kristensen & Alberg Mosgaard, 2020; Saidani et al., 2019). This points to a lack of scientific consensus on (1) what an assessment approach should be able to achieve (i.e. the goal of assessment) (2) its methodological approach. To establish a scientific overview of such different interpretations of CE assessment and better understand their heterogeneity, the first research question is therefore:

RQ1. What is the current state-of-the-art of CE assessment at the micro level?

With respect to the goal of assessment, the conceptual debate on the normative end-goal of a CE becomes important. Different authors have zoomed in on the relation between CE and sustainability

(Geissdoerfer et al., 2017; Sauvé et al., 2016; Schöggl et al., 2020; Schroeder et al., 2018), and various articles present a critical perspective stating that sustainability should not be considered a default consequence of CE (Blum et al., 2020; Calisto Friant et al., 2020; Corvellec et al., 2021; Millar et al., 2019). Throughout the articles of this thesis, this position is followed as well: CE is here interpreted as a toolbox of resource-efficiency strategies aimed at achieving positive impacts on the environmental, social and economic dimensions of sustainability, meaning that CE (or resource-efficiency) should not be a goal in itself.

This understanding of CE has direct consequences for its assessment, which becomes focused on assessing the sustainability impacts of CE strategies rather than determining a 'level of circularity'. For such impact assessment, existing methods such as Life Cycle Assessment (LCA) are available, and their application to assessment CE strategies has been evaluated by various authors and is currently gaining popularity (Niero & Kalbar, 2019; Pena et al., 2020). LCA is a standardized method (ISO 2006a; ISO 2006b) which allows to assess the potential environmental impacts of a product, process or services throughout its whole life cycle, from raw material extraction to the end-of-life (Guinée, 2002). LCA also occurs frequently among inventories of CE assessment approaches (Corona et al., 2019; Merli et al., 2018; Sassanelli et al., 2019). This emerging usefulness of LCA to assess the impacts of CE leads to the hypothesis that existing assessment tools can be used by companies to assess CE.

1.4.2.2 Methods and validation

To investigate the state-of-the-art of available CE assessment approaches for companies, two methods are applied: a systematic literature review and a review-of-reviews and comparative analysis.

Systematic literature review

The first method a systematic literature review (Grant & Booth, 2009; Snyder, 2019). It is used to inventory publications that propose approaches, methods, and tools to assess CE at micro level, after which their characteristics are categorized. While previous inventories of CE assessment approaches have been published, only a limited number focused on the micro level and none included a review of implementation considerations and inclusion of end-user needs. In the presented systematic literature review, a critical reflection on their methodological coherence allows to formulate key desirable properties of CE assessment. The review includes both peer-reviewed journals articles as well as conferences papers. The search was limited to publications in English, and was focused on key words. Grey literature has not been included, because of, among other reasons, the absence of a searchable grey literature database. However, a further study of grey literature assessment and how it relates to the results of LCA is included in the next part of the method for this research question. Scopus and ScienceDirect were used to collect publications, using three categories of search themes: circular economy, evaluation, and micro level. The search period is defined as from 2007 until 2019. Previously conducted CE assessment reviews are consulted to add additional approaches through the snowballing method (Wohlin, 2014). Subsequently, irrelevant papers were filtered out using a specific set of inclusion and exclusion criteria. A second step was to construct a review framework to categorize the characteristics of the inventoried approaches. Four perspectives were used: (i) a general perspective, (ii) a descriptive perspective, (iii) a normative perspective, and (iv) a prescriptive perspective. The results for theses perspective were analyzed to discover underlying patterns and formulate desirable properties of CE assessment.

Review-of-reviews and comparative analysis

The second method that is applied, following the hypothesis that existing methods can be used in CE assessment, is a comparative analysis. It analyzes to what extent grey literature (i.e. non-academic) CE assessment indicators and the LCA method are useful for CE assessment at micro level, and how their results compare. A two-step methodology is used: first, a theoretical overview is given, after which a comparative analysis of grey literature CE indicators and LCA is presented. Those methods are then applied to two different case-studies. The theoretical overview consists of a review-of-reviews of CE metrics at the micro level, aiming to identify existing indicators and their main characteristics. This is complemented by an integrative literature review, providing additional grey literature sources and adding methodological articles that discuss further connections between CE assessment and the LCA method (Snyder, 2019). Through this approach, the use of LCA in CE assessment is synthesized and grey literature indicators to be used in the comparative analysis are selected. This analysis focused on two case-studies in: i) the packaging sector and ii) the food waste management sector. This choice was made to include sectors representing both the "technical" and "biological" cycles (Ellen MacArthur Foundation, 2013). Inventory data related to both case-studies has been obtained starting from two previous studies performed by Salomone et al. (2013) and Mondello et al. (2017). This inventory data was used to calculate seven different grey literature CE metrics, and comparing their results with the results of the previously conducted LCAs.

1.4.2.3 Scientific contribution and thesis outputs

Summary results of systematic literature review

74 academic approaches to assess CE at the micro level (i.e. from material to supply chain level) were inventoried using a systematic literature review. A review framework was applied, evaluating the collected approaches through four review perspectives: a general, descriptive (methodological), normative (inclusion of SD/CE dimensions), and prescriptive (implementation-focused) perspective. Little methodological coherence within the available inventoried approaches was found: various different scales were applied, with the product and company level being the most popular, and the approaches had varying degrees of connection to existing methods, with close to half being related to LCA. Around half, however, were not based on any existing method, and most (almost 70%) of the approaches were designed to be applicable in different sectors. Evaluating the approaches' normative perspective also showed a broad variety of interpretations, with eighteen of the reviewed assessment approaches including all three dimensions of sustainable development (SD), in addition to a resource-focused or 'circular' dimension. Applying the prescriptive perspective, it was found that 20 out of the 74 inventoried approaches are designed in a participatory manner. This finding, in combination with the large variety of interpretations of the methodological and normative aspects might be causing a low uptake of CE assessment approaches by companies. Following the review framework, formulated desirable properties aim to guide the design of future CE assessment approaches with a higher eventual uptake by organizations, while promoting the ability of an CE assessment approach to accurately assess the sustainability of CE processes. These properties include having strong connections with existing sustainability assessment tools, inclusion of the environmental, social and economic dimensions in the assessment, and involving the intended end-user in the design of the assessment approach.

Summary results of review-of-reviews and comparative analysis

The results from the evaluation of the suitability and effectiveness of grey literature CE indicators and the LCA method in measuring circularity at micro level are provided in two parts. Firstly, the theoretical overview of micro level CE assessment showed that CE assessment approaches greatly vary in terms of their methodological structure – a finding that was also highlighted in the literature review on academic approaches. The LCA method occurs often in assessment approaches, and is described by various authors as applicable to CE assessment. Several practices and methodological challenges remain, such as LCAs perceived complexity, data intensity and allocation challenges when considering multiple resource loops. Still, the LCA method is considered an appropriate method to assess the environmental sustainability of CE strategies. Next, a comparative analysis was performed to analyze how the results of LCA and grey-literature indicators compare in analyzing environmental impacts, using case studies on packaging and food waste management. The results from this comparison indicate that, while such grey literature metrics have the potential to assist companies in the measurement of their transition to a CE, they are not always useful to sectors that involve materials from the biosphere. On the other hand, the LCA method enables the assessment of a broad spectrum of environmental impacts. Furthermore, when comparing the outputs of CE metrics and LCA, the results vary strongly depending on the type of grey literature CE indicator that is applied. Trade-offs between CE and environmental sustainability emerge. This points to applying CE indicators with care: strategies that carry good CE results might not deliver good environmental performance.

1.4.3. Company engagement with CE assessment

The second research domain, *company engagement with CE assessment*, has been studied in collaboration with the ESRs from WP5 Anna Walker (ESR 5.1) and Katelin Opferkuch (ESR 5.3).

1.4.3.1 Research gap and hypothesis

As mentioned previously, the level of implementation of CE assessment approaches by companies appears to be limited (Das et al., 2021; Niero & Kalbar, 2019; Stumpf et al., 2019; WBCSD, 2018). Interviewing 39 companies, the World Business Council for Sustainability (WBCSD) indicated that 74% of those companies use self-designed frameworks for measuring circularity (WBCSD, 2018).

Stumpf et al. (2019) analyzed 131 case studies and found that CE indicators from literature play an insignificant role in mainstream industrial assessment practices. The low uptake of CE assessment forms a barrier to CE implementation and prevents the assurance that implemented CE strategies result in their anticipated sustainability impacts (Kristensen & Alberg Mosgaard, 2020; Tecchio et al., 2017).

The process of assessment – i.e. obtaining data on the performance of any system, allowing for its effective management is well-described in literature (Beloff et al., 2004), particularly in the field of sustainability assessment (Johnson & Schaltegger, 2016). Simultaneously, data on the practical use of CE assessment specifically appears to be limited. with scarce empirical evidence on the assessment approaches applied by companies that actively participate in the CE transition (Hartley et al., 2020). The specific relation between – and joint application of - CE and sustainability assessment approaches is currently unknown, and in case companies design their own assessment approaches, the development process is still under researched (Brown et al., 2019; Niero & Kalbar, 2019). Finally, the perceived benefits of - and barriers to - CE assessment have also yet to be studied in detail (De Pascale et al., 2020; Rossi et al., 2020). Following these gaps in scientific literature, the main research question related to company engagement with CE assessment is therefore:

RQ2: How do companies engaged with CE assess CE & sustainability?

From the works referenced previously, it is hypothesized that companies indeed use a mix of tailormade (i.e. self-designed) and existing assessment CE and sustainability approaches.

1.4.3.2 Methods and validation

To provide insights into the assessment experiences of companies, a mixed-methods approach was employed (Creswell & Creswell, 2018). The first method was a semi-quantitative survey, identifying the applied approaches, while the second method consisted of semi-structured interviews to analyze how and why these approaches were used by companies (Adams, 2015). It should be mentioned that the survey and the interviews contained additional questions analyzed in the context of a separate study not included in this thesis (Walker et al., 2021). To identify companies actively engaged with CE practices in Italy and the Netherlands, a purposive sampling method was applied (Hibberts et al., 2012). The survey was sent to 809 companies, of which 155 completed it. The interview sample constitutes a subset of the survey respondents. 43 interviews were conducted through video calls, each with a duration between 45-90 minutes. The interviews were recorded and analyzed afterwards. All data, including the respondent attributes, were imported into the qualitative data analysis software NVivo R1 (QSR International, 2020). The 43 interviews were analyzed using thematic coding (Braun & Clarke, 2006). For the survey data, all survey data was exported from SurveyMonkey into the statistical analysis software IBM SPSS Statistics 26 (IBM, 2020). Descriptive statistics were analyzed through a univariate analysis approach. To identify whether variations in the answers correlated with the respondent' attributes, cross-tabulations were applied, and a contingency coefficient test was done to determine the significance of the correlations (Bartiaux et al., 2018).

1.4.3.3 Scientific contribution and thesis outputs

Analyzing 155 surveys and 43 interviews shows that, while academia has proposed a largely variety of assessment propositions, only few are implemented by companies. Generally, 36% of companies have not applied any of the approaches on either a product- or company level. On product-level, 53% of respondents do not apply any approaches, 7% of respondents apply one approach and the remaining 40% applied two or more approaches. More frequently occurring assessment approaches are so-called tailormade sustainability indicators, both with a life-cycle as well as a direct impact approach, single indicators, e.g. the volume of waste diverted from landfill, and environmental LCA. Large differences between different assessment approaches are observed: methods such as material flow analysis (MFA), the product environmental footprint (PEF), life cycle costing (LCC), and social life cycle assessment (S-LCA) are less frequently applied, while the carbon footprint approach is applied by more than half of the companies. The distinction between CE and sustainability assessment was found to be rarely explicit, but the results overall show that companies perceive sustainability assessment to have a wider scope and also includes the social dimension. CE assessment is more related to the environmental dimension of sustainability and mainly concerned with material use. Also, benefits of – and barriers to – CE assessment were analyzed in the interviews. It was found that companies identify benefits such as supporting external communication and providing strategic insights into resource use. Indicated barriers include the lack of an assessment standard, limited market demand and the presence of only moderate assessment capabilities and capacities.

1.4.4. Design and validation of CE assessment framework SCEIA

1.4.4.1 Research gap and hypothesis

The finding that CE assessment approaches seem to be used relatively rarely by organizations point to a lack of sufficient guidance to companies (Stumpf et al., 2019). Simultaneously, literature indicates that current assessment approaches might have shortcomings that could lead to burden shifting from reduced resource use to increased environmental, economic or social impacts (Corona et al., 2019; Harris et al., 2021). In their strategic decision-making processes related to CE practices, companies are in need of structured guidance – particularly since CE experimentation is often based on intuitive judgements and decisions, instead of on specific decision criteria (Konietzko et al., 2020). This strategic level is particularly relevant due to the fundamental (i.e. strategic) nature of the required changes to business to be able to reach the UN SDGs, among other global sustainability targets (Bonn & Fisher, 2011; Vermeulen, 2018). While indicator selection frameworks have been proposed (Kravchenko et al., 2021), and strategic frameworks for sustainability are available (Calabrese et al., 2019; Hallstedt et al., 2010), no guiding frameworks that include the impact assessment of strategic decision-making related to CE practices are currently available in literature. Exploring the process of designing and validating best practices of CE assessment forms the core of the third research question:

RQ3: How to design best practices for CE assessment at the company level?

Following the results from the (1) previously conducted systematic literature review, (2) comparative analysis and (3) overview of company assessment experiences, it is hypothesized that best practices of CE assessment build on existing assessment methods. Furthermore, they should be designed in cooperation with their end-users (companies), provide a holistic perspective on sustainability and be adjustable accordingly to the company at hand.

1.4.4.2 Methods and validation

To investigate best practices of CE assessment approaches for companies, first, a mixed-methods approach to designing and validating a CE assessment framework was used. Then, this framework was tested in practice using a pilot case study.

Design and validation of best practices for CE assessment

To design and validate best practices for CE assessment, a mixed-methods research design was applied. First, a preliminary framework was designed, using a critical literature review. Then, this preliminary framework was validated, using both an expert panel survey (Blessing, 2002; Kravchenko et al., 2021) and qualitative practitioner focus groups (O.Nyumba et al., 2018). This second research phase is considered a triangulation step: different perspectives are fed back into the preliminary framework to validate its methodological setup (Turner & Turner, 2017). To synthesize the core of the framework, substantiating the links between CE & Sustainable Development (SD), a critical literature review approach is applied to "assess, critique, and synthesize the literature on a research topic in a way that enables new theoretical frameworks and perspectives to emerge" (Snyder, 2019). This core is complemented by fitting methodological properties through a descriptive literature review, using existing CE frameworks (Paré et al., 2015). Next, strategic decision-making literature is consulted to further structure the framework and formulate its application routine. The framework was then validated through the triangulation steps, collecting qualitative data on its practical usefulness and hereby enhancing its effectiveness (Cornwall & Jewkes, 1995). A survey was designed to collect methodological feedback from an expert panel consisting of 4 private sector and 7 academic experts in CE assessment at company level (Blessing, 2002; Kravchenko et al., 2021). After providing them with an explanation of the research objective of the project and the framework, the survey was used to collect expert's comments and amendment proposals to the framework's methods and objectives. All collected feedback was evaluated and suggestions were incorporated when indicated by a majority (>50%) of participants. In the second triangulation step, the revised framework was validated on the basis of feedback by its envisioned end-users: a selection of five companies motivated to assess the sustainability implications of their CE activities. They delivered their considerations through various online focus group sessions (O.Nyumba et al., 2018; Cornwall & Jewkes, 1995). The companies were selected both European (Italy and France) and African (Tanzania, Ghana), with different levels of experience in CE and sustainability assessment. In advance of the focus groups, the companies were provided with documentation and, before each focus group, 30 to 60-minute interviews were held with each company to better understand their business context and assessment experience. The sessions were recorded and analyzed afterwards, and the results were obtained through thematic analysis (Maguire & Delahunt, 2017).

Testing the framework using a pilot case study

The framework was then applied in a real-world setting, in collaboration with a company with the ambition to lower their environmental impacts through the implementation of CE strategies. Due to the modular nature of the previously designed and validated framework and feasibility, the primary focus of the application was the use of LCA in assessing the environmental impacts of to-be-introduced CE strategies. These scenarios were based on market conditions and meetings with the company's management. The Life Cycle Assessment (LCA) methodology was based on the ISO 14.040 (ISO, 2006) standard. Data related to the production process was collected primarily in 2019 and 2020. SimaPro software (version 9.1) supported the data processing and the ecoinvent 3 database was used. The LCA is composed of four main steps: goal and scope definition, inventory analysis, impact assessment and interpretation. The LCA-type is attributional LCA, which was chosen to determine the baseline impact of the system, identifying and describing the environmentally relevant physical flows within the set system boundaries (Finnveden & Potting, 2014). The goal of applying the LCA in the context of the CE assessment framework is twofold: i) to analyze the environmental impact of the company's activities, with the functional unit of the LCA being: the total production and distribution of mineral water packaged in plastic and glass by the company in 2018, and ii) to quantify the environmental improvements of different CE strategies relevant to the company's operations, zooming in on the company's different product types. The selected CE strategies were i) the increased use of secondary (recycled) PET, ii) the increased use of reusable glass bottles, iii) the possibility to electrify the distribution system, iv) use an on-site solar PV system to generate electricity. Input data for the scenarios was partially extracted from relevant literature and other

LCAs. The ecoinvent 3.2 database and impact assessment method ReCiPe (H) were used for the analysis, using foreground data where possible.

1.4.4.3 Scientific contribution and thesis outputs

Design and validation of best practices for CE assessment

From the critical literature review, CE, as a concept, is considered to be valuable only when contributing positively to all three dimensions of sustainability. Next, following the descriptive literature review, an appropriate methodological structure is formulating, matching its previously defined normative core. The result consists of an ex-ante, holistic circular economy (CE) assessment framework called SCEIA (Strategic Circular Economy Impact Assessment), designed to be used at company level. It has five objectives, ranging from the ability to facilitate holistic assessment of CE practices before their introduction, to being applicable to the strategic level of decision-making. The SCEIA framework consists of a selection of methods such as LCA, Life Cycle Costing (LCC), Social Life Cycle Assessment (S-LCA), Material Flow Analysis (MFA) and a materiality assessment (MA) to select the impact domains most relevant to the company and its stakeholders. A Multi Criteria Decision Analysis (MCDA) approach in the form of Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is optional to assist in decision-making. The application procedure of those methods, in a context of decision-making processes with respect to introducing CE strategies, is formulated using existing strategic decision-making literature (Mintzberg et al., 1976).

Next, the framework is validated through a dual triangulation process, consisting of an expert panel survey and online practitioner focus groups with manufacturing companies. From the expert panel's results, several changes to the framework are implemented, such as stronger emphasis on its modular nature, including a 'maturity assessment' to evaluate the company's previous experience with assessment, and a repositioning of the materiality assessment. This revised framework is then presented in focus group sessions with five companies with assessment ambitions. They confirmed the framework's usefulness and highlighted maintaining assessment challenges such as companies' limited sphere of influence, context-related supply chain issues, and data collection challenges. The final SCEIA framework is designed to prevent trade-offs and burden shifting, and to deliver valuable insights in the impacts of company-level CE activities.

Testing the framework using a pilot case study

In testing the SCEIA framework, the company was determined to have low initial experience with CE and sustainability assessment. Therefore, a selection of phases of the framework was applied, and analysis focused on an environmental impact assessment approach. Firstly, the baseline impact of the mineral water company was investigated. The primary environmental impact category used in the analysis was the emission of greenhouse gasses (GHGs). Without accounting for production volume, PET line A showed to be responsible for around 62% of the overall GHG emissions annually. However, when accounting for the production volumes per line, the glass line showed to carry higher GHG emissions per liter of mineral water produced. Zooming in, this was mainly due to the use of the raw materials (glass) in its primary packaging.Next, the expected impacts of applying CE strategies were estimated. The assessed CE strategies all led to lower GHG emissions: using 100% rPET could lead to an overall decrease of 25%, increasing the use of reusable glass to an additional 10%, and, assuming that electricity generated by on-site solar photovoltaic (PV) panels could power all production processes, another 17% reduction could be expected from changing from grid electricity to solar PV. The effect of using electric transport is yet unclear, as literature indicates a range of improvements. While these results provide a first indication of the environmental impact of the to-be-applied CE strategies, they however have been subject to an in-depth LCA study: they are based on rough estimates, using ecoinvent 3 database processes and a specific set of assumptions. Further research will provide more in-depth insights.

With respect to the application of the SCEIA framework, several observations could be highlighted. Firstly, further research could focus on formalizing the current 'maturity assessment' table, zooming in on CE- and sustainability assessment as a trajectory, or a process. In next process steps, further developing the company's assessment maturity, its vision could, for example, be expanded with concrete, measurable impact reduction targets. Other phases of the framework that have currently been amended could be included, such as mapping the company's relevant stakeholders, using their inputs in a materiality assessment (MA). The environmental dimensions could be expanded to the social- and economic dimensions, and the company has expressed interest in doing so. Potentially, a MCDA approach could then be applied in order to select the most impactful yet feasible CE strategy. Besides expanding the assessment maturity and including these phases, the SCEIA framework has shown to be applicable in practice. The current results of this first pilot test case provide a broad indication of the potential impact of several CE strategies, aiding the decision-making process.

1.5. Deliverables of project

Table 3 and table 4 summarize the academic deliverables resulting from the research project.

Table 3. Publications as a lead author.

Type	Title	Authors	Publication outlet	Reference
Journal article	A Critical Review of Academic Approaches, Methods and Tools to Assess Circular Economy at the Micro Level	Erik Roos Lindgreen, Roberta Salomone, Tatiana Reyes.	Sustainability	(Roos Lindgreen et al., 2020)
Journal article	Exploring assessment practices of companies actively engaged with circular economy	Erik Roos Lindgreen, Katelin Opferkuch, Anna Walker, Roberta Salomone, Tatiana Reyes, Andrea Raggi, Alberto Simboli, Walter J.V. Vermeulen, Sandra Caeiro	Business, Strategy & The Environment	(Roos Lindgreen et al., 2021)
Journal article	Exploring the effectiveness of grey literature indicators and Life Cycle Assessment in assessing Circular Economy at the micro level: a comparative analysis.	Erik Roos Lindgreen, Giovanni Mondello, Roberta Salomone, Francesco Lanuzza, Giuseppe Saija	International Journal of Life Cycle Assessment	(Roos Lindgreen et al., 2021)
Conference proceedings	Approaches to evaluate CE at micro level - A systematic literature review	Erik Roos Lindgreen, Roberta Salomone, Tatiana Reyes	Proceedings ISDRS Conference 2019	(Roos Lindgreen et al., 2019)
Conference proceedings	Measuring Circular Economy at the micro level: is the social dimension included?	Erik Roos Lindgreen, Roberta Salomone, Tatiana Reyes	Proceedings AISME2020	(Roos Lindgreen et al., 2020)
Conference proceedings	Assessing Circular Economy at the company level: proposal of an ex-ante evaluation framework	Erik Roos Lindgreen, Roberta Salomone, Tatiana Reyes	Proceedings ISDRS Conference 2021	(Roos Lindgreen et al., 2021)

Table 4. Publications as a co- author.

Type	Title	Authors	Outlet	Reference
Journal article	What is the relation between circular economy and sustainability? Answers from frontrunner companies engaged with circular economy practices	Anna M. Walker, Katelin Opferkuch, Erik Roos Lindgreen, Andrea Raggi, Alberto Simboli, Walter J.V. Vermeulen, Sandra Caeiro, Roberta Salomone	Circular Economy and Sustainability	(Walker et al., 2021)
Journal article	Assessing the social sustainability of circular economy practices: industry perspectives from Italy and the Netherlands	Anna M. Walker, Katelin Opferkuch, Erik Roos Lindgreen, Alberto Simboli, Walter J. V. Vermeulen and Andrea Raggi	Sustainable Production and Consumption	(Walker et al., 2021)
Journal article	Thermodynamic rarity of electrical and electronic waste: Assessment and policy implications for critical materials	Kieran Campbell-Johnston, Erik Roos Lindgreen, Giovanni Mondello, Teresa Maria Gulotta, Walter J.V. Vermeulen, Roberta Salomone	Industrial Ecology	Under review.
Conference proceedings	Life Cycle Assessment for measuring Circular Economy at company level: is it suitable?	Roberta Salomone, Erik Roos Lindgreen, Giovanni Mondello, Tatiana Reyes	Proceedings Italian LCA Network Conference 2019	(Salomone et al., 2019)
Conference proceedings	Assessing circularity and sustainability - A survey-based analysis of companies with circular economy practices	Anna M. Walker, Katelin Opferkuch, Erik Roos Lindgreen, Andrea Raggi, Alberto Simboli, Walter J.V. Vermeulen, Sandra Caeiro, Roberta Salomone	Proceedings ISDRS Conference 2020	(Walker et al., 2020)
Conference proceedings	The relevance of social sustainability when assessing circular economy practices: answers from academia and industry practitioners	Anna M. Walker, Katelin Opferkuch, Erik Roos Lindgreen, Alberto Simboli, Walter J. V. Vermeulen, Andrea Raggi	INFER Conference 2020 Proceedings	(Walker et al., 2020)
Book chapter	Assessing Sustainability in Circular Inter-firm Networks - Insights from circular companies	Anna M. Walker, Katelin Opferkuch, Erik Roos Lindgreen, Alberto Simboli, Walter J. V. Vermeulen, Andrea Raggi	Routledge book "Sustainable Production in the circular economy context: Analysis of the implications for business and society"	Under review.
Conference proceedings	Thermodynamic rarity assessment of WEEE plant	Kieran Campbell-Johnston, Erik Roos Lindgreen, Giovanni Mondello, Teresa Maria Gulotta, Walter Vermeulen, Roberta Salomone	Proceedings Italian LCA Network Conference 2021.	In process.

1.6. Attended scientific conferences

Table 5 below summarizes the scientific conferences the PhD student has attended.

Table 5. Scientific conferences attended.

Date	Location	Event	Title of presentation or conference abstract
06/03/2019 – 07/03/2019	Brussels, Belgium.	European Circular Economy Stakeholder Conference, hosted by the European Commission and the European Economic and Social Committee.	N/A
13/06/2019 – 14/06/2019	Rome, Italy	Italian LCA Network Conference (Rete LCA) 2019.	Life Cycle Assessment for measuring Circular Economy at company level: is it suitable?
26/06/2019 – 28/06/2019	Nanjing, China	International Sustainable Development Research Society (ISDRS) Conference 2019, Nanjing University.	Approaches to evaluate CE at micro level: a systematic literature review.
07/07/2019 – 11/07/2019	Beijing, China	International Conference on Industrial Ecology (ISIE) 2019, Tsinghua University.	A critical review of available CE evaluation approaches at micro level.
28/01/2020 – 28/01/2020	Den Haag, The Netherlands	Symposium: The Circular Economy & Limits to Growth, organized by the Centre for Sustainability.	N/A
13/2/2020 – 14/2/2020	Salerno, Italy.	AISME Conference 2020.	Assessing circular economy at the micro level: is the social dimension included?
03/05/2020 – 07/05/2020	Online	SETAC Europe 30th Annual Meeting	N/A
09/12/2020 – 11/12/2020	Online	Italian LCA Network (Rete LCA) 2020.	Proposing a dynamic company-level framework for Circular Economy assessment.
15/07/2020 – 17/07/2020	Online	International Sustainable Development Research Society (ISDRS) Conference 2020.	Designing the foundations of a dynamic company-level CE assessment framework.
8/9/2021 – 11/9/2021	Graz, Austria	European Roundtable for Sustainability Production and Consumption (ERSCP) Conference, 2021.	Exploring assessment practices of companies actively engaged with circular economy.
22/9/2021 – 24/9/2021	Reggio Calabria, Italy	Italian LCA Network Conference (Rete LCA) 2021.	Thermodynamic rarity assessment of a WEEE plant
12/10/2021 – 14/10/2021	Online	World Resources Forum 2021	N/A

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Chapter 2. A critical review of academic approaches, methods and tools to assess circular economy at the micro level

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Abstract: Transitioning from the current linear economic development model to a circular economy (CE) is a hot topic in academic literature, public governance, and the corporate domain. Actors have implemented CE strategies to reduce their resource use and its associated impacts, while boosting economic competitiveness and generating positive social impact. Companies are identified as key actors in transitioning to a CE, and many academics have proposed tools to assess CE and guide them in this process. This paper critically reviews such academic 'assessment approaches' at the micro level in order to reflect on their key properties. Seventy-four approaches are inventoried through a systematic literature review of academic literature. A critical review framework is constructed and applied, containing four perspectives: A general perspective, a descriptive perspective (methodological aspects), a normative perspective (connections to Sustainable Development), and a prescriptive perspective (implementation-focused). Methodologically, the 74 approaches are highly diverse, having various connections to previously established methodologies. Eighteen of the reviewed assessment approaches include all three dimensions of Sustainable Development (SD), in addition to a 'circular' dimension. Roughly one quarter of the approaches apply a participatory design approach. Suggested key desired properties of CE assessment approaches include making use of existing assessment methodologies such as Life Cycle Assessment (LCA), and a closer collaboration between science and practitioners to consider end-user needs in the design of CE assessment approaches.

Keywords: circular economy; sustainable development; circularity metrics; sustainability assessment; micro level; corporate sustainability

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1. Introduction

Our current global economic development model revolves mostly around linear flows of materials and energy (Korhonen et al., 2018). This model generates waste, depletes natural resources, leads to emissions, and transforms natural landscapes, resulting in a complex web of pressing interlinked environmental, social, and economic problems (Geissdoerfer et al., 2017). The interest in replacing our current linear economic model with a circular economy (CE) model to facilitate moving towards a more sustainable society, has grown rapidly in the past 5–10 years (Reike et al., 2018).

Many definitions of CE are available (Kirchherr et al., 2017). One of the primary goals of establishing a CE has been described as decoupling global economic development from finite resource consumption by introducing closed resource loops, leading to reduced environmental degradation and positive social impacts while stimulating economic growth (Cullen, 2017; EMF, 2013). While the various roles of actors in moving towards a CE have not been formalized in literature, companies are expected to drive this transition (Urbinati et al., 2017), since firms are the entities that transform resources such as raw materials (natural capital) into goods and services (man-made capital) (Azapagic, 2003; Malovics et al., 2008).

A new field of research focuses on understanding how to assess CE at micro (products, firms), meso (industrial symbiosis networks), and macro (city, country, and beyond) level (Geng et al., 2012). Among other reasons, CE assessment tools are said to contribute to the advancement of the concept by facilitating information exchange, monitoring progress, inform decision-making, and improve circular business investment decisions (EEA, 2016; Saidani et al., 2019). Linder et al. (2017) summarize these reasons by referring to the idiom "what gets measured gets managed" (p. 545). At the same time, the absence of broadly accepted metrics has been described as a barrier to transitioning to a CE. Tecchio et al. (2017) for example, note that "the absence of adequate metrics and standards has been a key barrier to the inclusion of resource efficiency requirements" (p. 1533). Niero & Kalbar (2019) find that companies in the fast-moving consumer goods sector make limited use of performance indicators or quantitative CE assessments in their implementation of CE-related policies. Only a small fraction of investigated organizations presents a dedicated set of key performance indicators (KPIs) to their approach to CE. Similarly, some studies point towards low consciousness of the CE potential across various industries, and even lower levels of "alleged CE maturity" (Cristoni & Tonelli, 2018) (p. 107). Among others, Lieder & Rashid (2016) touch upon the importance of CE measurement tools by stating that to "(…) enable and accelerate CE transition driven by industry, integrative decision support tools to identify and tap potentials of CE transition scenarios on company and inter-company level are necessary" (p. 48).

In summary, the field of CE assessment has a low level of maturity, and the level of implementation of CE assessment approaches by organizations appears to be limited. This forms a barrier to transitioning to a more circular—and sustainable—society. To be able to explain the current lack of uptake and stimulate progress, this paper has two research objectives: (1) To categorize the characteristics of available academic approaches, methods, and tools to assess CE at the micro level; and (2) after applying the categorization, to suggest key desired properties of CE assessment at the micro level that guide future research. Both objectives aim to support the conceptual development and accelerate the uptake of CE assessment on the micro level.

The first research objective is realized by carrying out a systematic academic literature review, providing a complete overview of such 'micro level assessment approaches' from academic literature, and then applying a newly proposed critical review framework. This framework contains four perspectives: (i) A general perspective, (ii) a descriptive perspective (methodological foundations), (iii) a normative perspective (addressing sustainable development as the end goal of CE), and (iv) a prescriptive perspective (participatory construction methods and questions of implementation). For the second objective, the present research reflects on the coherence within the group of inventoried approaches after applying the review framework and, where possible, formulates key desired properties addressing the potential lack of consensus. Where this is not possible, directions for future research are indicated. The desired properties are formulated to satisfy two criteria: To promote the ability of CE assessment approaches to accurately assess the sustainability of CE processes, and to inform the design of future CE assessment approaches with a higher uptake by organizations.

The structure of this paper is as follows. In the second section, the interpretation of CE is presented and complemented with an overview of previous reviews of available CE assessment approaches. Hereby, the current state of the CE measurement research field is described, and the added value of the research here proposed is highlighted. In Section 3, the material and methods are described, and the core concepts relevant to conducting the systematic literature are addressed: i.e., the use of the term 'assessment approaches' and the interpretation of the term 'micro level'. In addition, Section 3 contains the systematic literature review methodology and a newly proposed critical review framework. Next, the last two sections describe and contextualize the results of the critical review, reflecting on key characteristics. Additionally, to aid the development of future approaches, suggested key desired properties are presented where possible. They are based on critically reflecting on the coherence within the presented results while adhering to the previously mentioned criteria. The final section summarizes the results and identifies directions for future research.

2. Overview of the research context

There is no clear evidence of a single origin or originator of the CE, and there are many definitions and interpretations of the concept available in literature (Kirchherr et al., 2017; Winans et al., 2017). The definition of Blomsma & Brennan (2017) describes CE as a conceptual framing of earlier resource management strategies and interdisciplinary fields. The ideas of exploring resource loops and biomimicry in the field of Industrial Ecology (IE) are notably present in CE (Bruel et al., 2018).

CE is sometimes interpreted as a vehicle to facilitate moving towards Sustainable Development (SD). Some authors specifically zoom in on the relationships between the two unbounded concepts

(Geissdoerfer et al., 2017). Millar et al. (2019) challenge the proposition that implementing CE is facilitating a move towards SD, while Sauvé et al. (2016) critically evaluate some epistemological problems of both concepts. In Kirchherr et al. (2017) reviewing available CE definitions, it is found that only a few studies link CE to all three dimensions of SD (society, economy, and environment). Overall, the relation between the two multifaceted concepts is undecided and strongly depends on the interpretation of CE. However, recent literature focusing on CE indicators often considers SD to be the desired end goal of circular strategies (Corona et al., 2019), and states that, for CE to successfully support SD, all three dimensions of sustainability must be included (Kristensen & Alberg Mosgaard, 2020). The authors of the study presented here have adopted this view as well.

Another principal component of CE is the presence of a hierarchy in ‘circularity strategies’ that are part of CE as a resource management model (Bocken et al., 2016; EMF, 2013; Zielińska, 2019). Resource management options that appear ‘higher’ in the hierarchy are presumed to be more beneficial in terms of environmental, economic and, although to less-formalized extend, social impacts. In literature on CE, such hierarchical resource management options are often referred to as ‘R-strategies’ or simply ‘Rs’: Resource value retention options (Reike et al., 2018).

In the study here presented, the concept of CE is interpreted as an umbrella concept: “A broad concept or idea used loosely to encompass and account for a set of diverse phenomena” (Blomsma & Brennan, 2017; Hirsch & Levin, 1999) (p. 604). Three fundamental principles can be identified (Figure 1): (1) CE focuses on value retention of resources, aiming at a decoupling of raw material extraction and growth, (2) the framework of CE options is hierarchical and guides preferred priorities in resource management options, and (3) CE is aimed at generating multi-dimensional impact with the overall end goal to facilitate reaching SD.

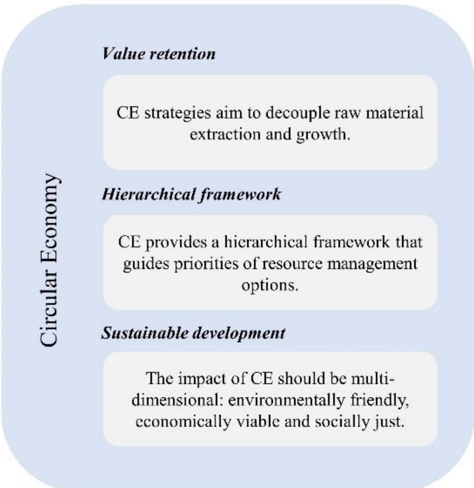

Figure 1. Interpretation of Circular Economy (CE) concept.

Research interest in the field of assessing CE at the micro level is expanding rapidly, and various authors have recently inventoried CE assessment approaches. Inventories and reviews that include the micro level perspective and are thus relevant to this study are summarized in Table 1.

Particularly relevant is the recent review by Kristensen & Alberg Mosgaard (2020) in which the authors collected, categorized, and assessed micro level indicators for a CE. The analysis presented in the present study carries some similarities, albeit with a slightly different scope (i.e., addition of CE- or resource-centered dimension) and different results. Corona et al. (2019) recently carried out a critical assessment of current circularity metrics, reviewing them on the basis of their validity: The degree to which a "metric measures what it intends to measure". The authors offer an extensive reflection on connections between the metrics and various methodologies and find that none of them fulfil their previously formulated validity requirements. Worth mentioning is the previously mentioned taxonomy of 55 sets of C-indicators on various levels by Saidani et al. (2019). The authors categorize the indicators based on, among other criteria, their 'transversality' (being generically applicable or sector-specific), level of CE implementation, and performance (intrinsic or consequential). Another publication applies a Multiple Correspondence Analysis (MCA) to assess 63 CE metrics and 24 features relevant to CE (Parchomenko et al., 2019). No distinction between micro-, meso- or macro-levels is made by the authors. Moraga et al. (2019) published a classification framework for CE indicators that zooms in on the differences in CE strategies and applied measurement scopes. To illustrate their framework, the authors apply it to quantitative micro level indicators from academic literature and macro scale indicators from the European Commission's 'CE monitoring framework'. The micro level indicators are particularly relevant to the study presented in this paper. The same holds for the work of Sassanelli et al. (2019), in which the authors also conducted a systematic literature review to find and describe 'CE performance assessment methods'. While the scale is not necessarily identical, the inventory's approach and findings are in line with this research and have been used to reflect on the collected approaches here.

The research proposed here presents an updated inventory of micro level assessment approaches. To the authors' knowledge, no previous work has applied the methodological, normative, and implementation-oriented review perspectives here presented (see Section 3.3). Additionally, previous publications do not consider the critical outlook of suggesting desired properties of the micro level assessment approaches.

Table 1. Previous reviews of available CE assessment approaches.

References	Number of Inventoried Approaches	Summary and Differences/Common Aspects with the Review here Proposed
(Corona et al., 2019)	72	Zooms in on 'validity', 'reliability', and 'utility' of metrics, and connection to existing methodologies (Life Cycle Assessment (LCA)/Material Flow Analysis (MFA), no focus on micro level.
(Kristensen & Alberg Mosgaard, 2020)	30	Focus on micro level, zooming in on 'CE categories' and connection to Sustainable Development (SD) dimensions. Less attention for implementation perspective. Also includes grey literature.
(Moraga et al., 2019)	20	Introduces classification framework for CE indicators, both on macro- as well as micro level. Addresses different CE strategies captured by indicators.
(Parchomenko et al., 2019)	63	Applies Multiple Correspondence Analysis (MCA) to assess metrics. No distinction between different levels of assessment.
(Saidani et al., 2019)	55	Proposes intricate taxonomy of indicators, applying 10 differentiation categories.
(Sassanelli et al., 2019)	45	Collects and reviews CE performance assessment methods. Primary focus on methodological foundation. No specification of level of assessment.

3. Materials and methods

This critical review focuses on academic publications that propose approaches, methods, and tools to assess CE at micro level. It has been carried out in order to provide an overview of CE 'assessment approaches' at the micro level and to enable the categorization of their characteristics. As a second objective, a critical reflection on the methodological coherence within the group of inventoried approaches is used to formulate key desired properties. As mentioned, these properties aim to satisfy two criteria: To promote their ability to accurately represent sustainability outcomes and to increase the uptake of future approaches. The literature review method is structured in three main steps: (i) Identification and clarification of the core concepts relevant to conducting the inventory process; (ii) implementation of a systematic literature review of the current state-of-the-art of the academic literature; (iii) developing and applying the review framework.

3.1. Clarification of core concepts

The terminology applied in the process of collecting the 'CE assessment approaches' at 'micro level' is based on the following theoretical foundation:

'Assessment approaches'—In previous research on the measurement of sustainability and CE at the micro level, the term 'indicators' has previously been used widely (Keeble & Berkeley, 2003; Saidani et al., 2019). However, some authors signal that a general understanding or definition of this term appears to be lacking (Kristensen & Alberg Mosgaard, 2020). Academic literature also interchangeably uses other terms for approaches to compress quantitative or qualitative information into manageable units; examples are: Variable, parameter, measure, metric, measurement, dashboard, index, framework, etc. (Saidani et al., 2019; Veleva & Ellenbecker, 2001). Most of them extend their scope beyond the traditional indicator as being a singular point of concentrated information. To capture the wide range of applied terms, in the present study, the term 'assessment approaches' has been used.

'Micro level'—This study focuses on approaches that assess CE on the micro level. Similar to the meso and macro levels, various interpretations of the meaning of this level exist between different assessment disciplines (Corona et al., 2019). In Dopfer et al. (2004), the authors describe the micro level as the "(…) complex structures of rules that constitute systems such as firms" (p. 267). This firm-perspective of the micro level will still include many different levels of scale, such as manufacturing plants (Geng & Doberstein, 2008) products (Kristensen & Alberg Mosgaard, 2020) or suppliers, producers, consumers, and designers (Bruel et al., 2018; Saidani et al., 2019). For the sake of creating a complete overview of available assessment approaches, the micro level is here considered to contain CE elements relevant to the decision-making context within firms. This wide-ranging interpretation includes products, business models, companies, and supply chains. Excluded from the scope are approaches focusing on eco-industrial parks (meso level) and cities, nations, and beyond (macro level).

3.2. Systematic literature review

In the systematic literature review of academic publications focused on CE assessment approaches at micro level, both peer-reviewed journals articles as well as conferences papers are included. The search was limited to publications in English, and was focused on key words. Grey literature and web-based assessment approaches, although potentially useful to organizations, have been omitted since they do not fall within the scope of the research objectives and do often not include documentation on how the proposed approach has been constructed (While some grey literature CE assessment approaches such as the Ellen MacArthur Foundation's (EMF) Material Circularity Indicator (MCI) contain enough documentation and appear to be applied in practice relatively frequently, they have been excluded since they do not originate from the academic community. The same holds for relevant CE standards such as the BS 8001 or Afnor's XP X30-901 standard (BSI, 2017; AFNOR, 2018). For a review that includes grey literature, even if with a different scope, see e.g., (Kristensen & Alberg Mosgaard, 2020). Another reason for exclusion is the absence of a searchable grey literature database enabling a systemic search process.

Academic publications have been collected from Scopus and ScienceDirect by using three categories of search themes: Circular economy, evaluation, and micro level. The search period is defined as from 2007 until 2019. The start date 2007 has been selected since it is generally considered the start of the launch of the development of CE literature, especially in the Chinese context (Kalmykova et al., 2018). The resulting inventory is complemented by applying the snowballing method to previously conducted CE measurement reviews (Wohlin, 2014). The first search category is CE, using key words 'circular economy' or 'circularity'. The second category is assessment, using key words 'assessment' or 'evaluation' or 'measurement' or 'quantification' or 'quantify' or 'tool' or 'metric' or 'indicator'. The third category refers to the micro level: 'Micro', 'company', 'business', 'product', 'supply chain'.

After each search, a selection routine was applied in which irrelevant papers were filtered out. For this, the inclusion and exclusion criteria in Table 2 were applied. The aim of this routine was to obtain a strict selection of papers that propose CE assessment methods on micro level. One example: The combination of the search terms "Circular economy", "Measurement", and "Product" resulted in 47 results in Scopus. After screening the title, abstract, and content of the publications, 16 of these publications were considered to be relevant to the topic of CE assessment approaches. Then, 11 of the publications were added to Mendeley, as five had already been found through search terms previously used. This process, using the same keywords, was then repeated in ScienceDirect.

Table 2. Inclusion and exclusion criteria used in the systematic review process.

Inclusion Criteria	Exclusion Criteria
Academic literature	Grey literature approaches
Micro level approaches	Meso or macro level approaches
Newly proposed CE assessment approaches (i.e., not based on conventional methodologies)	Conventional LCA, Life Cycle Costing (LCC), Social Life Cycle Assessment (S-LCA) studies, eco-design or eco-innovation studies
Approaches that combine or expand existing methodologies or indicators to propose new CE assessment approaches	Conventional eco-design, eco-innovation, and general sustainability assessment-oriented studies
	Applications of existing CE indicators such as Material Circularity Indicator (MCI)

This search process firstly resulted in 315 publications. After an in-depth selection process using the inclusion and exclusion criteria in Table 2, 63 publications remained. Key examples of research publications excluded from the analysis and removed from the search results in this evaluation round are conventional LCA, Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA) studies, eco-design or eco-innovation studies, meso and macro level CE assessments, and studies limited to applying existing CE indicators, such as the Material Circularity Indicator (MCI) (EMF, 2015). The reason for their exclusion is that these merely apply existing methodologies in a CE context, instead of proposing new assessment approaches. LCAs, LCCs, SLCAs, eco-design, eco-innovation, and general sustainability assessment-focused publications are excluded when they are not primarily involved with proposing CE-focused assessment approaches. Other inventories of metrics were also excluded for this reason. However, CE assessment approaches that combine different existing methods (standardized methods, such as LCA, or those proposed by grey literature, such as the MCI by the EMF), use only part of existing methods or expand them, have been included only when CE-focused. Meso and macro level assessment were excluded because they are not within the scope of this research.

To avoid missing certain approaches, in the complementing step, 11 more academic publications from cross-checking previously conducted inventories were added later. The previous inventories that were checked are summarized in Table 1, and the inclusion and exclusion criteria from Table 2 were applied. The structured search process of literature is summarized in Figure 2.

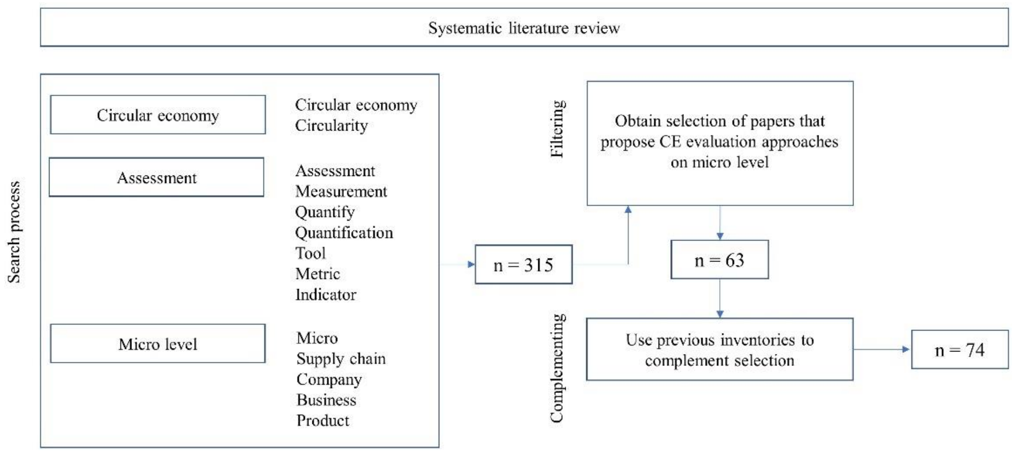

Figure 2. Summary of the structured search process of academic literature.

3.3. The critical review framework

Next, a new review framework was constructed to categorize the characteristics of the inventoried approaches. The review framework consists of four perspectives: (i) A general perspective, (ii) a descriptive perspective (methodological foundation), (iii) a normative perspective (addressing SD as the end goal of CE), and (iv) a prescriptive perspective (participatory construction methods and questions of implementation). The perspectives, their complementary review attributes and analyzed characteristics are summarized in Table 3. The structure of the framework has been inspired by management literature on decision making in a corporate setting, primarily in Bell et al. (1988). Here, a typology of analysis perspectives in a decision-making context is put forward, and, more specifically, the term "prescriptive" as a complement to "normative" and "descriptive" analyses is introduced.

Table 3. The four perspectives of the critical review framework.

Perspective	Goal	Attribute	Analyzed Characteristic
(i) General	To describe published approaches' general characteristics	Age	Year of publication
		Peer-reviewed	Yes/No
		Source	Name of journal, book, or other sources
		Country	Country of home university of author
		Name and abbreviation	Name and abbreviation of the approach
(ii) Descriptive	To assess methodologies underlying the inventoried approaches	Scale of assessment	Determine scale of application within 'micro level', establish categories of scale of application
		Sector specificity	Determine whether the approaches are designed to be applied in a specific sector, and, if so, document which sector
		Connection to existing methodologies	Determine methodological connections by applying search terms 'LCA', 'MFA', 'input output', 'MCI'. Complement after in-depth review of approaches
		Application of case study validation	Screen publications for occurrence of application of proposed approaches in case study setting
(iii) Normative	To obtain a better understanding of connections to the three dimensions of SD	Inclusion of the three SD dimensions	Determine whether and how the environmental, economic, and social dimensions of SD are considered
		Inclusion of 'CE' dimensions	Determine whether and how 'CE' (resource-related) dimensions are considered
(iv)Prescriptive	To evaluate the presence of implementation considerations and inclusion of end-user needs	Providing operational guidance	Does the publication mention 'implementation', 'practitioner', 'operational', or 'application'?
		Participatory approach	Is the end-user mentioned?
			If so, who is the intended end-user?
			Are the end-user or other stakeholders involved in the design of the evaluation approach?
		Ease of communication	Does the publication mention 'simplicity' or 'communication'?

(i) **General perspective**—the first perspective contains the general characteristics of the inventoried approaches.

(ii) **Descriptive perspective: Methodological connections**—according to Bell et al. (1988), descriptive analysis engages with what has happened in the past to better understand current phenomena. The question becomes: 'How has research constructed previous approaches to assess CE?' This leads to evaluating the following methodological traits:

- Scale of assessment—the micro scale of evaluation still contains a variety of sub-scales, and no scientific consensus on its definition exists. The entire range of categories of different micro level scales of assessment has been included in the review.
- Sector specificity—since product- and firm heterogeneity appear not to have been addressed in detail in literature, sector specificity has been included as an element of interest in the descriptive dimension of the critical review framework. The type of sector was analyzed as well.
- Connection to existing methodologies (LCA/MFA/input-output analyses)—it will be valuable to explore how decades of knowledge on sustainability quantification, resulting in the development of widely used tools, are exhibited in newly introduced concepts such as CE. Therefore, the connections between CE assessment and LCA, S-LCA, LCC, MFA, and input–output analysis have been included. These methods were later completed by frequently occurring underlying methods that were used in combination with other methods (i.e., MCI).
- Case study and validation—to test the practical application of their proposed approaches, authors use case studies as a source for input data. The inventoried publications were screened for the application of a validation approach using case study data.

(iii) Normative perspective: SD as the end goal of CE—Bell et al. (1988) describe a normative model as "(…) an abstract system that attempts to capture how ideal people behave" (p. 17). In stakeholder theory, the concept of a 'normative core' has been described as explicitly moral, and an effort to answer questions such as: 'What is the purpose of the firm?' (Parmar et al., 2010). In the context of CE assessment, this results in the question: 'What should the ideal outcome of applying CE be for the concept to be valuable?' The concept of CE is here interpreted to be valuable only when providing a pathway to SD (see Section 2). Hereby, this study intends to address (valid) criticisms of CE that state that resource-efficiency measures do not lead to sustainable outcomes per se (see e.g. Millar et al. (2019)). The present research refers to the model of sustainable development cited in Azapagic (2003), proposing SD indicators in the environmental, economic, and social domain. When other dimensions are included, it is checked whether these belong to any of these categories or are more suited to the separate 'circular' dimension, which could be seen as a box containing any resource-efficiency related dimensions.

(iv) Prescriptive perspective: Participatory design and questions of implementation—lastly, Bell et al. (1988) introduce the prescriptive decision-making model. This model addresses the question: "What should an individual do to make better choices? What modes of thought, decision aids, conceptual schemes are useful—useful not for idealized, mythical, de-psychologized automate—but for real people?" (p. 17). A very practical perspective that incorporates human—and organizational—limitations emerges. Three implementation-oriented prescriptive attributes are considered: The presence of providing operational guidance is assessed through using the search terms 'implementation', 'practitioner', 'operational', and 'application'. The application of a participatory approach was assessed in three steps: (1) By reviewing whether the intended end-user of the approach is mentioned, (2) if so, what the characteristics of these end-users are, and (3) whether end-users were involved in the design of the proposed approach. The authors' consideration of ease of communication is evaluated through searching for 'simplicity' and 'communication', 'user friendly', 'intuitive', and 'visualization'.

In addition to describing the results for each of the attributes of the perspectives above, the connections between the attributes of the descriptive, normative, and prescriptive perspective have also been analyzed to discover underlying patterns. The goal of this analysis was to discover the extent to which each attribute is linked to the others (i.e., do product-level assessment approaches more often employ the LCA methodology?). All combinations between attributes have been checked and the most relevant discovered patterns are described in the results section.

4. Results

In the following sections, the findings from the analysis of the inventoried 74 CE evaluation approaches at micro level are discussed according to the four dimensions of the proposed review framework. The general results can be retrieved in Appendix A, whereas more specific results for each perspective are presented below.

4.1. General attributes

Most of the inventoried approaches originate from peer-reviewed academic publications (60), while the remaining 14 are published in conference papers. Some journals that appear often are the Journal of Cleaner Production (17 times), Resources, Conservation, and Recycling (8 times), and Procedia CIRP for conference papers (7 times). As presented in Figure 3, the field is very young: Only 6 publications from before 2016 are included in the inventory. Presented on the right side of the graph, European countries such as Italy (9), the Netherlands (9), the United Kingdom (8), and Denmark (6) are well-represented. Only 15 publications are from outside of the EU. Research attention appears to have decreased slightly after its peak in 2018, but at the moment it is not possible to interpret this as a decline of interest or a simple oscillatory trend.

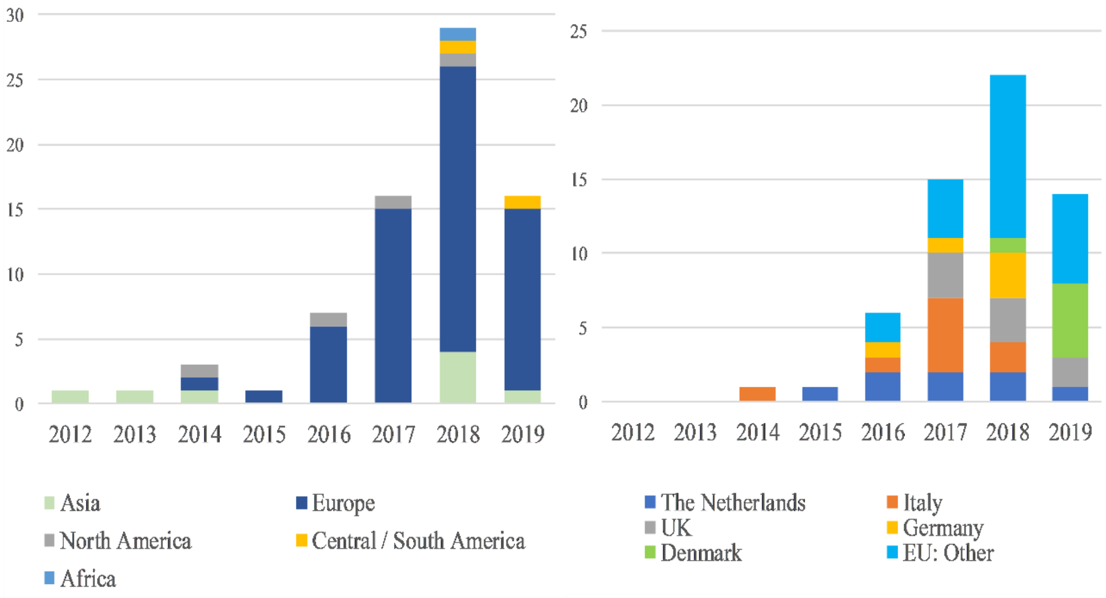

Figure 3. Publication dates of the inventoried approaches (globally and in Europe).

4.2. Descriptive perspective: methodological attributes

The inventoried approaches use a large variety of scales. As displayed in Table 4, most approaches focus on product (22) or company level (12). For the product level, some approaches are, to a varying extent, tailored to specific product categories. Within these, again, the products are very heterogeneous in size, composition, and use; for instance, compare the indicator for pharmaceuticals by Sheldon (2018) and the tool for evaluating the end-of-life performance of a hybrid scooter by Berzi et al. (2016). 'Business model' is technically not a scale of assessment, thus it was not among the search terms; it has nevertheless been included as a separate category because of its frequent occurrence, especially in relation with Product-Service Systems (PSS). Similarly, although 'material' was not explicitly included in the search terms, 4 of the approaches focus on the level of materials.

Table 4. Scales of assessment.

Scale	Approaches (N.)	General (N.)	Detailed (N.)
Product	22	Product (16)	Chemicals (1), energy-related product (1), gypsum product (1), automotive vehicle (1), product family (1), end-of-life product (1)
Company	12	Company (9)	Small and Medium-sized Enterprise (SME) (2), Circular Economy initiative (1)
Business model	11	Business model (6)	Product-Service System (5)
Other	9	-	Building (2), component (1), technology (1), sector/industry (1), farm (1), event (1), strategy (1), innovation (1)
Supply chain	6	Supply chain (6)	-
Material	4	Material (2)	Biobased polymers (1), waste (1)

Packaging	4	Product packaging (3)	Packaging chain (1)
Plant/installation	3	-	Treatment plant (1), installation (1), Wastewater Treatment (WWT) plant (1)
Various scales	3	-	Materials and products (1), products, services, or processes (1), company or strategy (1)
Total	74	42	32

Concerning sector specificity, 30% of the inventoried approaches are developed with the intention to be applied to a specific sector, while 69% are designed to be applied across sectors. This is supported by earlier findings by, e.g. Saidani et al. (2019). One publication proposes both a sector-specific as well as general approach (Gnoni et al., 2018).

An example of a widely cited non-sector specific approach in the inventory is the hybrid-LCA approach by Genovese et al. (2017), in which a traditional LCA approach is complemented with a number of ‘CE indicators’: Carbon emissions, kg’s virgin resources used, kg’s waste recovered. The level of assessment is product supply chain, and the proposed approach is applied in two explicitly different sectors: A chemical supply chain and a food supply chain. An example of a well-cited publication that involves a sector-specific approach is Sheldon (2018), in which the case is made that mass-based indicators for green chemistry and CE should be combined with LCA indicators. From comparing the attributes ‘scale of assessment’ and ‘sector specificity’, it is found that approaches designed to assess business model-, company level- or supply chain CE are almost never sector specific (4 out of 29). For the product level, this increases very slightly, but is still low: 7 out of 22 product level approaches are sector specific. As expected, the 7 approaches designed for more specific scales ‘packaging’ and ‘plant/installation’ (7 in total) are all sector-specific.

Regarding the connection to existing methodologies, the LCA methodology is used in 32 approaches (see Table 5). In 14 of those cases, LCA is used in combination with other existing methods. These combined methods are very diverse and include methods such as Material Flow Cost Accounting (Rieckhof & Guenther, 2018) or a Material Reutilization Score (Niero & Kalbar, 2019a). They are summarized in Table 6. Besides LCA, other methods appear to be used on the micro level: MFA is used in 5 cases, while the previously introduced MCI indicator is used three times. Interestingly, 3 publications apply fuzzy set theory in their works. One example is the case of Gnoni et al. (2018), in which Fuzzy Cognitive Mapping is applied to quantify direct and indirect effects of CE strategies on social, economic, and environmental dimensions. The category ‘other methods’ includes the Cumulative Energy Demand (CED) (Hildebrandt et al., 2017), the ISO 22,628 (ISO, 2020) standard and UNIFE Energy- and Material Recycling Factors (MRF and ERF) (Berzi et al., 2016), and the

Material Security Index (Mohamed Sultan et al., 2017). Deeper methodological connections between LCA and CE have been researched by Corona et al. (2019).

Table 5. Connections to existing methodologies.

Connection with…		Number of Approaches
LCA		32
LCA	18	
LCA + other methods	14	
MFA		5
Fuzzy set theory		3
MCI		3
Other methods		15
No connection to other methods		31

Almost half (31) of the inventoried approaches do not refer explicitly to existing assessment methods, but propose novel methods. The novel methods are highly heterogenous, primarily in terms of output, complicating the task to categorize their methodological development steps: 13 approaches develop a 'CE evaluation framework', the output of 9 consist of a set of indicators, 7 present single indicators, and 2 are classified as 'other form of output' (a computer model and a set of calculations).

In these 31 novel approaches, two forms of alternative methodological development emerged. First, it was found that many approaches made use of external (expert) input to construct and revise the proposed approach: 7 publications used expert input, 3 publications used interviews, 2 studies applied the Delphi method, and 4 publications revised an initial version of the approach after its application in practice. In other cases, the inputs come from students (1), stakeholders (1), users (1), or peers at a conference presentation (1). One publication bases its proposed framework on a previous framework proposed in the literature (Matschewsky, 2019). Eighteen approaches do not use any form of external consultation. Second, the 31 novel approaches often use a literature review approach: 15 papers first review the available existing methods or tools, highlighting and exploiting a gap in research, or building on lessons from the review. The other 16 do not provide such a review. In summary, most publications that do not explicitly refer to existing methodologies use either external expert input, a literature review or a combination of both.

The attributes 'sector specificity' and 'connection to existing methodologies' were analyzed jointly to identify patterns. Almost half (19) of the 43 inventoried approaches that are based on existing methods are designed to be applied to a specific sector. Interestingly, the 31 approaches that are not based on existing methods are much less often designed to be applied specifically: This occurs in only 3 cases.

A large majority of inventoried publications uses case study data to test and apply their proposed approaches. In almost all the 48 approaches that use a case study approach, the case study sector is different. Observing the links between the attributes 'scale of assessment' and 'case study validation', it is found that the company level approaches are not always validated by applying a case study approach (6 out of 12 approaches). On the contrary, for the product level, this ratio is much higher with 20 out of 22 approaches.

Table 6. Combinations of LCA and other methods.

Reference	Method
(Bradley et al., 2016)	LCA, LCC, S-LCA
(Cobo et al., 2018)	LCA, MFA, multi-objective optimization
(Fregonara et al., 2017)	LCA, LCC
(Garcia-Muiña et al., 2018)	LCA, LCC, S-LCA
(Genovese et al., 2017)	LCA, Environmental Input-Output (EIO)
(Huysveld et al., 2019)	LCA, Recyclability Benefit Rate (RBR), Recycled Content Benefit Rate (RCBR)
(Kiselev et al., 2019)	LCA, MFA
(Koch et al., 2018)	LCA, MFA, Constructive Technology Assessment (CTA), input-output analysis, LCC, Cost-Benefit Analysis (CBA)
(Niero & Kalbar, 2019a)	LCA, Material Reutilization Score (MRS), MCI
(Pauliuk, 2018a)	LCA, MFA, LCC, S-LCA
(Rieckhof & Guenther, 2018)	LCA, Material Flow Cost Accounting (MFCA)
(Sheldon, 2018)	LCA, E-factor
(Vaneeckhaute et al., 2018)	LCA, Net Present Value, Internal Rate of Return, questionnaire on stakeholder perception
(Verberne, 2016)	LCA, Environmental Product Declaration

4.3. Normative perspective: SD as the end goal of CE

The results for the application of the normative perspective to the inventoried approaches are described in Table 7. Eighteen of the approaches consider the three environmental, economic, and social domains of SD while also including a 'circular' dimension. On the other side of the spectrum, 20 approaches only include the circular dimension, which is interpreted differently by almost every author. Without the space to zoom in on all of them, some examples are: kg's of waste produced over lifecycle (Laurenti et al., 2018), ease of disassembly of products (Vanegas et al., 2018), materials quality and energy quality (Steinmann et al., 2019), and material efficiency (Braun et al., 2018). Seven approaches only include the environmental dimension in their assessment process, while 3 consider only the economic domain. Other groups of approaches combine information on the environmental and circular dimension (11 approaches), economic and circular dimension (1), or economic and environmental dimensions (3).

Some insights above have been previously described in literature. For example, the social dimension of CE is generally considered underrepresented (Kirchherr et al., 2017). In this study, it is found to be included in only 20 of the 74 proposed assessment approaches; these are the approaches that consider all three dimensions of sustainability. Additionally, the high amount of assessment approaches that focus on explicit CE characteristics is remarkable. Such approaches can be interpreted to fall under the umbrella of 'intrinsic' indicators (Saidani et al., 2019). They deliberately focus on 'CE' as a dimension of evaluation, instead of also including environmental, economic, and social impacts; an example is product-level circularity (Linder et al., 2017). Other studies, such as Bradley et al. (2016) or Gnoni et al. (2018) combine CE-dimensions with impacts on the three sustainability domains; essentially, they hereby interpret CE as a resource-efficiency based means to achieve SD. These approaches can perhaps also be said to be more in line with the characteristic of 'consequential' circularity (Saidani et al., 2019).

When comparing the results to the outcomes of Kristensen & Alberg Mosgaard (2020), some interesting differences can be noted. In Kristensen & Alberg Mosgaard (2020), the economic dimension is included most frequently: 17 out of the 30 indicators directly include economic parameters, and two indirectly. At the same time, the environmental dimension is included 12 times. In the present study, the environmental dimension (45) is included more often than the economic dimension (31). The difference is most likely caused by small differences in search terms and the selection process afterwards. The results of both studies for the social dimension are however quite similar, with an even more visible underrepresentation discovered in Kristensen & Alberg Mosgaard (2020): only 4 out of 30 indicators include the social dimension, predominantly focusing on job creation.

Subsequently, links between the descriptive and normative attributes were analyzed. When comparing 'scale of assessment' and the included dimensions, it was found that company-level approaches relatively often (7 out of 12) include the three SD dimensions as well as an additional resource efficiency-related parameter. For the business model scale, this ratio is 4 out of 11, while for the product level, it is much lower: Only 3 out of 22. This indicates that researchers more often use a holistic perspective when considering company level assessment than product level assessment. The other dimensions follow this general pattern as well. Zooming in on the product level, half of the approaches only include the single 'resource efficiency' dimension. The environmental- and economic dimension is included in 8 out of 22 approaches, while the social dimension only occurs in three out of 22 product level CE assessment approaches.

In addition, patterns between the attributes 'presence of existing methods' and the SD dimensions were analyzed. As expected, the connection between the underlying methods, and particularly with LCA, is strongly visible in the approaches that include the environmental dimension. Out these 45 approaches, 32 are based on LCA, or LCA in combination with other existing methods. For the approaches that include the economic dimension, this is slightly less obvious: Out of 31, only 18 use existing underlying methods, consisting of LCC. When focusing on the social dimension, which is included in 20 of the underlying methods, only 6 use S-LCA. Interestingly, with respect to the 18 approaches that offer a holistic view on CE and SD, 8 of these approaches are not based on existing methods. An example is Kristensen & Remmen (2019), proposing a qualitative sustainable value proposition framework based on narrowing, slowing, and closing resource loops.

Lastly, when considering the presence of case studies and the included dimensions, a potentially interesting finding is that the inventoried 'holistic' approaches are more likely to lack a case study approach (7 out of 18 approaches do not apply this) than the 'non-holistic' approaches, in which 9 out of 56 approaches do not apply a case study. Again, although the numbers are small, this could point towards the practical limitations that occur when researching CE assessment: Company level data in all three sustainability domains might not always be readily available, especially when considering the social and economic domains.

Table 7. Sustainable Development as goal of Circular Economy.

Number of Approaches	Environment	Economic	Social	Circular
18	X	X	X	X
2	X	X	X	
4	X	X		X
3	X	X		
11	X			X
1		X		X
7	X			
3		X		
25				X
74	45	31	20	59

4.4. Prescriptive perspective: participatory construction and questions of implementation

Lastly, the inventoried approaches are reviewed using the prescriptive perspective. They are screened for any form of operational guidance, mention of ease of communication, and application of participatory construction method in the design of the approaches. The findings show that 18 out of 74 approaches provide suggestions or guidance for the implementation of the proposed approaches. The operational guidance provided is often very brief. For example, Shen et al. (2013) provide a paragraph called 'managerial implications' that briefly describes how managers and supplier organizations can use their proposed approach for evaluating green supplier's performance. Another example is found in Barletta et al. (2018), albeit in a different form; the paper mentions: "(…) an organization that evaluates a new PSS must either have employees whom are LCA practitioners or must outsource these skills" (p. 722), providing a suggestion on the starting point of carrying out an environmental assessment of product-service systems (PSS). Rieckhof & Guenther (2018) present an extended table containing integrated LCA and MFCA implementation steps; interestingly, many of these steps also provide insights to companies on how to organize CE data collection, suitability, and quality control. Elia et al. (2017) make valuable remarks on the existence of top-down and bottom-up CE indicators, whereas the last are based also on appreciation of the preoccupations expressed by stakeholders.

Regarding the intended end-users of the proposed approaches, it emerges that in 27% of the inventoried approaches, the indented end-user, i.e., person or entity responsible for eventual application, is not mentioned. The remaining 54 approaches are intended to be used by a highly heterogeneous collection of users, as visualized in Figure 4.

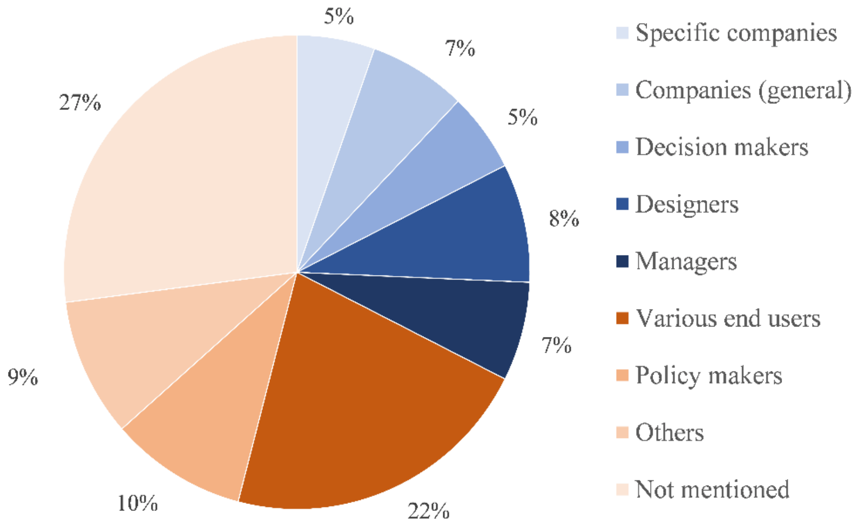

Figure 4. Intended end-users mentioned in CE assessment approaches.

As can be seen in the figure, authors sometimes mention ‘companies’, either specific or general, as end-users, while not specifying the position or function of the person(s) that will eventually apply the approach. Examples of specific companies are ‘manufacturing enterprises’ (Braun et al., 2018), ‘initiatives relating to the CE’ (Walker et al., 2018), and ‘small- and medium sized companies’ (Prieto-Sandoval et al., 2018). A detailed description of the intended company is provided in Cayzer et al. (2017), listing both the necessary skills of the end-users as well as the characteristics of the company (“manufacturing and/or retail companies of tangible goods with access to bill of materials”) (p. 3).

The roles and positions of the end-users that are more specific are often still multi-interpretable or very broad; examples are ‘decision-maker’ or ‘manager’. The relatively frequent occurrence of policy makers as end-users is somewhat unexpected at micro level scale. In the category ‘other’, the following end-users are included: ‘Academia’, ‘CEOs and production managers of manufacturing companies’, ‘consumers’, ‘industrial practitioners’, ‘non-experts’, ‘R&D managers and investors’, and ‘stakeholders’.

Sixteen approaches address their intended audience by listing multiple potential end-users, sometimes depending on the intended goal of analyzing an organization’s degree of circularity. For example, Mesa et al. (2018) describe how “the use of a particular set of sustainability indicators depends on the stakeholders involved in the case study analyzed. Therefore, the modifications during early design phases are strongly related to the interest and addressing efforts established by the designer, manufacturer or the company” (p. 1441). Some other authors, such as Mohamed Sultan et al. (2017) more straightforwardly list various end-users, in this case ‘other researchers, companies, countries, and stakeholders’. Similarly, Bertoni (2019) mentions both ‘process owners’ as well as ‘industrial practitioners’ as intended end-users. A more specific example is provided in Barletta et al. (2018), stating that the organization that evaluates a Product-Service System (PSS) must “either have employees whom are LCA practitioners or must outsource these skills” (p. 721).

With regards to involving these end-users in the design of the proposed approaches, it is found that 20 out of the 74 inventoried approaches are designed in a participatory manner. Some examples are listed hereafter. The Delphi method, a process for structuring communication processes in order to obtain consensus on complex issues, is used sometimes. Prieto-Sandoval et al. (2018)use this process in their participatory identification process of crucial CE elements in implementation in SMEs. Still, their participants are not necessarily involved in the application of a CE measurement tool as they consist of academia and consultants. Other studies focus on including stakeholder perceptions of CE. In a study by Vaneeckhaute et al. (2018), stakeholder perception is investigated to understand what drives stakeholders to utilize biofertilizer. It is not necessarily participatory in the sense that it does not involve end-user feedback for constructing an assessment approach, but it does involve the end-users of the system under assessment in the decision-making process. A study that clearly involves end-users is Ceptureanu et al. (2018), where surveys are used to link CE principles to business actions, specifically focusing on Romanian SMEs operating in the PVC joinery industry. The paper's approach is aimed at aiding entrepreneurs in "assessing and choosing the most suitable circular business model or set of business actions for their business" (p. 321). Bertoni (2019) explicitly includes participatory elements in their PSS assessment process, describing how, for example, "processes and tools for PSS assessment shall then be designed to facilitate participation in the definition of the evaluation criteria, mixing value- and sustainability-related considerations" (p. 2). Last, yet another participatory approach is found in Lee et al. (2014): in this case, the authors' approach to constructing a framework for end-of-life evaluation is guided by the preferences of designers, who are the end-users of the proposed tool.

It is found that in 17 out of the 74 approaches, the ease of communication is considered as a criterium for a well-functioning approach. For example, in Howard et al. (2018) CE indicators are described to fulfill purposes of monitoring, reporting, and "communicating progress towards the CE". Similarly, in describing the desired characteristics of a disassembly standard, Vanegas et al. (2018) mention the ability to "facilitate communication of product information to consumers to encourage comparison of ecodesign performances of products" (p. 326). More detail to the communication process is provided in Lee et al. (2014), in which an information management framework is presented that shows how designers and end-of-life managers should communicate. Ease of communication is in some cases incorporated through the visual presentation of the end result of a proposed CE assessment approach, see, e.g., in Fatimah & Aman (2018) and Van Schaik & Reuter (2016).

While many combinations did not result in any emerging patterns, some findings emerge when prescriptive attributes are analyzed in combination with the previous descriptive and normative attributes. Firstly, when comparing the presence of operational guidance with the attribute 'sector specificity', it emerges that of the 18 approaches that provide operational guidance, only 1 is sector-specific, while the others are designed to be applicable to various sectors. Contrarily, for the 56 approaches that do not offer guidance, 21 are sector-specific. This is unexpected: More focused approaches might be expected to offer more in terms of operational assistance. A similar pattern appears when zooming in on sector specificity and 'ease of communication': Of the 17 approaches that acknowledge that 'ease of communication' is important to a well-functioning approach, only 2 are sector specific.

The various attributes within the prescriptive perspective have also been analyzed comparatively. It is found that, for example, the 20 participatory approaches do not necessarily offer operational guidance; they do so in only 7 out of 20 cases. Vice versa, the 18 studies that offer operational guidance are not participatory in 11 cases. When studying the participatory approaches' end-users, most of these approaches are spread out relatively equally over the various intended end-users, and an interesting observation is that the 4 end-users' (specific) companies include 3 participatory approaches. The 20 approaches for which the end-user is not mentioned are much less likely to be participatory: Only 2 cases are designed in a participatory way. Other observed patterns can be said to be more in line with expectations. For example, almost all (18 out of 20) participatory approaches use a case study to validate their proposed approach.

5. Critical reflection and suggested key desired properties

Inventorying available approaches and applying the review framework provided insights into the first research objective of the present study: To enable a categorization of the characteristics of available academic approaches to assess CE at the micro level. Next, the second research objective of providing key desired properties of CE assessment at the micro level to guide future research is addressed. For this, the coherence of the results (i.e., how previous research addresses CE assessment) is reviewed and where possible, key desired properties addressing the potential lack of consensus are proposed. These key desired properties are connected to two criteria, emerging from the review framework: To promote the ability of CE assessment approaches to accurately assess the sustainability of CE processes, and to inform the design of future CE assessment approaches with a higher chance of uptake by organizations. The first criterium is connected to the interpretation of CE as an umbrella concept, generating multi-dimensional impact with the overall end goal to facilitate reaching SD (see Section 2 and the description of the normative perspective). The second criterium is selected to highlight that CE assessment approaches carry real-world value only when they are implemented (prescriptive perspective). Where formulating desired properties is not possible, directions for future research are indicated. An overview of the key desired properties is presented in Figure 5.

	Attributes	Desired properties (recommendations)
Descriptive perspective	*Scale*	No recommended scale (dependent on goal of evaluation)
	Sector specificity	Either sector-specific or general with the option to adjust to situation (dynamic and flexible).
	Connection to existing methodologies	Strong connections to existing, sophisticated assessment tools, particularly LCA.
	Application of case study validation	Tested using real-world data.
Normative perspective	*Inclusion of environmental, economic, social, 'circular' (resource-centered) dimensions*	CE as a concept is valuable only when providing a pathway to Sustainable Development (SD). If lacking any of the three dimensions of SD, apply existing assessment tools to complement approach.
Prescriptive perspective	*Providing operational guidance*	Detailed descriptions to guide implementation and operationalization.
	Participatory approach	End-user of approach is specified and strongly involved in design.
	Ease of communication	Communication of output of approach is considered in design.

Figure 5. Summary of desired properties micro level CE assessment.

Descriptive perspective—for this perspective, assessment scale, sector specificity, connection to existing methodologies, and application of case study validation are relevant. The inventoried approaches apply a variety of scales, as shown in Table 4. This is directly linked to the broad interpretation of micro level and the keywords used. It could also be interpreted to reflect the lack of consensus on the question of what constitutes a 'circular' organization. Large multinational companies with complex supply chains might need different tools to assess their circularity than small companies that produce only a single product, for example. These issues have been acknowledged in earlier research on corporate sustainability measurement (Keeble & Berkeley, 2003). Interestingly, in literature on CE evaluation, the connection to this earlier body of sustainability assessment approaches and theory does not seem to be made. Therefore, for this attribute, no suggested desired properties can be highlighted. On the contrary, it can be noted that the different scales likely all have a degree of relevance, depending on the end-user's characteristics and end goal. This can be said to be in line with applying different scales in methodologies such as LCA, in which product-, service-, and organizational level studies can all be relevant in different contexts.

Sector-specific approaches (30%) occur less frequently than approaches designed to be applied across sectors (69%). While the results show no consistent pattern, only future practical application will indicate which is more appropriate in which situation. Nevertheless, it is expected that generally applicable approaches might be more challenging to implement due to the high complexity and heterogeneity of organizations and their activities. Examples are differences in material use (biobased or fossil-based), supply chain complexity, or simply differences in whether an organization is inherently linear and needs transformative change or already operates in line with CE principles. When sketching such differences, approaches that are adequately tailored to the specifics of a sector might appear to offer more potential for change (Kravchenko et al., 2019). Another option could be to design frameworks that offer flexibility and can be adjusted accordingly to the situation at hand. Nevertheless, again, this preliminary finding will need to be tested in practice before any definite statements can be made.

It has emerged that 32 of the inventoried approaches are partly- or completely based on the LCA methodology, while 31 are not based on any previous methodology. In other words, no coherent message on which existing methodology to apply—or whether to apply one—is found in academic literature. Using LCA for evaluating the environmental impact of CE solutions still carries some methodological issues (Corona et al., 2019), and there are some doubts around its complexity and costs (Di Maio & Rem, 2015; Elia et al., 2017). Still, it is currently the most sophisticated environmental assessment methodology available, and less sophisticated tools and methods might not capture the full range of environmental impacts, potentially missing important trade-offs (Walker et al., 2018a). In the light of the current climate- and ecological crisis, missing such trade-offs is undesirable. For the economic- and social dimensions, the less-developed state of the field of measurement is reflected in the low occurrence of S-LCA and LCC methods. Similar to the environmental dimension, it is however recommended to reflect on these impacts using the most sophisticated assessment tools available. Still, further research could elaborate on the usefulness of both tools in a more practical setting.

From the 74 inventoried approaches, 48 use a case study approach for validation. This process, using real-world data, allows for signaling potential risks: e.g., in term of data collection, time consumption, and costs, but also an approach’s ability to accurately reflect a real-world scenario.

Normative perspective—the inventoried approaches show low coherence with respect to which dimensions are included in CE assessment (see Table 7). Eighteen publications include both the 3 domains of SD as well as a ‘circular’ dimension. As presented in Section 2 and considered in the description of the normative perspective of the review framework, the present study considers the concept of CE to be valuable only when providing a pathway to SD, generating positive impacts in the environmental, economic, and social domains. A note should be made that the many approaches that adopt a less holistic view could be combined with existing LCA, LCC (see, e.g., Clement et al. (2009) or S-LCA methodologies. The same holds for the approaches that, for instance, only include the environmental- and CE dimensions: By complementing them with other available tools such as

LCC and S-LCA, or even with available qualitative impact assessment approaches, a comprehensive picture of a decision's impact can still be established.

A lingering issue of the dimension of 'circularity', and perhaps of the concept of CE altogether, is that solutions that perform best in terms of environmental, economic, and social impacts might not be based on resource-efficiency oriented CE principles. This interpretation informs the previously mentioned first criterium for selecting desired properties. Naturally, CE could be interpreted merely as a pathway towards lowering impacts on these dimensions, instead of being a goal in itself. This raises the key question of whether it is worthwhile to, as an organization, evaluate your degree of circularity. Indeed, as many other authors point out, the relation between CE and SD is an assumed one, and should not be considered to be self-evident. The popularity and rapid adaptation of the concept could lead to the risk that decision makers shift their focus from reaching SD to reaching resource-efficiency goals, which might consequently not necessarily have positive overall effects on all the three sustainability dimensions.

Prescriptive perspective—The implementation-oriented attributes appear to have received relatively little attention in the inventoried approaches: Roughly a quarter of the inventoried approaches offers operational guidance, applies a participatory design method, or mentions the ease of communication as an important factor in the design and use of the proposed approaches. As described in Section 3.2., literature on the success factors of implementation of CE or sustainability assessment approaches is scarce. Still, the key factors that prevent implementation by companies are both internal shortcomings, i.e., shortcomings of the implementing organization, and external deficiencies, i.e., shortcomings of the approaches themselves (Johnson & Schaltegger, 2016). From this, it could be argued that a CE assessment approach could be designed by establishing the optimal mix of these two factors; understanding the end-user's desires and limitations in the use of such an approach and making sure the proposed approach matches this appropriately. Incorporating human—and organizational—limitations, potentially leading to higher rates of implementation, can be realized in close collaboration with the end-users of the approach. Remarkably, such a participatory approach has only been observed in 20 out of 74 publications. Returning to the notion of consensus within the inventoried approaches, in around three-quarters of the publications, the needs of the end-user are not considered in the design, potentially making them less likely to be implemented in the future. Perhaps, from this finding, it can be suggested that stimulating closer connections between science and practice might lead to higher uptake of assessment approaches and the concept of CE altogether. Referring to the second criterium for formulating desired priorities, the desired properties of designing future CE assessment approaches at micro level entail closely collaborating with the end-user of the approach, incorporating human and organizational limitations.

6. Conclusions

In this study, approaches to assess CE at the micro level have been inventoried using a systematic literature review. A newly constructed review framework allowed for the application of four review perspectives: A general, descriptive (methodological), normative (inclusion of SD/CE dimensions), and prescriptive (implementation-focused) perspective. Results for each of these perspectives provide insights into academic authors' different interpretations of assessing CE, ultimately arriving at suggestions for desired properties of to-be-designed approaches. Little methodological coherence within the available inventoried approaches was found, while the normative perspective (i.e., the perceived outcome of a CE) also showed a broad variety of interpretations. These two primary findings might, in combination with little attention for the eventual implementation of an approach, be fundamental to the low uptake of CE assessment approaches by organizations. The formulated desired properties aim to guide the design of future CE assessment approaches with a higher eventual uptake by organizations, while promoting the ability of an CE assessment approach to accurately assess the sustainability of CE processes.

This work is limited to approaches that were extracted from academic literature; it could be expanded by reflecting on approaches from grey literature. In particular works by the EMF and various private sector organizations could be added to better understand different interpretations of micro level CE assessment. Additionally, CE assessment approaches that have been developed and implemented by organizations could be collected and studied in a similar manner. For some of the review perspectives, especially the normative and prescriptive perspectives, a clear limitation is that only some elements have been explored. For example, more types of participation could be investigated (see Bell et al. (1988), p. 297). Lastly, a similar review, perhaps expanding the review perspectives, could be undertaken for approaches that are designed for the meso- and macro levels.

After conducting the inventory and review, various gaps in current literature on CE assessment approaches on micro level can be identified. First, the review shows that most approaches are very different in terms of methodology, both when reflecting on their scale of assessment as well as use of existing methodologies. Previous reviews have signaled this as well, and point towards the different understandings of the concept of CE (Corona et al., 2019) or the various interpretations of the micro level (Kristensen & Alberg Mosgaard, 2020) as some of the underlying reasons. With respect to the latter, a gap in understanding what constitutes a 'circular' company becomes apparent. How to deal with supply chain complexity in CE assessment, and how to understand an organization's responsibility in achieving supply chain sustainability is currently investigated by many organizations and academics, and provides much room for further work. Additional transdisciplinary research projects will provide insights into the question whether sector-specific or more generic CE assessment is preferred. The goal of the assessment will be a large determinant in this choice.

Another gap present in the inventoried approaches, and currently receiving much attention in CE literature, is that of the links between CE and SD. The position taken in this article is that CE is considered to be valuable only when providing a pathway towards SD; otherwise, it carries the risk of diverting the attention of solving some of our global climate- and ecological crises by focusing on incremental instead of systemic change, driven by the promises of economic gains through resource efficiency. However, the relation between the two concepts is still fuzzy, in terms of the environmental and economic impacts of CE, and especially in the context of integrating social equity—and related—impacts into CE.

Furthermore, applying the prescriptive perspective of the critical review framework indicated that the connections between academic research and practical implementation of CE assessment approaches are in an early stage. As indicated in the framework of suggested desired properties, this area of research offers many opportunities for further work. Relatively little is known about company needs, operational-, mid-management-, or strategic must-haves and skillsets, decision-making contexts, internal- as well as external barriers to implementation, and other real-world attributes that appear to be relevant to CE assessment. Further research on the assessment of CE could potentially employ a more transdisciplinary research strategy to establish valuable insights into these questions.

Finally, a better understanding of needs, goals, and implementation of CE assessment approaches might also lead to a better understanding of the concept of CE and its role in shaping a sustainable future. As assessments and measurements are part of any adaptive learning system, the rapidly developing field will expose deeper links between the evaluated concepts and their relation to finding practical-, real-world solutions to global challenges (Veleva & Ellenbecker, 2001).

Appendix A

Table A1. Overview of all inventoried approaches.

Reference	Name Approach	Scale	Sector Specific	Connection to Methods	Case Study	Number of SD Dimensions/CE Dimension Included	Provides Operational Guidance	Intended End-User	Ease of Communication	Participatory
(Akrivos et al., 2019)	N/A	Various	No	No	No	0/Yes	No	N/A	No	No
(Alamerew & Brissaud, 2019)	PR-MCDT	Product	No	No	Yes	3/Yes	Yes	Managers	No	Yes
(Angioletti et al., 2017)	CPA (and CPI)	Product	No	No	Yes	0/Yes	No	N/A	No	No
(Ardente & Mathieux, 2014)	REAPro	Product	No	Yes, LCA	Yes	1/Yes	Yes	Various	No	No
(Azevedo et al., 2017)	SCI	Company	No	Yes, MCI	No	3/Yes	Yes	Managers	Yes	No
(Barletta et al., 2018)	e-BEP	Business model	No	Yes, LCA	Yes	1/No	Yes	Other	Yes	Yes
(Bertoni, 2019)	N/A	Business model	No	No	Yes	3/Yes	Yes	Various	Yes	Yes
(Berzi et al., 2016)	N/A	Product	Yes	Yes, ISO 22628, UNIFE (MRF/ERF)	Yes	0/Yes	No	Various	No	No
(Bradley et al., 2016)	N/A	Other	No	Yes, LCA, LCC, S-LCA	Yes	3/Yes	No	Designers	No	No
(Braun et al., 2018)	N/A	Supply chain	No	No	Yes	0/Yes	No	(Specific) companies	No	No
(Bressanelli et al., 2018)	N/A	Company	No	Yes, LCA	Yes	3/Yes	No	Managers	No	Yes
(Cayzer et al., 2017)	CEIP	Product	No	No	Yes	0/Yes	No	(Specific) companies	Yes	Yes
(Ceptureanu et al., 2018)	N/A	Business model	No	No	No	0/Yes	No	N/A	No	Yes

(Cobo et al., 2018)	CI	Plant/installation	Yes	Yes, LCA, MFA, multi-objective optimization	Yes	0/Yes	No	Policy makers	No	Yes
(Cordella et al., 2018)	N/A	Product	Yes	Yes, LCA	No	1/Yes	No	N/A	No	No
(Czikkely et al., 2018)	CEV	Other	No	Yes, MCI and the Korse model	Yes	0/Yes	No	N/A	No	No
(De Pádua Pieroni et al., 2018)	N/A	Business model	No	No	No	3/Yes	No	N/A	No	No
(Di Maio & Rem, 2015)	CEI/KRI	Product	Yes	No	Yes	1/Yes	No	Policy makers	No	No
(Di Maio et al., 2017)	VRE	Other	No	No	Yes	1/No	No	Policy makers	Yes	No
(Elia et al., 2017)	Various	Various scales	No	Yes, LCA	No	1/No	No	N/A	No	No
(Fan et al., 2018)	Environmental-economic assessment	Other	No	Yes, LCA	Yes	2/No	No	N/A	No	No
(Fatimah & Aman, 2018)	RSI	Company	Yes	Yes, LCA	No	3/Yes	No	N/A	Yes	No
(Favi et al., 2017)	N/A	Product	No	No	Yes	2/Yes	No	Designers	No	No
(Figge et al., 2018)	N/A	Company	No	No	Yes	0/Yes	No	Various	No	No
(Flipsen et al., 2017)	Repairability Indicator	Product	Yes	No	Yes	0/Yes	No	Other	No	Yes
(Fogarassy et al., 2017)	CEV	Other	No	No	Yes	0/Yes	No	N/A	No	No
(Franco, 2019)	N/A	Product	No	No	No	0/Yes	No	Various	No	No
(Franklin-Johnson et al., 2016)	Longevity indicator	Product	No	Yes, MFA	Yes	0/Yes	No	Managers	No	No
(Fregonara et al., 2017)	N/A	Other	Yes	Yes, LCA, LCC	Yes	2/No	No	Designers	No	No

(Garcia-Muiña et al., 2018)	LCA, SLCA, LCC and CBM	Business model	No	Yes, LCA, LCC, S-LCA	Yes	3/No	Yes	Managers	Yes	No
(Garza-Reyes et al., 2018)	CMT	Company	No	No	Yes	3/Yes	Yes	N/A	No	No
(Genovese et al., 2017)	Hybrid LCA	Supply chain	No	Yes, LCA, EIO	Yes	1/Yes	No	Policy makers	No	No
(Gnoni et al., 2017)	N/A	Product	Yes	Yes, ‘Streamlined’ LCA	Yes	1/Yes	No	N/A	No	No
(Gnoni et al., 2018)	N/A	Supply chain	Yes and No	Yes, Fuzzy Cognitive Mapping	Yes	3/Yes	No	Policy makers	No	No
(Hildebrandt et al., 2017)	N/A	Material	Yes	Yes, CED	No	1/Yes	Yes	Designers	No	No
(Howard et al., 2018)	N/A	Company	No	No	No	0/Yes	Yes	Companies	No	No
(Huysveld et al., 2019)	RBR	Material	Yes	Yes, LCA, RBR, RCBR	Yes	1/No	No	N/A	No	No
(Jensen et al., 2019)	N/A	Business model	Yes	Yes, LCA	Yes	3/Yes	No	Companies	No	No
(Jiménez-Rivero & García-Navarro, 2016)	N/A	Product	Yes	No	Yes	3/Yes	No	Other	No	No
(Kazancoglu et al., 2018)	N/A	Supply chain	No	Yes, LCA	No	3/Yes	Yes	Various	No	No
(Kiselev et al., 2019)	N/A	Plant/installation	Yes	Yes, LCA, MFA	Yes	0/Yes	No	Various	No	No
(Kjaer et al., 2019)	N/A	Business model	No	No	Yes	0/Yes	No	Other	No	No
(Koch et al., 2018)	N/A	Other	No	Yes, LCA, MFA, CTA, I/O analysis, LCC, CBA	Yes	3/Yes	No	Other	No	No
(Kravchenko et al., 2019)	N/A	Company	No	No	No	3/Yes	No	Decision makers	No	No

(Kristensen & Remmen, 2019)	N/A	Business model	No	No	Yes	3/Yes	No	Companies	No	No
(Laurenti et al., 2018)	PWF	Product	No	Yes, LCA	Yes	0/Yes	No	Other	Yes	No
(Lee et al., 2014)	N/A	Product	No	No	Yes	2/Yes	No	Designers	Yes	Yes
(Liang et al., 2018)	CE Evaluation Index System	Company	Yes	Yes, QUALIFLEX & VIKOR	Yes	1/Yes	No	Decision makers	No	No
(Ligthart et al., 2018)	EnvPack	Packaging	Yes	Yes, LCA	Yes	1/No	No	Various	No	No
(Linder et al., 2017)	Product-level circularity	Product	No	No	Yes	1/No	No	N/A	No	No
(Manninen et al., 2018)	EVPT (Environmental Value Propositions Table) + step-by-step evaluation.	Business model	No	Yes, LCA	Yes	1/No	Yes	Companies	No	No
(Matschewsky, 2019)	N/A	Business model	No	No	Yes	0/Yes	No	Various	No	No
(Mesa et al., 2018)	N/A	Product	No	Yes, LFI by EMF	Yes	0/Yes	Yes	Various	No	Yes
(Niero & Kalbar, 2019)	MRS, MCI, LCA, MDCDA	Packaging	Yes	Yes, LCA, MRS and MCI	Yes	1/Yes	No	N/A	No	No
(Olugu & Wong, 2012)	N/A	Supply chain	Yes	Yes, Fuzzy set theory	Yes	2/Yes	No	Decision makers	Yes	Yes
(Park & Chertow, 2014)	Reuse potential	Material	No	No	Yes	0/Yes	No	Various	Yes	No
(Pauer et al., 2019)	N/A	Packaging	Yes	Yes, LCA	No	1/Yes	No	Designers	No	No
(Pauliuk, 2018)	Dashboard of quantitative system indicators	Company	No	Yes, LCA, MFA, LCC, S-LCA	No	3/Yes	Yes	N/A	No	No

(Prieto-Sandoval et al., 2018)	N/A	Company	No	No	No	0/No	Yes	(Specific) companies	Yes	Yes
(Rieckhof & Guenther, 2018)	LCA and MFCA	Company	No	Yes, LCA, MFCA	Yes	2/No	Yes	Various	Yes	Yes
(Rossi et al., 2016)	N/A	Company	No	No	Yes	3/Yes	No	Companies	Yes	Yes
(Saidani et al., 2017)	Hybrid top-down and bottom-up framework	Product	No	No	Yes	0/No	Yes	Other	Yes	Yes
	EVR & CTF	Business model	No	Yes, LCA	Yes	1/Yes	No	N/A	No	No
(Schmidt Rivera et al., 2019)	N/A	Packaging	Yes	Yes, LCA	Yes	1/Yes	No	Various	No	Yes
(Sheldon, 2018)	E-factor, PMI, RME, LCA	Product	Yes	Yes, LCA, E-factor	Yes	1/Yes	No	N/A	No	No
(Shen et al., 2013)	N/A	Supply chain	No	Yes, Fuzzy set theory	Yes	1/Yes	Yes	Decision makers	No	No
(Steinmann et al., 2019)	QC	Material	No	No	Yes	0/Yes	No	Various	No	No
(Mohamed Sultan et al., 2017)	RDI	Product	No	Yes, MSI, TRL	Yes	1/Yes	No	Various	No	Yes
(Van Schaik & Reuter, 2016)	RI	Product	No	No	Yes	0/Yes	No	Various	Yes	No
(Vaneeckhaute et al., 2018)	N/A	Plant/installation	Yes	Yes, LCA, NPV, IRR, questionnaire on stakeholder perception	Yes	3/No	No	Policy makers	No	Yes
(Vanegas et al., 2018)	eDIM	Product	No	No	Yes	0/Yes	Yes	Policy makers	Yes	No
(Veleva et al., 2017)	‘Expanded Zero Waste’	Various scales	No	Yes, LCA	No	3/Yes	No	N/A	No	No

(Verberne, 2016)	Building Circularity Indicator	Other	Yes	Yes, LCA, EPD	Yes	2/Yes	No	N/A	No	Yes
(Walker et al., 2018)	N/A	Other	No	Yes, LCA	Yes	1/No	No	(Specific) Companies	No	Yes

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Chapter 3. Exploring the effectiveness of grey literature indicators and Life Cycle Assessment in assessing Circular Economy at the micro level: a comparative analysis.

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Abstract

Purpose. Methods and tools to measure Circular Economy (CE) are in an early stage of development, especially on the micro level, and only limited guidance is available to companies' decision-making processes related to CE solutions. In this context, the aim of this paper is to explore the suitability and effectiveness of grey literature CE indicators and the Life Cycle Assessment (LCA) method in measuring circularity at product or process level.

Methods. The analysis is based on two different comparative case-studies specifically related to the packaging sector, including glass and polyethylene terephthalate (PET) bottles, and to the food waste (FW) management sector, focusing on specific FW treatment activities. A review-of-reviews of CE metrics at the micro level is presented first in order to provide a theoretical overview on this specific theme and identify the available grey literature CE indicators and the role of LCA. Then, inventory data from both case studies are used as input to calculate LCA indicators as well as selected product-level grey literature CE indicators. Finally, the results are compared to critically analyze the potentiality in assessing circularity of these two streams of CE micro level assessment (LCA and CE indicators).

Results and discussion. The main findings underscore that despite the common purpose of the selected CE indicators, the results related to the circularity performance may strongly vary depending on the evaluated case study and on the type of grey literature CE indicator that is applied. Regarding the application of the LCA method, the results highlight that, although a product may present high circularity performance, it does not necessarily carry lower environmental burdens. In addition, the LCA method allows obtaining useful information about both the environmental and circularity performance of the assessed case-studies.

Conclusions. The LCA method is presented as a suitable and effective method that businesses can apply to start a commitment towards CE. LCA can be considered the basic structured system on which to build a more complete metric framework for quantification of CE, specifically for companies that are aiming to operate more sustainably. On the contrary, grey literature CE indicators may not be always appropriate for assessing specific sectors or effectively contribute to assess environmental sustainability.

Keywords

Circular Economy assessment, metrics, micro level, circular perspective, LCA, CE, food waste, packaging

1. Introduction

The transition from a linear and unsustainable system towards a Circular Economy (CE) has become a relevant and urgent issue, in public policies as well as in business strategies (Korhonen et al. 2018). CE is a recently popularized concept that is composed of a diverse set of resource management concepts and ideas from environmental- and sustainability sciences, introduced since the 1960s (Blomsma and Brennan 2017; Friant et al. 2020). According to the CE vision, the linear traditional "take-make-use-waste" economy, with its negative impacts, should evolve in a CE that entails closing resource loops - e.g. through the 9Rs paradigm: Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover energy (Potting et al. 2017) - which is supposed to have both a positive impact on the environment and on economic growth, and, to a lesser studied extent, on the social domain (Stahel 2016; Potting et al. 2017; Reike et al. 2018; Korhonen et al. 2018; Kirchherr et al. 2017). The connections between CE and Sustainable Development (SD) are the topic of current world-wide debate and questions around the characteristics and developments of CE have led to a proliferation of academic and non-academic literature, reporting on many CE-related issues (definitions, guidelines, toolboxes, frameworks, etc.) (Suárez-Eiroa et al. 2019).

In this lively debate, an accepted universal and standardized definition of CE is still missing (Millar et al. 2019). One of the most complete definitions could be considered the one proposed by Kirchherr et al. (2017) analyzing 114 CE definitions: CE is "*an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations. It is enabled by novel business models and responsible consumers*". This definition highlights that there are three perspectives in the implementation of CE strategies (as pointed out also by many other authors, such as: Yuan et al. 2006; Geng et al. 2012; Linder et al. 2017): *i)* the *macro level* perspective, which aims to adjust the structures of industry, society and the global and/or national economy by promoting sustainable production and consumption activities, realized through efforts in designing and implementing proper public policies (COM 2014; Korhonen et al. 2018; Hu et al. 2018); *ii)* the *meso level* perspective, observed as an inter-firm level in which CE strategies should encourage the development of networks focused on energy cascading, sharing of local infrastructure, exchanging by-products and recycling wastes, etc. (Yuan et al. 2006; Geng et al. 2012); *iii)* the *micro level* perspective, focused on products, companies and consumers, where companies are encouraged to reduce resource consumption, minimize pollution and waste, design more environmentally friendly products, adopt cleaner technology and cleaner production in their manufacturing processes, include environmental management systems, product-life extension, new business models, and new modes of consumption, and publicly release information on their environmental performances (Geng et al. 2012; Linder et al. 2017; Kristensen and Alberg Mosgaard 2020). Some authors identify a fourth level of circularity (e.g. Saidani et al. 2017; WBCSD 2018), the *nano level*, which refers to products, components and materials, while the micro level refers to companies and consumers.

To support the practical implementation of the transition to a CE at these different levels, a variety of diverse strategies are available, ranging from technological innovation to new business models and stakeholder collaboration (Scheepens et al. 2016; Witjes and Lozano 2016). Obviously, in order to understand how effective a chosen strategy is in reducing the impacts of a system, a quantitative assessment is necessary. Several researchers have engaged with this question and proposed methods to measure the impacts of a CE (or the progress towards a CE). The advancement of monitoring and evaluation tools for CE is indeed considered to be an essential means to promote CE implementation, especially at the level of organizations (Saidani et al. 2018). But, at the same time, the field of CE assessment is relatively underdeveloped, especially with respect to the micro level of analysis (Merli et al. 2018; Kristensen and Remmen 2019; Sassanelli et al. 2019; Moreno et al. 2021). The recent nature and complexity of the concept of CE have resulted in a large number of different strategies, and micro level indicators are also generally described as very heterogeneous (Kristensen & Alberg Mosgaard 2020; Roos Lindgreen et al. 2020). Therefore, the consequent absence of standardized CE assessment methods and/or CE performance indicators, at micro level, can be said to form a barrier to advancing the inclusion of resource efficiency requirements by organizations, and, consequently, to the transition to a CE (Tecchio et al. 2017). Indeed, the micro level is particularly relevant, given the central role of companies in carrying the transition to a CE (Lieder and Rashid 2016): the transition towards a CE highly depends on policymakers and their decisions, but it cannot be reached without a significant change at the level of single products, companies and consumers. This concept is clearly stressed by Lieder and Rashid (2016) when pointing out that "*for succeeding in CE implementation a concurrent top-down and bottom-up strategy is required*". Furthermore, a CE transition is attractive for industry parties due to the various benefits associated with circularity: firm profitability, increase of competitiveness through cost savings, new sources of innovation and revenue, improved customer relationships, and improved resilience for organizations (EMF 2013; Stahel 2016; BSI 2017). It is however highlighted that circular options do not necessarily carry lower environmental burdens or effectively contribute to sustainability: also, the impact of CE on closing material cycles is yet unknown (Pauliuk 2018; Stewart and Niero 2018; Blum et al. 2020). Thus, in order to evaluate and plan their internal changes, companies urgently need methods to measure the impact of their CE strategies (Geng et al. 2011; Niero and Hauschild 2017).

In this context, this paper zooms in on the micro level perspective of the implementation of CE strategies, exploring the specific theme of how to assess them. This theme is investigated with a double focused perspective, one on grey literature metrics and the other on the potential role of Life Cycle Assessment (LCA) in measuring circularity. The focus on the grey literature metrics is motivated by the fact that while there is some evidence that companies are increasingly measuring their level of CE, relatively little is known about which CE measurement approaches they have implemented. In the present research, it is assumed that approaches from grey literature are, after self-developed approaches, most popular; this is supported by the findings of the World Business Council for Sustainable Development, WBCSD (WBCSD 2018) which, interviewing 39 companies, found that 74% of them had their own framework for measuring circularity and 24% used Ellen MacArthur Foundation's butterfly diagram. Other measurement approaches are only applied by between 3-5%, with the 9R framework being the only CE measurement approach from academic literature (WBCSD 2018). This finding is also supported by Stumpf et al. (2019) who highlight the popularity of self-designed CE measurement approaches and the lack of implemented approaches originating from academic literature. At the same time, no previous CE measurement review focuses on grey literature, while academic literature on CE metrics at company level has been analyzed in detail by authors such as Kristensen & Mosgaard (2020), Roos Lindgreen et al. (2020), and Corona et al. (2019). The focus on LCA is motivated by the fact that it is recommended relatively frequently as the foundation of existing CE metrics at company level and has been put forward by various authors as a suitable method to evaluate the environmental impacts of CE (e.g. Pauliuk et al. 2018; Chen & Huang 2019; Corona et al. 2019; Moraga et al. 2020). Furthermore, the connections and differences between these two streams of CE micro level assessment appear not to have been assessed in detail, even if explored by some authors (Niero & Rivera 2018; Walker et al. 2018).

Starting from these considerations, the aim of this paper is to explore the suitability and effectiveness of grey literature CE indicators and the LCA method in measuring circularity at product or process level. Here, both methods are compared by using two case-studies that focus on the packaging sector and the food waste (FW) management sector, in order to better understand their potential contribution to an effective measurement of circularity at the micro level, which includes the consideration of environmental sustainability aspects.

The paper is organized as follows:

- Introduction, reporting main information related to the research theme and summarizing the aim of the paper and its structure.
- Methods, in which the applied analysis framework is discussed and the methodological setup of the comparison between CE-indicators and LCA is explained.
- Results and discussion, reporting the main findings related to the application of the grey literature CE-indicators and the LCA method in the specific context of the packaging sector and FW management sector; the results obtained are also discussed and compared following a critical point of view.
- Conclusions, summarizing the main findings and discussing the implications for further future research.

2. Methods

The analysis of CE assessment at micro level is here focused on two objects of analysis: grey literature CE assessment indicators and the LCA method. While different interpretations of the definition of grey literature exist (Mahood et al., 2014), grey literature CE assessment indicators are here intended to capture documents published by non-academic bodies such as consultancy organizations and policy institutes. It is here therefore mainly in line with the grey literature category of ‘reports’ as put forward in (Farace & Schöpfel, 2010). On the contrary, LCA is a standardized method (ISO 2006a; ISO 2006b), it allows to assess the potential environmental impacts of a product, process or services throughout its whole life cycle, from raw material extraction to the end-of-life (Guinée 2002).

The methodological structure of the study here presented, graphically described in Figure 1, is based on two steps of analysis: a theoretical overview, which starts from a review-of-reviews of CE metrics at micro level, and a comparative analysis of grey-literature CE indicators and LCA, applied on two different case-studies.

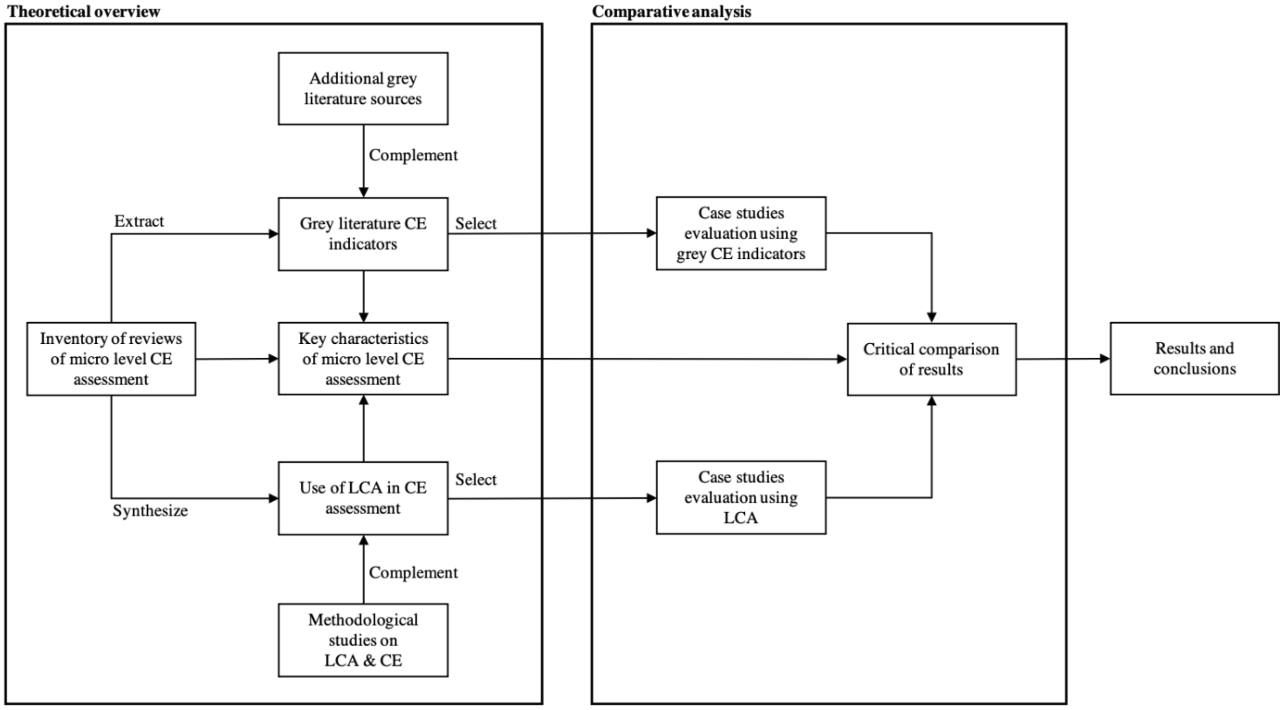

Figure 1. Step-by-step overview of the methodological structure.

First, a review-of-reviews of CE metrics at the micro level has been carried out in order to provide a theoretical overview of the key theme explored in this article: how to assess CE micro level strategies. Starting from a previous study performed by Roos Lindgreen et al. (2020), the review-of-reviews focused on studies that inventory CE indicators, with the aim to identify existing indicators and their main characteristics as well as LCA contributions to assess CE. Concurrently, an integrative literature review has been implemented to widen the extent of the critical analysis and better "*synthesize the literature on a research topic in a way that enables new theoretical frameworks and perspectives to emerge*" (Snyder 2019). Thus, the review-of-reviews was complemented with additional grey literature sources, to better understand the identified grey CE indicators, and with methodological articles that discuss connections between CE assessment and the LCA method. This first step of analysis allowed to synthesize the use of LCA in CE assessment, extract grey literature CE indicators from which to select the ones to be used in the subsequent analysis phase, and delineate the key characteristics of a CE metric at company level.

Then, a comparative analysis was carried out, focusing on two different case-studies related to: *i)* the packaging sector and *ii)* the FW management sector. This choice was made to include sectors representing both the "technical" and "biological" cycles (EMF 2013), as well as to include material flows relevant for circular and/or environmental considerations. In this respect, accordingly to Meherishi et al. (2019), the packaging sector has particular potential to explore its role within the CE due to its vast impact on several ecosystems. From a CE perspective, the waste management of packaging is no longer perceived as a problem, but as an opportunity to return waste back into the production cycle. Regarding the environmental considerations connected to FW production, the importance of its management and evaluation has been underlined by several authors (e.g. Papargyropoulou et al. 2014; Mondello et al. 2017; Salomone et al. 2017).

Inventory data related to both case-studies has been obtained starting from two previous studies performed by Salomone et al. (2013) and Mondello et al. (2017). In the first article, LCA is used to compare two different packaging materials for extra virgin olive oil, glass and polyethylene terephthalate (PET) bottles, considering the whole life cycle from raw material extraction to the end-of-life (EoL). In the second article, LCA is applied to compare five treatments for FW produced by a mass-retail company (landfill, incineration, composting, anaerobic digestion, bioconversion by insects); in the present study, only data related to the treatments with the highest environmental performance (anaerobic digestion and bioconversion by insects) have been used. Furthermore, the so-called avoided product has been also considered. The inclusion of the avoided productions allows estimating the environmental benefits connected to the substitution of a conventional product with an alternative one that satisfy the same function (Salomone et al., 2017). Main characteristics of the two case studies, useful for CE indicators and the LCA calculation, are summarized in table 1.

The inventory data was used to calculate seven different grey literature CE indicators: the Material Circularity Indicator MCI (EMF and Granta 2015), the Material Reutilization Score MRS (C2C 2014), the ResCom Circularity Calculator (Ideal & CO 2017), the UL 3600 (UL 2018), and the Circular Transition Indicators CTI (WBCSD 2020), for which the “Close the loop” – circular material inflow and circular material outflow, has been adopted. The percentage of recycled materials (the assumed amount of material to be recycled) has been adopted for calculating the MCI, while the recycling efficiency value of each material was adopted for the MRS, the ResCom Circularity Calculator, and the UL 3600. Both percentages of recycled materials and recycling efficiency were used for the CTI. The description of these indicators is included in section 3.2.

Concerning the LCA method implementation, regarding the results provided in Salomone et al. (2013) and Mondello et al. (2017) - in which Ecoinvent 2 (Frischknecht et al. 2017) and CML 2 baseline 2000 (CML 2002) respectively were adopted as database and impact assessment method –LCA results presented here have been updated using Ecoinvent 3 (Moreno Ruiz et al. 2013) and the CML-IA baseline method (CML 2016)

Table 1. Main characteristics of the two case studies. (a) packaging materials and (b) FW treatment processes.

Case study (a) packaging materials

Bottle	Material	Type of Input	Recycling efficiency (%)***	Recycled material (%)****
Glass bottle	Green glass (bottle)	Virgin	90.1	72.8
	Aluminum (cap)	Virgin	79.3	63.4
	Aluminum (capsule)	Virgin	79.3	0
	PVC (capsule)	Virgin	57.71	0
	PE (dropless)	Virgin	90	43.5
	Paper (label)	Virgin	86.11	0
PET bottle	PET (bottle)	Virgin	75.5	43.5
	PET (capsule)	Virgin	75.5	43.5
	PE (cap)	Virgin	90	43.5
	Paper (label)	Virgin	86,11	0

Case study (b) FW treatment processes

FW treatment	Type of input	Recycling efficiency (%)	Output	Avoided product
Anaerobic digestion	Food waste	100	Compost	Electricity
			Biogas	Urea
Bioconversion	Food waste	100	Compost	Fertilizer (N)
			Dried larvae	Soy meal

*Polyvinyl chloride (PVC); **Polyethylene (PE); ***Rigamonti et al. 2009; ****ISPRA 2019

3. Results and discussion

This "results and discussion" section is organized to reflect the different outputs of the step-by-step methodological structure previously described: first, the theoretical overview is synthesized, after which the identified grey literature CE indicators are described. Subsequently, the key characteristics of micro level CE assessment are delineated, also highlighting the specific role of LCA. Finally, the results of the comparative analysis of CE indicators and LCA implemented in the two case studies are presented with a critical discussion.

3.1 Theoretical overview

The summary of the review-of-reviews is reported in table 2. Various review articles pointed out that the goals of CE measurement and the methodological setup of the available CE indicators, metrics, tools and measurement methods, appear to show great variability (Saidani et al. 2018; Corona et al. 2019; Moraga et al. 2019; Kristensen and Alberg Mosgaard 2020; Roos Lindgreen et al. 2020). Almost all reviews include grey literature indicators and the connections between CE measurement and LCA are described frequently.

Table 2. Summary contents of review articles on CE indicators at micro level

References	Number of Inventoried Approaches	Included level of CE metrics	Inclusion of Grey literature metrics	Micro level grey literature metrics extracted	Describe the role of LCA
Corona et al. (2019)	72	Micro Meso Macro	Yes: 4 relevant consultancy reports and 7 policy reports (not specified)	Material Circularity Indicator (MCI) (EMF 2015)	Recommends building on current sustainability assessment frameworks, such as LCA or MFA
Kristensen & Mosgaard (2020)	30	Micro	Yes: 4 indicators proposed in grey literature	Circular Economy Toolkit (CET) (Evans and Bocken 2013), the Material Circularity Indicator (MCI) (EMF and Granta 2015), the Circularity Calculator (CC), (IDEAL&CO Explore BV 2016), Material Reutilization Score (MRS) (C2C 2014).	States that methods developed in other fields can be applicable to CE assessment (e.g. LCA, MFA, LCC, CSR, etc.)
Moraga et al.(2019)	20	Micro Meso Macro	Yes: 1 grey literature indicator	MCI (EMF 2015)	States that existing methods such as LCA and MFA can provide a starting point for evaluating CE functions.
Parchomenko et al. (2019)	63	Micro Meso Macro	Yes: 4 grey literature indicators included, also on macro level	Circular Economy Toolkit (CET) (Evans and Bocken 2013), MCI (EMF and Granta 2015)	Finds flexible incorporation of LCA in a variety of metrics.
Saidani et al. (2019)	55	Micro Meso Macro	Yes: 19 grey literature indicators included, many not available online anymore or macro level	Material Reutilization Score (MRS) (C2C 2014), Circularity Calculator (CC), (IDEAL&CO Explore BV 2016), Benchmark Circular Business Practices (VBDO 2015), MCI (EMF 2015)	Highlights that various previous studies advise the use of LCA in CE assessment to avoid trade-offs.
Sassanelli et al. (2019)	45	Level of assessment not specified	No grey literature indicators excluded	-	Finds LCA as the most common method present in CE assessment.
Roos Lindgreen et al. (2020)	74	Micro	No grey literature indicators excluded	-	Recommends to connect CE metrics to existing methods such as LCA.

Kristensen and Alberg Mosgaard (2020) collect and review micro level CE indicators, of which 4 out of 30 have been proposed in grey literature. The inventoried indicators, from academic- and grey literature, show great heterogeneity, both in terms of type and scope as well as with respect to their interpretation of the alignment between sustainability (SD) and CE. Considering connections to existing methodologies, the authors acknowledge that LCA and other methodologies, such as Material Flow Analysis (MFA), Life Cycle Costing (LCC), and Corporate Social Responsibility (CSR), are likely to be applicable to CE, and that further research is needed to better understand their potential.

The critical assessment of circularity metrics carried out by Corona et al. (2019) focuses explicitly on the connections between CE assessment with LCA and MFA. With respect to the inclusion of grey literature indications, additionally to inventorying 72 scientific metrics, their work also collects 4 relevant consultancy reports and 7 policy reports. In addition to the micro level, regional-, country- and global level approaches are also included. The review finds LCA to be the most used framework to assess circular strategies and highlights that circularity metrics should be able to measure the contribution of CE strategies to SD without burden shifting from reduced material consumptions to increased environmental, economic or social impacts. A similar view is presented in the systematic review of CE performance indicators by Sassanelli et al. (2019), who specifically exclude grey literature indicators from their analysis. Although no differentiation between the assessment scales is made, their work finds LCA to be the most commonly used methodology and provides examples of a variety of performance indicators that use LCA (Sassanelli et al. 2019).

An extensive taxonomy of currently available CE indicators is provided by Saidani et al. (2019). Micro, meso and macro level indicators are included, both from academic and grey literature, and a distinction is made between measuring the degree of circularity (‘intrinsic circularity’) or the sustainability impacts of certain circular measures (‘consequential circularity’). The micro-level grey literature indicators included, and still available online, are Material Reutilization Score (MRS) by C2C (2014), the ResCom Circularity Calculator by Ideal&Co (2016), the Benchmark Circular Business Practices by VBDO (2015), and the Material Circularity Indicator (MCI) by EMF (2015). On the micro level, it is stated that combining CE indicators with LCA results may reveal potential trade-offs between ‘resource circularity’ and the reduction of environmental impacts. Moraga et al. (2019) classify various CE indicators on different levels, also including the MCI by EMF (2015), and, in their conclusion, state that LCA and MFA could provide a starting point for evaluating CE ‘functions’, such as multifunctionality or product sharing. Roos Lindgreen et al. (2020) carry out a systematic literature review and categorize academic micro level CE assessment approaches based on their general and methodological characteristics. Recommendations for CE assessment include the use of existing tools such as LCA, incorporation of the three dimensions of SD, and a participatory design approach, for example by involving end-users in the design of the CE assessment approach. Lastly, Parchomenko et al. (2019) apply a Multiple Correspondence Analysis (MCA) of CE indicators and find that LCA-based methods are relatively widely distributed. In a number of cases, the LCA method is complemented by other metrics. According to the authors, this highlights the flexibility of LCA but, at the same time, makes it more challenging “*to identify clearly opposing CE elements for LCA-based metrics*”.

The analysis of previous reviews points out that the number of interpretations is wide and that there are no official or recognized indicators, methods and tools to measure performance in the shift from a linear to a more circular microsystem; furthermore, there is still disagreement on many issues, such as *methods*, *metrics*, *objects of measurement*, and *main characteristics* that the assessment method should have. A second finding is that while grey literature indicators are often included in the studied reviews, none of them focuses specifically on this body of relevant literature.

The LCA method occurs often in the analyzed reviews and it is described as a suitable and effective tool to measure the environmental impact of CE strategies on the micro level, since it provides decision makers with a tool to prioritize actions toward the development of the most eco-efficient and eco-effective solutions. It can thus support companies to measure the environmental performance of a specific circular strategy and compare it with other circular and linear solutions (Walker et al., 2018; Saidani et al. 2018). The results from the previous reviews underline that LCA can be described as the structured system on which to build a more complete metric framework for quantification of CE: it is widely diffused among approaches to assess CE (Merli et al. 2018; Corona et al. 2019; Parchomenko et al. 2019; Sassanelli et al. 2019).

Various other studies zoom in on the methodological connections between LCA and CE measurement. Niero and Kalbar (2019) explore the idea of using the synergies between CE and LCA to evaluate product-level CE. They propose to couple material circularity indicators, such as the MRS (C2C, 2014), the MCI (EMF and Granta 2015) and life cycle-based indicators (climate change, abiotic resource depletion, acidification, particulate matter, water consumption) via Multi Criteria Decision Analysis (MCDA). LCA is described as the operative tool to assess product-level CE; optionally in combination with CE indicators. Further research is needed to identify the proper tools to quantitatively assess the trade-offs between increasing material circularity and subsequent environmental impact. While LCA is able to assess the environmental impact of CE practices, the authors state that its implementation has currently not been exploited accordingly.

In earlier work, Niero and Riviera (2018) explore the idea of using the synergies between CE and the Life Cycle Sustainability Assessment (LCSA) framework to evaluate company-level CE implementation. As the foundation, they use the British Standard BS 8001: 2017 “framework for implementing the principles of CE in organizations”. The authors explore the integration of the standard with the LCA framework by identifying methodological connections and a case study application. The result is a hybrid framework that is used to prioritize the selection of the most feasible CE-options that can be implemented in an organization. Interestingly, the authors highlight that an integrated sustainability assessment of CE could be realized by applying Social-LCA (S-LCA) and LCC. Similarly, Pauliuk (2018) uses the BS standard in combination with indicators extracted from MFA and LCA to construct a dashboard for CE strategy assessment. The maturity of the LCA (and MFA) methodology is put forward as an enabling factor to use it in providing specific suggestions to CE strategies. Another study that points towards the use of LCA in CE assessment is of Walker et al. (2018), in which the LCA method is recommended as suitable for quantifying the environmental benefits of material efficiency and CE strategies. Furthermore, the authors state that indicators relating to the circularity of materials should also preferably be supported by LCA-based studies (Walker et al. 2018).

Following these opportunities for the use of LCA to assess CE strategies, several challenges remain. They can generally be divided into methodological- and practical challenges. With respect to the first challenges, Corona et al. (2019) address the ongoing discussion among LCA scholars on how to allocate burdens and credits of circular processes throughout different phases within a product system, and how to model complex open-loop recycling systems. They acknowledge that three different approaches to allocating burdens between primary and secondary materials exist: the 100:0 (cut-off approach), allocating the burden of recycling activities to the recycled product, the 0:100 (End-of-Life, with substitution) approach, in which the burden/credits of recycling are awarded to the producer of the primary material, and the 50/50 approach, in which the burden/credits are shared. While most of the LCA/CE case studies that the authors review uses the second approach, no consensus on which approach represents reality most accurately has been established. An overview of this methodological issue is addressed by Civancik-Uslu et al. (2019), who zoom in on the complex question of how recyclability credits should be awarded when the recycled output has lost its original properties. Other criticalities refer to the suitability of the LCA in measuring circularity in recycling activities over multiple life cycles.

Regarding the practical challenges, other authors highlight that even if LCA is a well-known and standardized multiple indicator method that well describe the main requirements of CE strategies, several practical challenges remain: LCA requires an extensive amount of data, its application is time consuming compared to other methodologies, and its results communication requires an expert audience (Di Maio and Rem 2015; Elia et al. 2017). More fundamentally, it provides information only on the environmental domain of CE, neglecting the economic and social ones which should be addressed simultaneously, given the link between CE and sustainability. Another different perspective can be pointed out: CE specifically encourages to recycle, reuse, etc. a specific material and the product life cycle extension, while LCA focuses on identifying the environmental impacts at a life cycle level, in order to then plan options to improve the product environmental performance: this may not necessarily imply circularity. However, most of these challenges can be properly faced with an accurate modeling of the goal and scope and of the LCI phase or by integrating LCA with other assessment methods (Niero and Olsen 2016; Niero et al. 2017; Niero and Rivera 2018). Also, the extensive amount of data required to perform a complete and consistent LCA study could precisely be what companies need to contrast the lack of information, confidence and capacity that actually still affects CE solutions.

3.2 Grey literature micro level CE indicators

The results of the review-of-reviews allow extrapolating a list of grey literature micro level CE indicators, reported in chronological order in table 3. The indicators are further analyzed by using the underlying grey literature sources, in order to point out the *object of measurement*, the *method of measurement* and the *metric*. The *object of measurement* refers to the scale of circularity: a single material, a product or a company. Indicators/methods mainly focus on the product dimension, some of which are also adaptable to a company dimension. For example, the MCI can be calculated also at the organization level and this “company MCI” is calculated as a weighted sum of MCIs values estimated for all the company’s products (EMF 2013; EMF and Granta 2015). The *method of measurement* refers to the methodology used to assess circularity; for example, some authors prefer using a single indicator in order to propose a simple and easy-to-communicate measure.

The *metric* refers to the fact that some authors focus on the physical flows, mainly with a perspective of resource scarcity and environmental impact, disregarding the economic implications. This is, for example, the case of the MCI (EMF 2013; EMF and Granta 2015), as well as for the LCA method (ISO 2006a; ISO 2006b). Table 3 contains two relevant categories: qualitative and quantitative measurement approaches, including indicators, and standards, that offer guidance for implementation (BSI 2017; UL 2018). The latter are relevant since, despite the growing attraction of the CE vision at business level, only limited guidance is available to companies that aim to make CE operational in their activities (EMF and Granta 2015; Ghisellini et al. 2016; Cayzer et al. 2017; Linder et al. 2017; Saidani et al. 2017; Niero and Rivera 2018; Pauliuk 2018).

Table 3. Grey literature CE measurement at the micro level.

Reference	CE indicator	Method of measurement	Metric		Object
		Single indicator (final score)	Qualitative / quantitative	Type	
Evans and Bocken (2013)	Circular Economy Toolkit (CET)	no	Qualitative	no points questionnaire	product
C2C (2014)	Material Reutilization Score (MRS)	no	Quantitative	physical flows + social fairness	product / company
EMF and Granta (2015)	Material Circularity Indicator (MCI)	yes	Quantitative	physical flows	material / product / company
VBDO (2015)	Benchmark Circular Business Practices	yes	Qualitative	aspects of circular business practice	company
BSI (2017)	BS 8001:2017	no	Qualitative / quantitative	guidance document	site / company
Ideal & CO (2017)	ResCom Circularity Calculator	yes	Quantitative	physical flows + financial value	product and business model
Ecopreneur.eu (2018)	Circularity Check	yes	Qualitative / quantitative	% score questionnaire (self-assessment)	product
UL (2018)	UL3600	no	Qualitative / Quantitative	guidance document	product / site / company
Circle Economy (2019)	Circle Assessment	no	Quantitative	score	company
WBCSD (2020)	Circular Transition Indicators (CTI)	no	Quantitative	physical flows + value added	product
EMF (2020)	Circulytics	yes (composed of 21-30 indicators)	Qualitative / quantitative	physical flows + various ‘enabler’ indicators	company

Evans and Bocken (2013) propose a *Circular Economy Toolkit* (CET): an online tool created by various CE experts that identifies and assesses the potential improvement of products' circularity. It consists of 33 questions (in a trinary format: yes/partly/no or high/medium/low) and allows to assess a "qualitative metric" to identify potential improvement of products towards circularity.

The Cradle-to-Cradle Products Innovation Institute (C2C) proposes the *Cradle to Cradle Certified™ Product Standard*, a guide for companies that aim to continually improve their products according to five quality categories: 1. material health (MH), 2. material reutilization (MR), 3. renewable energy and carbon management (RE&CM), 4. water stewardship (WS), and 5. social fairness (SF). For MH, the ultimate goal is to ensure that the product is manufactured using only materials that have been optimized and do not contain any X or Grey assessed materials (i.e., toxic materials according to the C2C certification). The MR criterion is quantified by the so-called *Material Reutilization Score* (MRS). In the case of a material belonging to the technical cycle, the MRS includes two variables: the % of the product considered recyclable (i.e., a material that can be recycled at least once after its initial use stage) and the % of recycled content (RC) in the product (C2C, 2014): $MRS = [2 \cdot (\% of\ the\ product\ considered\ recyclable) + (\% RC)]/3 \cdot 100$.

For RE&CM, WS, and SF, performance at production and organization levels need to be included in the optimization strategy. Finally, product assessments are performed by a qualified independent organization in order to assign a Basic, Bronze, Silver, Gold, or Platinum achievement level that allow companies to document their progress in applying the C2C standard and getting closer to the goals of the different levels (C2C 2014).

A well-known micro level CE single indicator is the *Material Circularity Indicator* (MCI) developed by the Ellen MacArthur Foundation (EMF and Granta 2015). It measures, for a certain material within a product or organization, which linear flow has been minimized and which restorative flow has been maximized. Also, the duration and intensity of product use is compared to a similar industry-average product. The MCI consists of two factors (the linear flow index and the utility factor). Data needed for its calculation are: *i)* mass of virgin materials used in the product; *ii)* amount of reused materials and recycled content in the product; *iii)* efficiency of recycling; *iv)* mass of unrecoverable waste, attributed to the product, that goes to landfill/incineration; *v)* utility factor that accounts for the duration and intensity of the product's use. A linear product has an MCI of 0 (100% virgin materials content), a product that uses a large amount of recycled materials (and/or an extended lifespan or a high recycling efficiency) has an MCI value closer to 1 (EMF 2013; EMF and Granta 2015).

The VBDO, a Dutch Association of Investors for SD, developed an approach to assess and compare the circularity of organizations. The self-developed approach, named *Benchmark Circular Business Practices*, consists of a set of criteria linked to different aspects of circular business practice. Users' feedback from 14 public, private and nonprofit organizations was used to establish the 31 final criteria, divided into the following categories: strategy and governance, implementation, innovation, and communication & engagement (VBDO 2015). The approach is more holistic and business-oriented than most of the other proposed indicators.

In general, little guidance to implementation of CE measures is available to organizations. To fill this gap the British Standard Institution developed the "*BS 8001:2017 – Framework for implementing the principles of the circular economy in organizations*" (BSI 2017). The standard does not contain requirements (thus it is not possible to claim a certification according to its compliance) and mainly functions as a guide providing definitions, advice, and recommendations assisting organizations in the transition towards a more circular and sustainable mode of operation (BSI 2017). The standard establishes a minimal set of six CE principles that organizations can refer to (systems thinking, stewardship, transparency, collaboration, innovation, value optimization) and an eight-stage flexible framework to assist organizations to develop a road map for continual and transformational improvement (framing, scoping, idea generation, business case, prototyping, implementation, monitoring) (BSI 2017). The BS 8001:2017 lacks various generic elements which might limit its applicative potential, such as the link between CE and sustainability and the monitoring and measurement aspect (Pauliuk 2018). While the standard does not contain a specific indication on how to measure CE, it clarifies that choosing appropriate performance indicators is a responsibility of the organization implementing CE (Niero and Rivera 2018; Pauliuk 2018; Niero and Kalbar 2019).

The *ResCom Circularity Calculator* is an online tool created by the Ideal&Co Explore (Ideal & CO 2017) in collaboration with a number of 'manufacturers leading the CE' and has been promoted by the EMF. It is part of a larger collection of CE tools that assist manufacturers towards designing CE-oriented products, under the name ResCom (Resource Conservative Manufacturing). The tool consists of a matrix that simulates the design process, allowing for both the input of various resource-related parameters (reuse rates, recycling rates) as well as financial parameters. Its goal is not purely to arrive at quantitative estimations, but also to stimulate and facilitate discussions among designers. Another tool that was developed as part of the ResCom project is the *ResCom Circular Pathfinder*, which can be used by designers as a quick scan to identify the most suitable circular pathways for the designed or manufactured product. The tool does not provide a quantitative estimation of the degree of circularity, but again mainly stimulates knowledge exchange on available strategies.

The European Sustainable Business Federation and MVO Nederland, in cooperation with WeSustain and Circular Future, developed the free online self-evaluation tool *Circularity Check* consisting in a questionnaire of about 60 questions aimed at determining a circularity score for a product/service. The tool allows to calculate a total score of circularity (0-100%) and partial scores on 5 indicators (0-100%) related to design/procurement/manufacturing, delivery, use, recovery, and sustainability (Ecopreneur.eu 2018).

Another relevant grey literature document is the UL3600, developed by UL, an American standards organization. It is a certification document for measuring and reporting CE aspects of products, sites and organizations (UL 2017). In contrast to the BS 8001:2017, it is more focused on quantitative aspects (material flows and the impacts of those flows), using an approach similar to the GHG protocol. The document also contains guidance for conducting product portfolio circularity and corporate circularity.

Circle Economy (2019) has created the *Circle Assessment tool* that enables organizations to quantify its level of circularity and identify opportunities to minimize future risks by adopting circular business practices. It is an online tool that score companies according to seven categories (prioritize regenerative resources; preserve and extend what's already made; use waste as a resource; design for the future; collaborate to create joint value; rethink the business model; incorporate digital technology) identified after having mapped various terms and definitions used by over 20 organizations (NGOs, government agencies, academia, consultancies, etc.).

In early 2020, the WBCSD developed the *Circular Transition Indicators V1.0*, together with 25 companies. This indicator framework is designed to be suitable for organizations within any industry, value chain position or size; is aimed at quantifying the extent to which circularity has been achieved across the entire operations of an organization; allows for monitoring CE progress over time; and includes 7 CE themes (strategy and planning, people and skills, systems, processes and infrastructures, innovation, external engagement, inputs and outputs). Furthermore, it is based on an assessment of material flows within the company's operations, which is combined with indicators on material efficiency and the ability to produce a desired result.

Lastly, the EMF introduced *Circulytics* in the beginning of 2020: a company-level measuring tool aimed at quantifying to what extent a company has achieved circularity across its entire operations (EMF, 2020). The tool generates a single score, comprising two categories: enablers (ability to capture CE business opportunities in the future) and outcomes (the company's current level of circularity). The tool is highly comprehensive, with seven CE themes including: strategy and planning, people and skills, systems, processes and infrastructures, innovation, external engagement, inputs and outputs.

3.3. Key characteristics of micro level CE assessment and the connection with LCA

To connect the methods of LCA and CE assessment, the key characteristics that a CE metric should satisfy to deliver impact assessment guidance to companies are here identified. These characteristics are extracted starting from the previous literature review, integrated with additional sources of information from the BS 8001:2017 standard, which identifies CE principles, Linder et al. (2017), which describe desirable qualities of CE metrics, and the recommendations suggested by the WBCSD (2018). The role of LCA (ISO 2006a; ISO 2006b) in answering to these characteristics is also highlighted in Table 4 and in the following discussion.

a) A CE metric should be able to provide operational guidance towards CE – a CE metric should assist companies in the process of introducing resource efficiency-related solutions, aiming to make the transition from a linear to a circular company. Pathways to incorporate CE elements into the company's operations and performance management systems should be identified and CE metrics have the potential to play an important role in supporting the decision-making processes related to CE strategies implementations. However, as resulting from the literature review, attention should be paid to unwanted trade-offs that might result from CE options, generally focused on resource efficiency (Pauliuk 2018). Role of LCA: LCA provides valuable support in integrating environmental sustainability targets into design of products and business operations (Sala et al. 2012). The application of LCA in conjunction with the information provided by (optional) CE metrics will be essential to avoid the aforementioned unwanted trade-offs in the environmental domain (Pauliuk 2018).

b) A CE metric should be science-based and standardized – quantitative assessment methods are essential to evaluate company- or product performance associated with CE strategies but, in order to avoid inaccurate and partial measurement, "*indicators need to be backed up by rigorous scientific accounting and assessment methods*" (Saidani et al. 2017). However, as indicated in the literature review, many companies use self-developed frameworks for CE measuring (WBCSD 2018) and the design of a common science-based CE assessment framework is lacking. Role of LCA: LCA is a science-based method, standardized by the ISO 14040 standard. It is one of the most commonly used and accepted methods for the environmental assessment of products and organizations. The method can be applied to very different products and systems, allows for making comparisons and carries the advantage of having high flexibility and adjustability following choices in the goal and scope, system boundaries, functional unit, etc. If common rules are defined for performing the LCA study (e.g. the Product Category Rules for type III labelling - ISO 2006c), results are reproducible and comparable for products having the same function, by properly identifying the functional unit.

c) A CE metric should be based on a multi-dimensional scoring system - CE metric should not be focused only on resource-related performance, but include the impact of a solution on the different CE dimensions. For example, the effects on the *material quality* within the system under assessment should not be disregarded. It is recommended to include material quality assessments in CE assessment and study how this limits or influences resource circulation activities. When combining this with information on the different dimensions of sustainability, balancing the need for a single indicator and a complex assessment framework is essential. While indicators have the ability to summarize complex information related to CE, the use of a single score prohibits capturing CEs complexity (Saidani et al. 2017). Thus, it becomes essential to apply a consistent and transparent aggregation methodology in order to balance difference indicators in case of contrasting results and to avoid unwanted trade-offs. Role of LCA: LCA has the capacity to optimally represent the different dimensions of CE by using a wide range of different LCA-based indicators covering a broad spectrum of environmental impacts and many Life Cycle Impact Assessment (LCIA) methods provide consistent, accepted and recognized aggregation principles. In addition, *material quality* changes over multiple lifecycles can be included, considering the co-functions in the functional unit, in order to avoid any overestimations of the benefits gained from recycling. In particular, in the assessment of a product CE strategy the functional unit should describe both the main function of the assessed product and the supply of resource after its use stage for a specified number of recycling loops. When modelling recycling in the LCI phase, recycling has to be faced as a case of multifunctionality accordingly a closed-loop recycling (material recycled in the same product system) or open-loop recycling (material recycled in a different product system). Both closed- and open-loop recycling approaches are coherent with CE principles and can be modelled in different ways, but should include the downgrading of materials, in terms of intrinsic technical property changes of the recycled material or by the inclusion of a ratio between the quality of the secondary and the primary material (Niero and Olsen 2016).

d) The CE metric should be structured according to a phased and iterative approach - in order to allow CE to become a SD goal, the three dimensions of sustainability have to be included in the metric. Indeed, CE measures should not be seen as a goal in itself but rather a means to an end, which is to achieve a more sustainable society; this can be done through "replacing the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes" (Kirchherr et al., 2017). Thus, CE strategies should first be mapped in terms of material flows (materials that enter, flow within and eventually leave the system under study) in order to assess the environmental performance of the different potential ways to close the loops; then the economic and social viability of the chosen strategies needs to be verified. Some authors stress this concept by highlighting that CE strategies focus on the introduction of closed-loop products, resources, and material cycles as a means to improve resource efficiency, and the economic value is a consequence of the gained efficiency (Hu et al., 2018; Linder et al., 2019). The preeminent focus on the environmental dimension is also present in the monitoring framework that the European Commission (EC) is preparing to assess the progress towards CE - "*CE strategies should be firstly environmentally motivated and then socio-economically supported"* (COM, 2018a) – which uses the existing scoreboards (the Resource Efficiency Scoreboard and the Raw Materials Scoreboard) as a starting point. <u>Role of LCA</u>: organizations can use LCA to trace the materials and energy that pass through the product system, to identify the connected potential environmental impacts, reduction opportunities and improvement options through an iterative approach and to compare alternative optimization scenarios related to a baseline system. Indeed, there are different, potentially alternative, ways to close resource loops and LCA allows to make the trade-offs tangible, thus enabling identifying the most relevant type of loop for a material/ product in terms of environmental sustainability. Thus, through LCA, it is possible to test the impacts of CE strategies, obtain feedback for improvement and foster circularity over time. This can be done both using an attributional or consequential LCA modeling. With an attributional LCA, the focus is on the environmental impacts associated to the functional unit; consequential LCA allows to trace the consequences that the proposed activities will cause in the change in demand of other systems and in the environment. Also, the BS 8001:2017 recommends organizations to "*map the system using relevant systems thinking tools and techniques, such as: system mapping for resource/material flows; value networks for stakeholder and relationship mapping; and existing Life Cycle Assessment studies*" (BSI, 2017). The standard also mentions the social aspects, risks, and the ethical responsibilities linked to the different CE options and recommends S-LCA as monitoring tool. Following this line, Niero and Rivera (2018) argue that "*the life cycle assessment of environmental and social aspects has cemented a base to help the sector and industries to start a commitment towards circular economy*". Thus, after having assessed the environmental dimension using the LCA method, the economic and social dimension can be measures by adding LCC-based and S-LCA-based indicators; then, potential trade-offs emerging from the LCSA results could be handled through a MCDA (Niero and Kalbar 2019).

e) The CE metric should be structured according to a system perspective and a life cycle thinking approach – in order to identify resource efficiency opportunities and to gather the data necessary for product or service assessments, a company needs close cooperation with its value chain partners (Prosman and Sacchi 2016). This also contributes to finding support for broad-based acceptance and success of interventions towards circularity. In selecting a preferred CE strategy, burden shifting between stakeholders in the value chain should be prevented for all different dimensions of sustainability. Therefore, a CE metric should entail a system perspective and life cycle approach, as also indicated in two of the BS 8001's six CE principles (BSI 2017). Role of LCA: in LCA the system thinking approach encompasses the product life cycle and its connections with other systems, depending on how system boundaries are defined and according to the goal and scope of the analysis. Burden shifting is avoided by using multi-indicator impact assessment methods along the supply chain. Lifecycle- and systems-thinking are essential for an effective CE product strategy: in LCA they ensure innovation options to be evaluated throughout the value chain, rather than solely on end-of-life solutions.

f) The CE metric should be transparent and easy to communicate – a CE metric should be able to be communicated unambiguously and clearly, both internally as well as externally. It should therefore consist of a transparent, accurate, timely, honest and complete set of information. Role of LCA: LCA results can be communicated in a transparent way by using third-party verified labels e.g. Ecolabel, type III labels EPD; Product Environmental Footprint (PEF), etc. Additionally, the EC is currently in the process of evaluating how product labels, such as Ecolabel, PEF, etc., may support the CE policy (European Commission, 2020).

Table 4. Key characteristics of a CE metric at company level.

A CE metric at company level should be:	Principles of CE (BS 8001:2017)	Desirable quality Linder et al. (2017)	Recommendations WBCSD (2018)	Role of LCA in terms of CE metric
Able to provide operational guidance towards CE. To effectively integrate CE principles into a company's mission or strategy, it must be clear how to incorporate those elements into the company's operations and performance management systems.	2 – *Innovation.* Continually innovate to create business value through the sustainable management of resources in products and services		7. *Drive culture change and provide guidance*. Allow to include elements that ingrain circularity into the company culture	LCA provides valuable support in identifying improvement option and in integrating environmental sustainability targets into design, innovation, and evaluation of products
	5- *Value optimization.* Keeping all products, components and materials at their highest value and utility at all times (identify opportunities to realize new potential from waste)			LCA provides meaningful information to be used in an informed decision-making process
Scientifically assessed and standardized. The metric needs to be backed up by scientific and standardized assessment methods		*Reliability.* Give similar values under consistent conditions	6. *Build upon existing frameworks and standards*. Recognize relevant existing standards and frameworks	LCA is a science-based method, standardized by the ISO 14040 standards
			4. Ensure flexibility and inclusion. Be flexible and standardized ensuring applicability to companies of all industries, value chain positions and maturity levels in their CE thinking	If common rules as defined, LCA results are reproducible and comparable for products having the same function
		Generality. Compare products independently of industry/technology		LCA is highly flexible (depending on the choice made in the goal and scope: system boundaries, functional unit, etc.)
Based on a multi-dimensional scoring system. A balance between a single indicator and a complex assessment framework should be found. The indicators should describe the different aspects of circularity and the different dimension of sustainability		*Construct validity.* Measure circularity "the fraction of new products that come from used products"	*1.Drive circular business performance.* Indicators should allow companies to identify improvements in financial, environmental and social performance over time, not circularity itself	LCA has the capacity to represent CE by using a wide range of different LCA- based indicators
				Data from the life cycle inventory is useful for measuring circularity
				Material quality can be taken into account with a proper modelling of the LCA study. Life Cycle Impact Assessment methods provide consistent, accepted and recognized aggregation principles

		Aggregation principles. Ensure consistent and transparent aggregation principle	3. *Cover a comprehensive sustainability scope.* Account for the financial, environmental and social aspects of its circularity	By adding LCC- and S-LCA- based indicators the three dimensions of sustainability can be represented. Potential trade-offs emerging from LCSA results could be handled through a MCDA
Structured according to a phased and iterative approach. The assessment process should include the sustainability dimensions and be articulate in different procedural steps: CE strategies should be firstly environmentally motivated and then economically supported.	*3 Stewardship.* Managing the direct and indirect impacts of organization activities within the wider system they are part of and taking into account the economic, environmental and social impacts		5. *Adopt a phased approach to incorporating capitals*. Ensure that the framework addresses natural, financial and social capital	LCA allows to prioritize different types of loops in order to identify the most relevant loop for a material or product in terms of environmental sustainability. LCC and S-LCA can then be added as screening tools to test the practical viability of the different options previously environmentally assessed
Structured according to a system perspective and a life cycle thinking approach. The system-thinking approach helps to identify the opportunities for closing the loops with a holistic	*1. System thinking.* Having a holistic approach. and understand how individual decisions and activities interact within the wider system			In LCA, LCC and S-LCA, the system thinking approach encompasses the product system and its connections with the other systems in order to avoid burden shifting
	4- Collaboration. Internal and external collaboration through formal and/or informal arrangements			Cooperation among the different actors of the product system is a key aspect in LCA and in the other LCT methods
Transparent and easy to communicate. *Results should be unambiguously and clearly communicated internally and externally*	*6. Transparency.* Being open about decisions affecting CE and communicate these in a clear, timely, honest and accurate manner	*Transparency.* Communicate unambiguously and clearly the results	2.*Target specific audiences depending on company objectives*. Communicate circular performances	LCA results can be communicated in a transparent way by using third-party verified labels.

3.4 Comparative and critical analysis

In order to increase the relevance of the comparison between the suitability of the CE indicators and the LCA method for evaluating circularity, given that the LCA is a quantitative based-assessment method, only CE-indicators applying quantitative metrics have been selected. In addition, a focus on product assessment has been chosen. Therefore, starting from the information reported in table 3, the CE indicators selected are: the MCI, the MRS, the ResCom Circularity Calculator, the UL 3600 and the CTI, for which the “Close the loop” – circular material inflow and circular material outflow have been adopted. The indicators are focused on data calculation and online tools. In addition, considering that the ResCom Circularity Calculator allows measuring the circularity performance by estimating the percentage of materials to be destined to open loop or closed loop recycling, two different scenarios (SC1 and SC2) for glass and PET bottles have been proposed. In particular, for both types of bottles, virgin materials are used for the production, then an open loop recycling process for bottle components (caps, capsule, dropless) and a closed loop recycling process for glass and PET bottles have been considered in SC1, while it has been assumed that all the materials (bottles and bottle components) are designated to open loop recycling, in SC2. Table 5 shows the results related to the circularity performance of glass and PET bottles, evaluated throughout the selected grey literature circularity indicators.

Table 5. Circularity performance of glass and PET bottles through grey-literature CE indicators.

CE Indicator	Unit	Reference value		Glass bottle	Pet bottle
		Linear	Circular		
Material Circularity Indicator (MCI)	Pt	0	1	0.31	0.29
Material Reutilization Score (MRS)	%	0	100	57.65	56.78
Rescom Circularity Calculator (RESCOM CC), scenario 1 SC1	%	0	100	89.00	69.0
Rescom Circularity Calculator (RESCOM CC), scenario 2 SC2	%	0	100	45.00	36.0
UL 3600	%	0	100	44.61	36.1
Circular Transition Indicators (CTI) (Close the loop – inflow)	%	0	100	0	0
Circular Transition Indicators (CTI) (Close the loop – outflow)	%	0	100	67.87	32.32

An in-depth analysis of each of the assessed products underscores that, despite the common scope of the CE indicators consisting of providing information about the circularity performance, the results are strongly connected to the type of indicator selected. For example, focusing on the glass bottle, the MCI shows a low circularity efficiency (0.31 Pt) considering that this indicator has value between 0 (linear product) and 1 (circular product), but, on the contrary, the ResCom Circularity Calculator (SC1) shows a high circularity performance (89%). This also highlights that differences in the results may occur when a formula-based calculation indicator (MCI) is adopted instead of a CE indicator based on an online tool (ResCom Circularity Calculator), for which parameters and formulas are not available.

Regarding the analysis of both products, the results reveal that for all applied grey literature CE indicators, the glass bottle shows a higher circularity score when compared to the PET bottle. The percentage related to the CTI (Close the loop – inflow) of the products is 0% because both the glass and PET bottles are made with virgin materials. This finding would indicate that a company should move in the direction of glass packaging in order to increase its circularity performance.

When LCA is applied to both the packaging options, the characterization results as reported in figure 2 highlight that for all assessed impact categories, the PET bottle shows the lowest potential environmental impact. Considering, for example, the Global Warming GW (GWP 100a) the percentage difference is about 50%. The highest contribution to the potential environmental impacts caused by the glass bottle is mainly due to the production process of the green glass packaging material, for which Ecoinvent 3 secondary data were adopted. The GW impact category, the production of the green glass causes an overall contribution to the impacts for about 47.3% Thus, despite the glass may be considered a good packaging option in terms of CE efficiency, this is not reflected on the LCA environmental characterization results. This means that, based on the type of indicator/method adopted, a product that satisfies the CE prerogatives is not always also environmentally preferable. This trade-off between circularity and environmental impact may cause problems in decision making processes at company level.

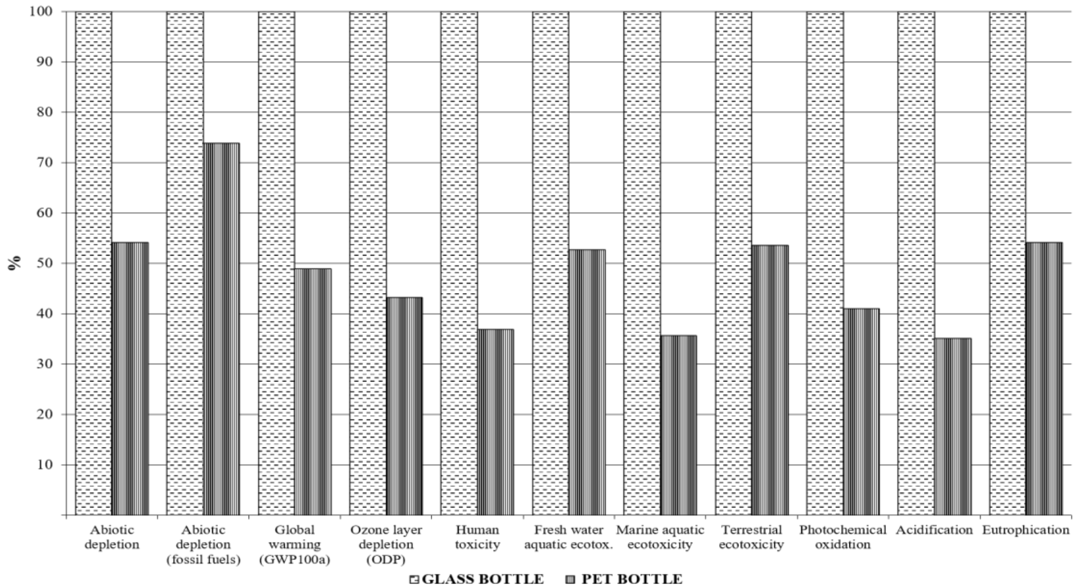

Figure 2. Environmental performance of glass and PET bottles through LCA (characterization results updated from Salomone et al. 2013).

In the second example, related to the comparison of FW management options, the scope is to evaluate service systems included in the biological cycle (anaerobic digestion and bioconversion). Results of the selected grey-literature CE indicators applied to the two investigated FW treatments (Table 6) firstly highlight that some of them - the MCI and ResCom Circularity Calculator - cannot be applied for the assessment of biological cycles (EMF 2013; EMF and Granta 2015; IDEAL&CO Explore BV 2016). In addition, considering the intrinsic characteristics of the adopted indicators and of the assessed systems (FW recycling), the results related to the other indicators show the highest possible circularity performance (100%) for both options, because all the material as object of the analysis is recycled. This makes the selection of the most efficient option impossible, highlighting that there is a lack of CE indicators able to evaluate recycling services within the biological cycles.

On the contrary, the LCA method allows to assess the environmental performance of both FW treatments. Indeed, the characterization results (Figure 3) highlight that the bioconversion scenario is responsible for lower environmental loads in all selected impact categories, except for GW, in which the highest environmental performance is related to the anaerobic digestion option; in particular, the main contribution to climate change of the bioconversion process is due its electricity consumption, contributing 14.8%.

Table 6. Circularity performance of food waste treatments (anaerobic digestion and bioconversion by insects) through grey literature CE indicators.

CE Indicator	Unit	Reference value		Anaerobic digestion	Bioconversion
		Linear	Circular		
Material Circularity Indicator (MCI)	Pt	0	1	NA*	NA*
Material Reutilization Score (MRS)	%	0	100	100	100
Rescom Circularity Calculator (RESCOM CC),	%	0	100	NA*	NA*
UL 3600	%	0	100	100	100
Circular Transition Indicators (CTI) (Close the loop – inflow)	%	0	100	0	0
Circular Transition Indicators (CTI) (Close the loop – outflow)	%	0	100	100	100

*Not available

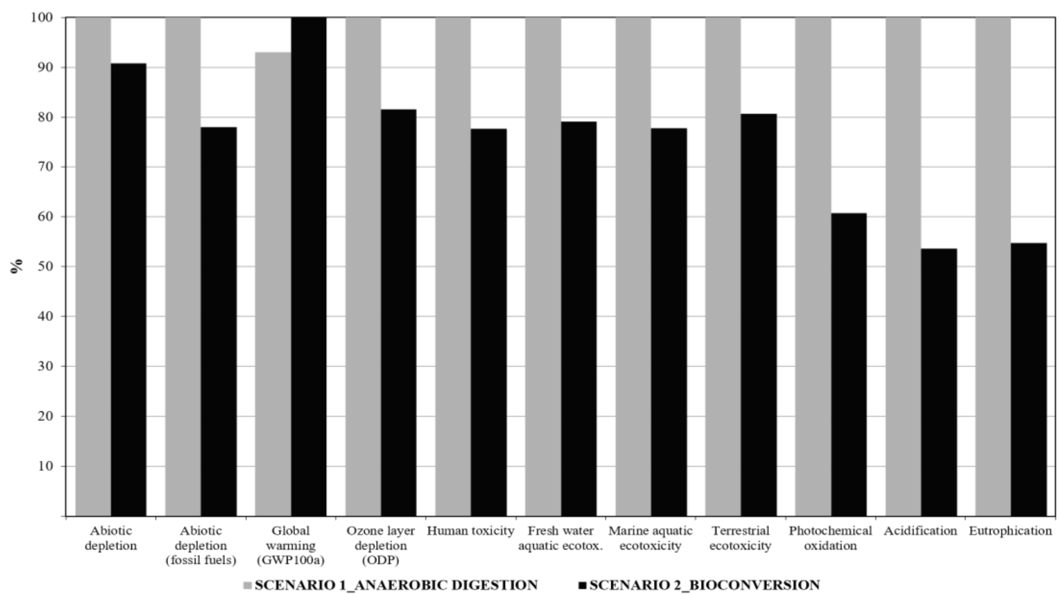

Figure 3. Environmental performance of food waste management systems (anaerobic digestion and bioconversion by insects) through LCA (characterization results updated from Mondello et al. 2017).

In addition, the LCA method allows for including so-called avoided productions; hereby, the environmental benefits resulting from introducing circularity can be estimated by through the substitution of a conventional product with an alternative one that satisfies the same function. In this context, the results reported in figure 4 show higher benefits in terms of negative environmental impacts due to the circularity of the bioconversion process, resulting in avoiding the production of conventional fish meal and fertilizers; they are substituted, respectively, by the larvae meal and compost produced by the treatment of FW.

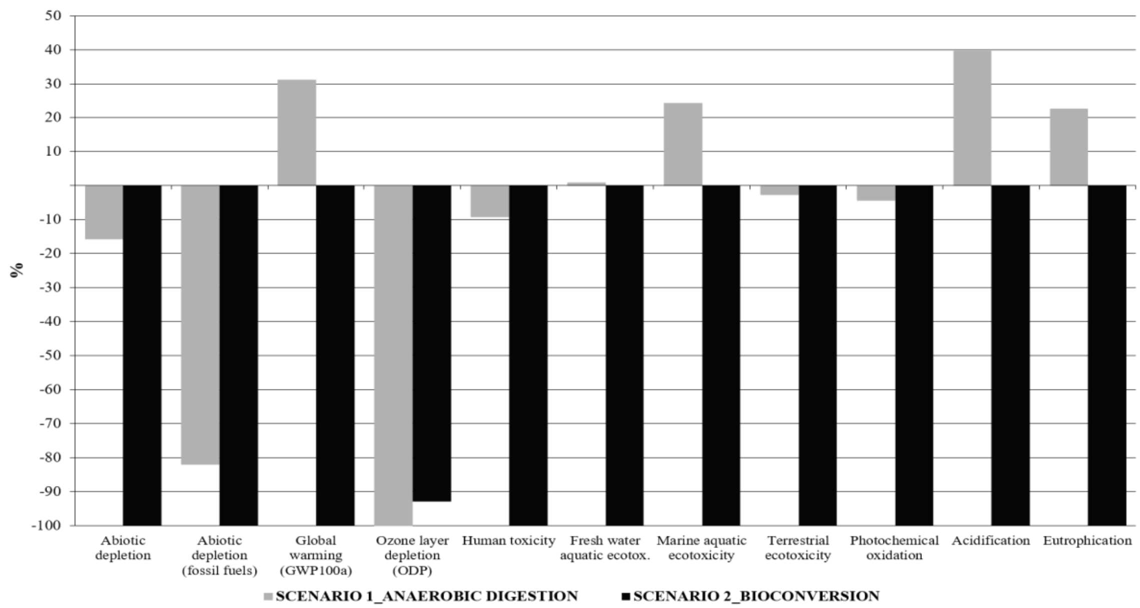

Figure 4. Environmental performance of food waste management systems (anaerobic digestion and bioconversion by insects) through LCA with the inclusion of the avoided product (characterization results updated from Mondello et al. 2017).

In conclusion, from the comparison of the results obtained by applying the selected CE grey literature indicators and the LCA method to two different case-studies, additional considerations about their suitability and effectiveness in measuring circularity at product or process level can be made. The main results related to the comparison between PET and glass bottles showed that the circularity performance of a product is strongly connected to the type of CE indicator adopted. Considering for example the MCI, for which the circularity of a product ranges from 0 Pt to 1 Pt, the results highlighted that the use of a glass bottle results in a higher circularity score (0.31 Pt) in comparison to a PET bottle (0.29 Pt). On the contrary, a low overall circularity was found if the MCI is compared to the results obtained from the ResCom, for which the highest value for glass bottle was 89%, pointing out higher circularity performance. When focusing on the results obtained from all the applied indicators, it is possible to highlight that the glass bottle may be the preferred solution of a company searching for higher circularity performance. On the contrary, the LCA results on the same packaging case study indicate that using glass bottles causes higher environmental impacts than PET ones. This shows that a product that can be considered circular, may be not the best option in terms of environmental performance. This trade-off between circularity and environmental performance may cause misunderstandings in the decision-making process, resulting in difficulties in the selection of the best solution to be implemented.

The results from the analysis of the anaerobic digestion and bioconversion processes show that the selected CE grey-literature indicators cannot be used for comparing the two FW treatment options. Indeed, the guidelines of MCI and ResCom indicators suggest they cannot be applied for evaluating biological systems. In addition, the assessment procedures and characteristics of MRS, UL 3600 and CTI complicate drawing conclusions on the performance of anaerobic digestion and bioconversion, because for both treatments the results in terms of circularity were 100% for MRS, UL 3600 and CTI (close the loop – circular outflow), while 0% for CTI (close the loop – circular inflow). On the contrary, the LCA method allowed to identify the FW treatment process with the better environmental performance (the bioconversion system), also from a circularity perspective by including the incidence of avoided products in the assessment.

Despite this, it should also be highlighted that LCA only covers the environmental dimension of sustainability, but CE should ideally strive to consider all three pillars of sustainability simultaneously. Adding indicators from the LCC and S-LCA methodologies to include the economic- and social domains of SD is, while commendable, potentially more challenging since these methods are not yet fully developed and, for S-LCA, the impact assessment method still needs further scientific advancement. However, the science that underlies both methods is progressing and there has been increased attention for a holistic perspective on sustainability assessment (Fauzi et al. 2019). While the BS8001:2017 standard doesn't contain a specific indication on how to measure and monitor progress towards CE, it mentions, additionally to the use of mapping resource flows and LCA, the social aspects, risks, and the ethical responsibilities linked to the different CE business options and recommends S-LCA as a monitoring tool. Thus, complexity increases when the life cycle perspective is expanded to the economic and social dimensions, e.g. through the Life Cycle Sustainability Assessment (LCSA) framework (Finkbeiner et al. 2010; Niero and Kalbar 2019).

4. Conclusions

This study builds on the finding that one of the main factors that hinders the implementation of CE at micro level is the lack of consensus on how to measure circularity, and the resulting diversity of methods, tools and criteria available for the evaluation of the CE impacts at product and company level. In this context, the aim of this study was to evaluate the suitability and effectiveness of grey literature CE indicators and the LCA method in measuring circularity at micro level.

The theoretical overview of micro-level CE assessment showed that CE measurement approaches have a great variability in terms of methodological structure. Although the debate with respect to the methods and objects of measurement continues, various authors find that the LCA method occurs relatively often and is described as applicable to CE measurement. Practical challenges of LCA such as its perceived complexity and data requirements are assumed to be addressed through accelerated development of available tools for LCA, and expected increased maturity of organizations in facilitating the analysis required. The LCA method not only allows to assess the environmental sustainability of a CE strategy by measuring the reduction in the resource use (resource efficiency), but also allows to assess other CE perspectives, such as slowing and closing resource loops, while taking into account how to avoid burden shifting between life cycle stages.

In order to analyze how the results of LCA and available grey-literature indicators compare in adequately addressing environmental impacts, a comparative analysis was performed, using data from previous studies on packaging and FW management. The overall results obtained from the study indicate that grey literature provides a variety of approaches that have the potential to assist companies in the measurement of their transition to a CE, but CE indicators may be not always appropriate for assessing specific sectors, in particular when the object of the analysis is focused on biological cycles. On the contrary, the LCA method allows covering the key characteristics that a CE metric at company level should satisfy and is suitable to evaluate a broad spectrum of environmental impacts, including product circularity, as emerged in the comparative analysis. Despite this, it should be considered that its complexity, data requirements and time consumption are more demanding than CE indicators and may cause difficulties in its application at company level.

Furthermore, the results related to the circularity performance strongly vary depending on the type of grey literature CE-indicator that is applied, and trade-offs between circularity and environmental sustainability emerge when results from CE indicators are compared with LCA results. Future studies should be oriented in finding an appropriate multi-criteria analysis to solve the trade-offs between circularity and environmental performance. In addition to the focus on comparing grey literature CE indicators with LCA, future studies could be oriented in applying this approach to comparing the outcomes of CE metrics extracted from academic literature with LCA results.

Finally, with respect to the quantification of the economic- and social perspectives, a remaining challenge is to find the balance between comprehensiveness and applicability, as well as how to relate such indicators to the absolute sustainability perspective. Therefore, for future studies, it is important that the development of indicators does not stop at this stage. Indeed, social, economic and ecological analysis need to be combined and studies should concentrate on their interaction rather than on just the environment itself.

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6. Author contributions

ERL, GM, and RS contributed fully and equally to the whole body of the research and manuscript. FL and GS helped to design the study, critically reviewed it and provided suggestions for its additional improvement.

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Chapter 4. Exploring assessment practices of companies actively engaged with circular economy

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Abstract

An emerging research area is dedicated to developing approaches for assessing the 'circularity' of companies and their products, within the context of sustainability goals. However, empirical evidence on the uptake of these assessment approaches remains scarce. Using a purposive sampling, we conducted a survey receiving 155 responses and held 43 semi-structured interviews with Dutch and Italian companies active in circular economy (CE), pursuing three research aims: to explore the use of CE and sustainability assessment approaches; to study the process of developing assessment approaches; and to uncover benefits of - and barriers to - CE assessment. While we find high variability of assessment approaches, most often, companies develop tailormade sustainability indicators and apply life cycle assessments to CE strategies. Importantly, assessment development for CE practices requires and facilitates collaboration with external stakeholders. Finally, we reflect on the paradox of standardisation vs. tailoring of assessment approaches within the CE reality, and recommend establishing company needs and capabilities before designing assessment approaches.

Keywords

Stakeholder engagement, circularity indicators, corporate sustainability, material flow analysis, mixed methods, sustainability assessment.

1. Introduction

The Circular Economy (CE) is proposed as a potential solution to the imbalance of the current linear economic system between limited resource supply and increasing demand for goods (Marino & Pariso, 2020). It has been described as an umbrella concept, building on fields in sustainability science, such as Industrial Ecology (IE) and eco-efficiency, and aims at retaining value embedded in materials through a series of systemic feedback loops between different life-cycle stages (Hobson & Lynch, 2016). Within EU-level policies on sustainable growth the Circular Economy Action plan plays a key role in the European Green Deal (European Commission [EC], 2019). Simultaneously, CE is growing as a business paradigm (Murray, Skene & Haynes, 2017). Indeed, private sector initiatives are an important driver of the CE transition in many countries and the diversity of CE business models is increasing (EC, 2020; Henry et al., 2020; Santa-Maria et al., 2021). In literature, CE is dominated by a corporate and technocentric perspective, aligning CE with current business paradigms, such as innovation and green growth (Calisto-Friant, 2020; Schöggl et al., 2020). Perceived benefits for companies implementing CE are related to lowering environmental impacts, realising social improvements and economic benefits, such as cost savings and developments of new markets - or growing existing ones (Laubscher & Marinelli, 2014). Therefore, the putative promise of CE practices lies in reducing negative sustainability impacts without jeopardizing growth and prosperity (Ferasso et al., 2020).

While companies are becoming increasingly aware of the potential benefits associated with improving their resource efficiency, the uptake of CE practices is still lacking (Hartley et al., 2020). Translating the concept of CE into corporate strategies is obstructed by various technical and non-technical barriers, ranging from high start-up costs to the complexity of current supply chains (Jaeger & Upadhyay, 2020). Companies need to develop and apply dynamic capabilities to overcome such barriers and enable the implementation of CE practices (Khan et al., 2020). One of such capabilities, which has not yet received considerable attention in academic literature and is the focus of this article, is that of assessing CE practices and their sustainability impacts (Roos Lindgreen et al., 2020).

This assessment is essential because for many CE solutions and business models available to companies, it is unclear whether - or to what extent - they actually lead to more sustainable outcomes (Blum et al., 2020; Harris et al., 2021). Therefore, in order to contribute towards reaching the United Nations Sustainable Development Goals (SDGs) (UN, 2017), assessing the sustainability impact of CE practices before implementing them is key. Otherwise, well-intended CE strategies might actually lead to unintended sustainability impacts and burden shifting (Blum et al., 2020; Corona et al., 2019). Indeed, Roos Lindgreen et al. (2021) have found that applying resource focused CE metrics in isolation can lead to contradicting results when compared to impacts calculated through life cycle assessments (LCAs). Different terms for managing units of information are used in academic literature on sustainability or CE assessment, such as metric, variable, indicator, methodology, or index, etc. (Saidani et al., 2019; Sala et al., 2013; Veleva & Ellenbecker, 2001). Since we aim to capture a wide range of applied approaches from practice, we use the term 'assessment approaches' here. For a company, such an assessment approach includes obtaining data on the sustainability performance of any system (product- or company level), allowing for its effective management (Beloff et al., 2004). The obtained information can be used for internal purposes, such as monitoring and evaluating company performance towards SD goals, but also for external purposes e.g. communication to guarantee compliance with legislation or benchmarking between companies (Bae &

Smardon, 2011). While discussing the value of both sustainability and circularity assessment[1], it is important to remember that for most companies, especially small and medium enterprises (SMEs) which are not required to produce a mandatory sustainability report, these assessments are voluntary activities (EC, 2014). Thus, with limited incentives promoting the assessment of circularity or clarity regarding its integration with sustainability assessment, the motivations of companies to conduct additional assessments remain unknown.

While private sector engagement with CE and assessment approaches for CE from academic literature have been investigated, (Santa-Maria et al., 2021; Kristensen & Alberg Mosgaard, 2020), empirical evidence on the assessment approaches applied by companies that actively participate in the CE transition is scarce (Hartley et al., 2020). Furthermore, research gaps exist with respect to the joint application of CE and sustainability assessment approaches, as well as the process of developing them, given the collaborative nature of most CE practices (Brown et al., 2019; Niero & Kalbar, 2019). Finally, the perceived benefits of - and barriers to - CE assessment have also yet to be studied (De Pascale et al., 2020; Rossi et al., 2020).

Therefore, we study CE and sustainability assessment practices of frontrunner companies already engaged with CE, which thus are inclined to assess their CE practices. First, we study the practical application of CE and sustainability assessment approaches at company level. Secondly, the process of developing tailormade CE assessment approaches and the involvement of stakeholders in this process is investigated. Our third aim is to reveal the benefits and barriers of implementing CE assessment. We use an explorative mixed-methods approach consisting of a semi-quantitative survey and semi-structured interviews with companies which are members of national or international CE networks and operating in Italy or the Netherlands. In both European countries, such networks play an active role in sharing knowledge, practices and connecting stakeholders, resulting in a thriving ecosystem of companies engaged with CE (Institut National de l'Économie Circulaire, 2020). Such networks were thus used within this study to identify a diverse range of companies engaged with CE, both in terms of sector as well as size.

In the remainder of this article, we present the theoretical background to the study, underlining the addressed research gaps and resulting research questions (Section 2), as well as the mixed-methods approach employed (Section 3), and the results of the survey and interview approach (Section 4). Then, the discussion section amalgamates these results in the context of existing - and future - research directions (Section 5), while the last section offers concluding remarks (Section 6).

[1] Within this article *circularity assessment* and *CE assessment* are used interchangeably.

2. Theoretical background

This section highlights the research gaps identified in the three CE assessment-related areas investigated in this article: i) practical application of CE and sustainability assessment approaches at company level; ii) use of tailormade CE assessment approaches; iii) benefits and barriers of implementing CE assessment. From the identified research gaps three main research questions are formulated to guide the study.

2.1. CE and sustainability assessment approaches for companies

A considerable number of review articles on CE assessment approaches for companies have been published in the past three years (e.g. Corona et al., 2019; De Pascale et al., 2020; Kristensen & Mosgaard, 2020; Moraga et al., 2019; Roos Lindgreen et al., 2020; Saidani et al., 2019; Sassanelli et al., 2019; de Oliveira et al., 2021). These articles describe various assessment approaches and their characteristics, such as their connection to different sustainability dimensions and specific CE strategies. Generally, they focus on the environmental and economic domains, with social elements rarely being considered (de Oliveiro et al., 2021). Indicators with an economic focus might be more attractive to business, but carry the risk of detaching CE from environmental and social sustainability (Kristensen & Alberg Mosgaard, 2020). Furthermore, many indicators are centred around resource use or specific strategies from the "R-hierarchy" (Potting et al., 2017), a framework commonly associated with CE by companies (Walker et al., 2021a), making them unsuitable to assess the three-dimensional sustainability performance of circular systems (Corona et al., 2019).

From the wide range of available assessment approaches, we recognize four general categories relevant to companies. First, life-cycle based methods enable the quantification of impacts across all phases of a product's or system's life cycle, from the extraction of raw materials to its disposal (Finkbeiner et al., 2010). A precursor to such life-cycle based methods are material flow analysis (MFA)-based methods, which establish an overview of resource and energy flows across the life cycle of a system (Brunner and Rechberger, 2016). These MFA-based methods have provided the blueprint for more recent industry-developed CE metrics such as the Circular Transition Indicators (CTI) (WBCSD, 2020). Footprint tools, such as the carbon footprint approach, take on a similar approach and are therefore included in this category (WBCSD & WRI, 2004). Second, also relevant are the several available sustainability reporting frameworks, such as GRI Standards, which have the goal to create a common language and format for organizations to report on their sustainability impacts (Global Reporting Initative, 2018). Next, various authors point out the presence of single indicators: quantitative indicators presenting circularity as a single number, which are mainly orientated around metrics such as recycling rate or resource use (Kristensen &

Mosgaard, 2020). Lastly, and as discussed in the next section, the category of tailormade indicators, which could be based on a life-cycle approach or direct impact, allow for tailoring the CE or sustainability assessment more closely to a company's specific context (Kravchenko et al., 2020). As opposed to life-cycle tailormade approaches, direct impact here refers to 'scope 1' impacts occurring from sources that are controlled or owned by an organization (WBCSD, 2004).

Some authors (e.g. Geissdoerfer et al., 2017; Schroeder et al., 2018) have already stressed that the complex nature of the relation between CE and sustainability affects its assessment. However, a lack of consensus persists on the issue whether CE- and sustainability assessment are different or the same, and whether one forms part of the other (Vinante et al., 2020; Walzberg et al., 2021). Indeed, some authors consider it essential to complement resource-focused CE assessment with the respective assessment of its sustainability impacts, given that applying resource-focused assessment approaches only could lead to a risk of pursuing 'CE for the sake of CE' (Harris et al., 2021; Kristensen & Mosgaard, 2020). Furthermore, CE assessment approaches may potentially distract the decision-making process, or even provide a greenwashing vehicle when the results do not point towards sustainability, allowing companies to pick CE indicators which suit their corporate narrative (Pauliuk et al., 2018). Various other scholars nevertheless regard resource-focused CE metrics as valuable for decision-making and product comparisons (Parchomenko et al., 2019; Sassanelli et al., 2019). It has further been established that, to ensure the quantification of CE solutions' sustainability impacts, existing sustainability assessment methods could be used (Roos Lindgreen et al., 2020; Walzberg et al., 2021).

While available CE assessment approaches for companies are well-documented, information on their practical application is scarce (Kristensen & Remmen, 2019; Stewart & Niero 2018). One of these few practical studies showed that about three quarters of the 39 involved companies applied a self-made CE assessment framework, instead of using existing frameworks developed by consultancy companies or academia (WBCSD, 2018). Similarly, Stumpf et al. (2019), analysing 131 case studies from the Circular Economy Industry Platform, found CE indicators from literature to play a negligible role in mainstream industrial assessment practices. Regarding sustainability assessment approaches, the capability of companies to carry out this assessment has been emphasized as a prerequisite for corporate sustainability (CS) (Maas et al., 2016). For small and medium enterprises (SMEs), this capability increases when a company develops more sustainable (and holistic) business practices (Witjes et al., 2017). Since sustainability assessment is a field with a longer history, more information on its degree of implementation by companies is available. In fact, sustainability tools, initiatives and approaches, such as corporate social responsibility (CSR) and the Global Reporting Initiative (GRI), are well known among companies (Lozano et al., 2020), however, their uptake of CE issues is lacking and less concrete (Opferkuch et al., 2021).

From the above, we highlight a lack of empirical evidence on the implementation of CE and related sustainability assessment approaches by companies, leading to the following research questions:

RQ 1: How do frontrunner companies assess CE & sustainability?

RQ 1A: Which assessment approaches are applied?

RQ1B: What are the differences between CE & sustainability assessment?

2.2. Development process of tailormade CE and sustainability assessment approaches

It is in the nature of CE practices to go beyond company boundaries and ideally encompass the whole life cycle of a product, thus requiring increased collaboration (Brown et al., 2019). Within the scope of this collaboration, companies are starting to assess the impacts of these CE practices. The development and implementation of tailormade CE assessment frameworks indicates that companies are utilizing the CE concept based on how it is most material to their core business (WBCSD, 2018). In literature, the selection of specific CE KPIs suitable to a company's CE strategy is recommended (Kravchenko et al., 2019). This would also be in line with the long-standing finding in the field of sustainability assessment that indicators should reflect the business realities of a particular organisation; as such, they should not be limited to general methodologies or standards (Keeble et al., 2003). However, there are certain points of reference that could be considered universally applicable, such as the planetary boundaries (Rockström et al., 2009) or the Paris Agreement (UN, 2015). Furthermore, Niemeijer and de Groot (2008) have developed a framework for indicator selection based on causal networks which has found widespread uptake from scholars for discussion with the environmental domain. They point out the importance of looking at the integration of the indicator set rather than focusing on single indicators. Similarly, Addison et al. (2020) propose the creation of an assessment framework for evaluating the biodiversity impact of business practices, and mention the central role of involving stakeholders in the assessment, if the assessment scope goes beyond company boundaries. This is particularly relevant for CE practices, given that they mostly require collaboration of companies within their supply chain network (Brown et al., 2019). Moreover, the involvement of stakeholders in general is described as a methodological necessity for sound sustainability assessment by several scholars (Sala et al., 2013; Troullaki et al., 2021). It is by way of this transdisciplinary involvement, that the assessment approaches can be adapted to the contextual specificities of the sustainability impacts to be assessed, while also including some standardised indicators based on international consensus (Kühnen & Hahn, 2018).

However, evidence on *how* companies develop such context-specific CE assessment approaches is limited in literature (WBCSD, 2018). As in sustainability assessment, one key element in this process is the involvement of stakeholders; especially in connection to the flourishing field of CE consultancies and research agencies that offer CE assessment services (Pereira & Vence, 2021). For example, for public sector organizations, a co-developed CE assessment framework with the active involvement of internal stakeholders has been proposed; it emphasizes including sector specifics in CE assessments of organisations (Dröge et al., 2021). With respect to the involvement of academic stakeholders, for micro-level CE assessment approaches from academic literature, only a low number have been designed in a participatory manner (Roos Lindgreen et al., 2020). Yet, to our knowledge no research exists on how companies engaged with CE practices develop assessment practices either internally or with external consultation and how, if at all, the process differs from the development of sustainability assessments.

Following this, we address this lack of empirical data on the development of CE assessment approaches by companies and their stakeholders through inquiring specifically about their development process. To improve the development of future CE assessment approaches, company needs with respect to external expertise throughout the assessment process are extracted, revealing at what scale assessment tools are needed.

RQ 2: What is the process of developing tailormade CE & sustainability assessment approaches?

RQ 2A: How are stakeholders involved in the creation of assessment approaches for CE practices?

RQ 2B: What are the assessment needs and preferences of companies engaged with CE?

2.3 Benefits of - and barriers to - CE assessment

Considerable research exists regarding the identification of drivers and barriers for embedding CS assessment processes within organisations (Triste et al., 2014; Lozano, 2020). The assessment process is a critical element of strategic management, facilitating and driving change towards CS within a company (Doppelt, 2003; Lozano et al., 2016). Bae & Smardon (2011) determined that the measurement and disclosure of sustainable business indicators allowed companies in manufacturing industries to integrate sustainable business practices into decision-making processes. This integration enabled companies to transform their practices from only environmental management towards broader sustainable business strategies (Bae & Smardon, 2011). Other, more general, benefits of assessing sustainable business practices are related to stakeholder communication, benchmarking between companies (Zimek & Baumgartner, 2019), and organisational learning (Sala et al., 2015). To complement this, several studies have identified barriers which can be both internal to the company (e.g. lack of awareness on sustainability issues, an absence of perceived benefits, lack of resources), as well as external (e.g. insufficient drivers, complexity of available tools) (Johnson & Schaltegger, 2016; Lozano, 2007). The identification of barriers enables the development of corresponding capabilities, allowing companies to not only overcome these barriers, but to go further than only compliance (Hart, 1995; Khan, Daddi & Iraldo, 2020). In addition, the identification of barriers supports the revision of assessment approaches themselves, to improve their applicability and relevance to companies. For instance, evidence points towards SMEs experiencing more significant barriers to sustainability assessment (Johnson & Schaltegger, 2016; Jaramillo, Sossa & Mendoza, 2019), which has led to the development of new or modified assessment approaches for smaller companies (Garza-Reyes et al., 2018; GRI, 2018). These advancements are critical as SMEs represent more than 99% of all companies in the EU (Eurostat, 2018). Companies implementing CE strategies are faced with critical challenges in terms of stakeholder management, financial and regulatory aspects, resource management and consumer acceptance (Ritzén & Sandström, 2017; Stewart & Niero, 2018). Several studies have focussed on such barriers to the implementation of CE business models and strategies (De Jesus & Mendoca, 2018; Mont et al., 2017; Ranta et al., 2018). However, the exploration of barriers exclusively for the assessment of CE practices has only been addressed by Dröge et al. (2021b), focusing on Portuguese public sector organisations. To date, no study has identified the barriers related explicitly to the assessment of CE practices from private sector companies. Furthermore, no study has addressed the motivation and benefits of companies which voluntarily conduct a CE assessment.

From the above, the following research question emerges:

RQ 3: Why do (or don't) companies conduct CE assessment?

3. Methods

Figure 1 illustrates the mixed methods approach (Creswell & Plano Clark, 2018) consisting of two complementary research methods to obtain insights from frontrunner companies engaged with CE: a semi-quantitative survey and semi-structured interviews (Adams, 2015). We chose the combination of these two methods to identify the approaches that were applied and by whom (through the survey) and how and why companies applied these approaches (through interviews). It should be highlighted that the survey and the interviews contained additional questions analysed in the context of a separate study (Walker et al., 2021a).

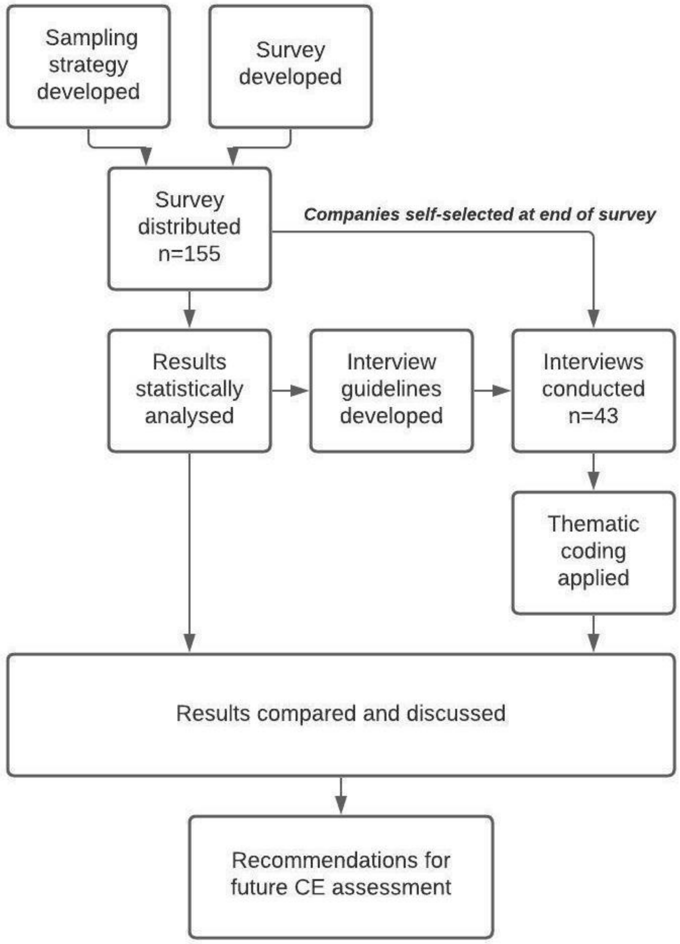


Figure 1. Illustration of overall research steps employed in this study.

3.1. Sampling procedure

To identify companies actively engaged with CE practices in Italy and the Netherlands, we applied a purposive sampling method (Hibberts et al., 2012). Namely, we only included companies which are members of existing national and international CE networks since we assume they are frontrunners in CE and its assessment. A list of the included CE networks can be found in Appendix A. In order to be included in the survey, besides being part of a CE network, respondents needed to satisfy two other criteria: being a private sector organisation, according to national law; and having an official website. The survey was delivered through the online survey tool SurveyMonkey (2021), with personalised email invitations and was open from July until the end of September 2019. At the end of the survey, respondents had the option to opt-in for successive interviews; thus, the interview sample consists of a subset of the survey respondents. These interviews were conducted between May and June 2020 through video calls. Both the survey and the interview participants were aware that the results of the study would be anonymised.

3.2. Sample description

The survey was sent out online to a total of 809 companies and was fully completed by 155 (survey response rate: 19%). Of the responding companies, 46% were based in Italy and 52% in the Netherlands. Two respondents were part of Italian or Dutch CE networks whilst being based outside of these countries: one from Luxemburg and one from Austria. In the interviews the distribution of companies (n = 43) was nearly the same, with 20 companies based in Italy and 23 in the Netherlands.

The companies were subdivided into the EuroStat classification scheme for SMEs. For the 155 survey companies, 45% consisted of micro companies (1-9 employees), 33% of SMEs (10-249 employees), and 22% of large companies (250+ employees). For the 43 interview companies, this was almost the same, with 49% micro companies, 26% SMEs, and 25% large companies.

The respondents categorised their company sectors themselves according to the statistical classification of economic activities in the European Community (NACE) (Eurostat, 2008). Though both samples were diverse, Figure 2 and Figure 3 show that the most frequently named sector in both cases was "Manufacturing", followed by "Other service activities", and "Professional, scientific and technical activities", both of which represented consultancy companies. Whereas the former category would actually be assigned to repair services, the analysis of individual survey answers revealed that several companies in this category were in fact consultancy companies. As to be expected, "Waste & water management" companies were also present in the sample, given the inherent circular qualities of their business models.

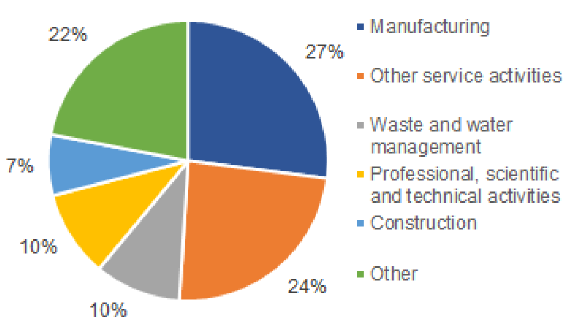


Figure 2. Industry sector of survey respondents (n = 155).

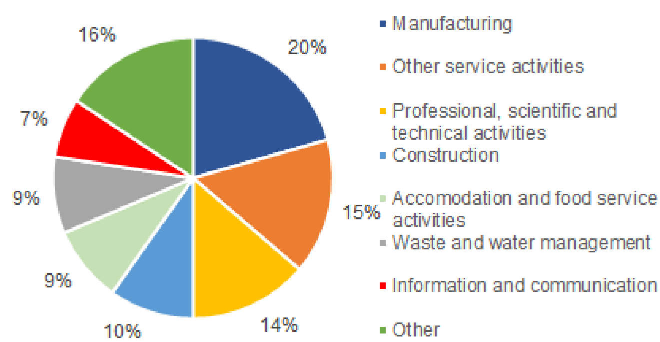
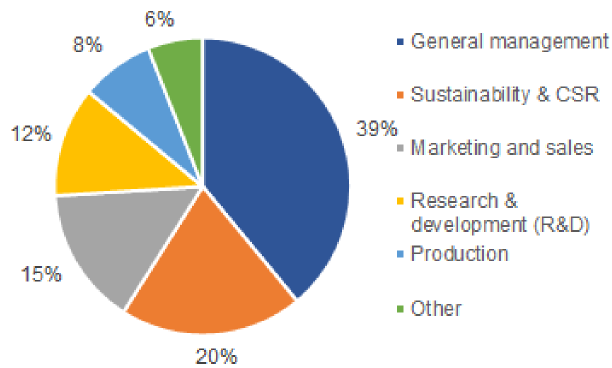


Figure 3. Industry sector of interview respondents (n = 43).

Finally, Figures 4 and 5 prove that the survey and the interviews collected information from decision-makers with generally high authority and knowledge on the topic of sustainability and CSR. Interestingly, in the interviews the share of respondents from the "General management" and "Sustainability & CSR" was notably larger than in the survey, representing a higher willingness of these respondents to discuss sustainability and CE-related matters.



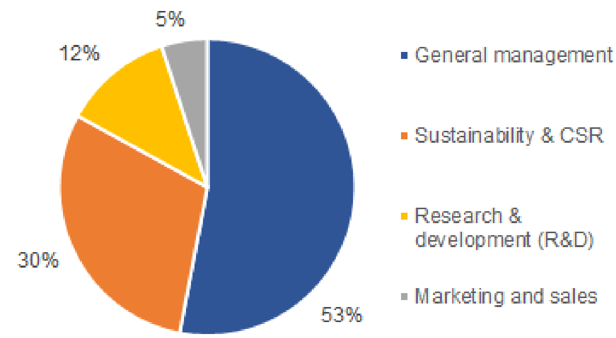


Figure 4. Department of survey respondents (n = 155).

Figure 5. Department of interview respondents (n = 43).

3.3. Survey development

For a detailed description of the creation of the overall survey and its distribution to 809 companies, readers should refer to Walker et al. (2021a). Regarding the survey questions addressed in this paper, we first asked companies whether they regarded a list of assessment approaches as either CE or sustainability assessment, and whether they applied them on a company or product level. The identification of CE and sustainability assessment approaches was based on literature (Corona et al., 2019; Ness et al., 2007; Vinante et al., 2020; Sala et al., 2013), as well as input from a sustainability consultancy specialised in life-cycle based assessments. As identified in Section 2, the assessment approaches were categorized into life-cycle based/footprint, reporting frameworks, tailormade indicators and single indicators, depicted in Table 1.

Table 1. Assessment approaches and their abbreviations.

Category	Assessment approach	Abbreviation	References
Life-cycle based /footprint	Carbon Footprint	CF	WBCSD & WRI, 2004
	Ecological Footprint	EF	Wackernagel & Beyers, 2019
	Product Environmental Footprint	PEF	European Commission, 2013
	Environmental Life Cycle Assessment	E-LCA	ISO, 2006a, 2006b
	Life Cycle Costing	LCC	Hunkeler et al., 2008
	Material Flow Analysis	MFA	Brunner and Rechberger, 2016
	Social Life Cycle Assessment	S-LCA	UNEP, 2020
	Water Footprint	WF	Hoekstra et al., 2011
Reporting framework	Environmental Accounting	EA	Bebbington et al., 2021
	GRI Standards	GRI	GRI, 2016
Tailormade indicators	Tailormade circularity indicators based on a life cycle approach	TCEI (life cycle)	N/A
	Tailormade circularity indicators based on direct impact	TCEI (direct)	N/A
	Tailormade sustainability indicators based on direct impact	TSI (direct)	N/A
	Tailormade sustainability indicators based on a life cycle approach	TSI (life cycle)	N/A
Single indicators	Material Circularity Indicator (by Ellen MacArthur Foundation)	MCI	EMF and Grata, 2015
	Material durability	MD	Figge et al., 2018
	Recycled content	RC	Kristensen and Mosgaard, 2020
	Recycling Rate	RR	Kristensen and Mosgaard, 2020
	Time for disassembly	TfD	Vanegas et al., 2018
	Volume of non-renewable resources not extracted	VNRRne	Kristensen and Mosgaard, 2020
	Volume of virgin material production prevented	VVMp	Kristensen and Mosgaard, 2020
	Volume of waste diverted from landfill	VWdL	Kristensen and Mosgaard, 2020

We also asked what system boundaries companies considered when doing assessments and whether they had developed their own assessment systems besides those postulated by the authors. In case companies had developed their own assessment frameworks, we further inquired whether this had happened in collaboration with external stakeholders or not, in order to get a better understanding of the development process of such assessment approaches. Finally, we posed the question in what assessment phase, of both sustainability or circularity assessment, companies would benefit most from external expertise. These assessment phases were composed of the steps of the life cycle assessment (LCA), the identification of suitable indicators (Kravchenko et al., 2020), the communication of the results to internal and external audiences and their inclusion into corporate decision-making (Bae & Smardon, 2011). This would help identify if company needs were different regarding CE or sustainability assessment and whether there were specific phases of assessment where support would be particularly useful. In all questions it was possible to provide additional comments in open text fields.

3.4. Interview guideline development and process

To get a better picture of how frontrunner companies engaged with CE practices develop assessment approaches and why they do (or why they don't) implement these, we interviewed 43 respondents between 45 and 90 minutes. The interview questions focus on companies' understanding of CE and sustainability assessment, the assessment creation and application, as well as barriers and benefits of assessing CE (available in Appendix B). These questions emerged from the survey results and, in particular, from the open answer fields. Since the interviews were held in English, Dutch and Italian, we applied the Loubere's (2017) Systematic and Reflexive Interviewing and Reporting (SRIR) method. This method requires scholars to hold frequent meetings to discuss the findings and impressions of the individual interviews, instead of writing and analysing full transcripts.

3.5. Data analysis and integration

After the survey was closed, we exported the answers from SurveyMonkey into the statistical analysis software IBM SPSS Statistics 26 (2020). Then, we took a univariate analysis approach and analysed the descriptive statistics. To identify whether variations in the answers correlated with the size (micro, small-medium and large) as well as the sectors (divided into production and service sector) of the respective companies we employed cross-tabulations (Bartiaux et al. 2018) and conducted a contingency coefficient test to determine the significance of the correlations.

Regarding the interviews, we jointly analysed the interview notes in the qualitative data analysis software NVivo R1 (QSR International, 2020) with an inductive coding approach based on thematic analysis (Braun & Clarke, 2006). After assigning codes to the responses for each sub-question, we compiled them into major themes, as presented and discussed in the following sections. This inductive approach was chosen following the (1) novel nature of the research topic, and the inherent conceptual ambiguities between sustainability and CE, as described in chapter 2, and (2) the scarcity of empirical evidence on company engagement with CE assessment. Lastly, for a comprehensive analysis, the findings from the survey answers were confronted and complemented with the findings from the interview responses in an iterative manner.

4. Results

This section presents the results according to the three main research questions formulated in section 2.

4.1. Assessment of CE and sustainability by companies

4.1.1 Application of assessment approaches

As seen in Figure 6, the application rate of the 22 approaches, previously introduced in Table 1, shows large variability, both overall as well as within each of the categories. Generally, 36% of companies have not applied any of the approaches on either a product- or company level. On the product-level, 53% of respondents do not apply any approaches, 7% of respondents apply one approach and the remaining 40% applied two or more approaches. Looking at the frequency of approaches applied at company level, 46% of respondents do not apply any approaches on a company level, 10% apply only one approach and the remaining 44% apply two or more approaches.

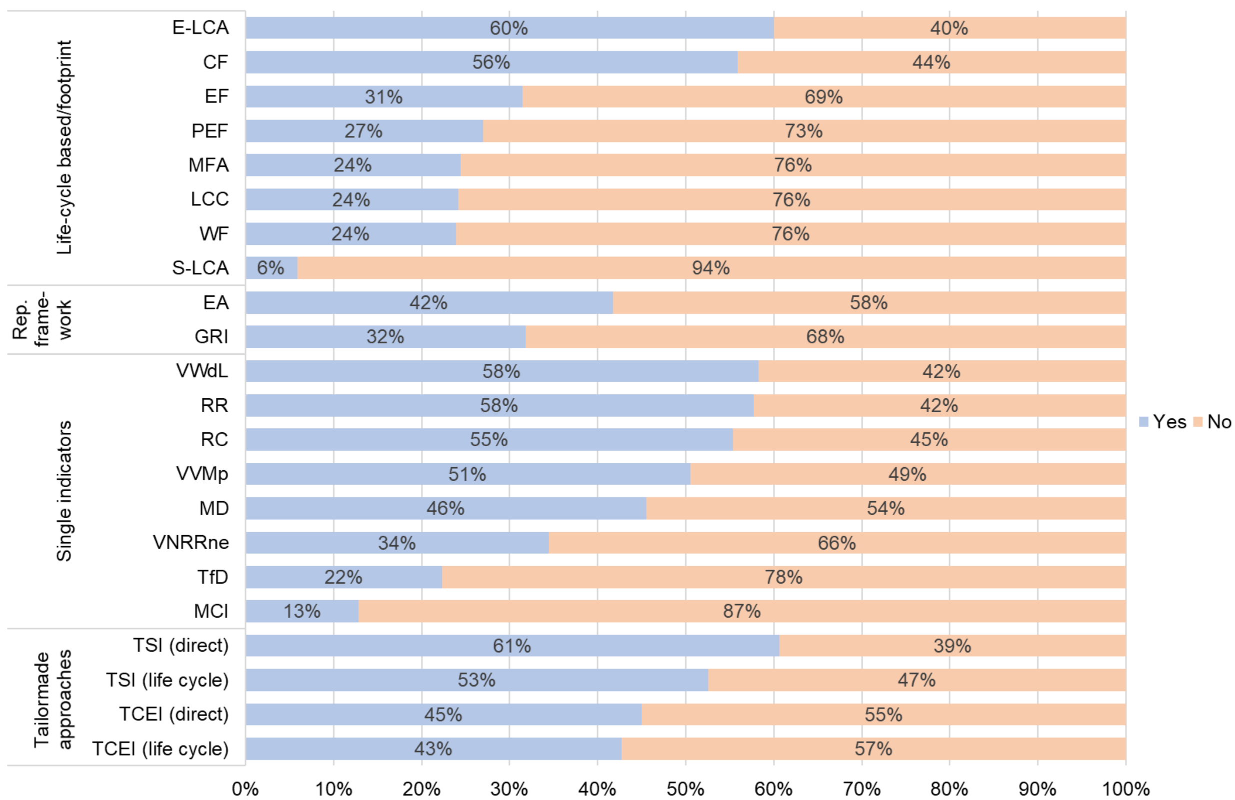


Figure 6. Application of CE- and sustainability assessment approaches (n = 98). CF, carbon footprint; EA, environmental accounting; EF, ecological footprint; E-LCA, environmental life cycle assessment; GRI, GRI standards; LCC, life cycle costing; MCI, Material Circularity Indicator (by Ellen MacArthur Foundation); MD, material durability; MFA, material flow analysis; PEF, product environmental footprint; RC, recycled content; RR, recycling rate; S-LCA, social life cycle assessment; TCEI (direct), tailor-made circularity indicators based on direct impact; TCEI (life cycle), tailor-made circularity indicators based on a life cycle approach; TfD, time for

disassembly; TSI (direct), tailor-made sustainability indicators based on direct impact; TSI (life cycle), tailor-made sustainability indicators based on a life cycle approach; VNRRne, volume of non-renewable resources not extracted; VVMp, volume of virgin material production prevented; VWdL, volume of waste diverted from landfill; WF, water footprint

Figure 6 shows that popular assessment approaches are tailormade sustainability indicators, both with a life-cycle as well as a direct impact approach, single indicators, e.g. the volume of waste diverted from landfill, and E-LCA, especially on the product level. In the group of life-cycle based methods, MFA, PEF, LCC, and S-LCA in particular are less frequently applied, the latter having the lowest application count. In contrast, CF is applied by more than half of the companies.

While the application of assessment approaches is in most cases not entirely attributable to either company or product level, there are some cases where differences were observed which may relate to the intended goal of these assessment approaches. The GRI standards, designed to help companies assess and report their impacts, are applied by >80% on company level. The same holds for EA (75%) and for tailormade sustainability indicators with direct impact (75%). E-LCA is, on the other hand, applied by around 70% of companies at the product level, signalling a high application rate within the sample. Appendix C (Table C1) provides more insights on the level on which the other approaches are applied.

The companies were also able to leave comments with respect to their assessment of sustainability and CE. Several pointed out that company size and sector were important determinants when applying a certain approach or not; therefore, the relation of both company size (micro, SME, large) and sector (production or service) with assessment application has been analysed. The complete results of this analysis are presented in Appendix C. After performing Pearson Chi-Square Tests, the correlation results between company size and CF, LCA and GRI showed statistical significance (Table 2): large companies are more likely to implement these three approaches than SMEs or micro companies. For the remaining 19 assessment approaches, no statistically significant results were obtained that suggest company size influences the use of each of the assessment approaches. In the same vein (Table 3), production companies were more likely than service companies to apply LCA, and the single indicators RR, RC and VWdL, whereas for the other assessment approaches the sector did not influence their application in a statistically significant manner.

Table 2. Applied assessment approaches differing by company size (n = 98).

Assessment approach applied	Company size			Statistical significance	
	Micro	SME	Large	p-value	Contingency Coefficient
CF	36%	60%	83%	0.001**	0.360
E-LCA	46%	56%	87%	0.004**	0.320
GRI	20%	17%	70%	0.000**	0.435

** Statistically significant at 99th confidence interval.

Table 3. Applied assessment approaches differing by company sector (n = 98).

Assessment approach applied	Sector		Statistical significance	
	Production	Service	p-value	Contingency Coefficient
LCA	69.2%	48.8%	0.043*	0.203
Recycling rate	66.7%	46.5%	0.046*	0.199
Recycled content	67.3%	40.5%	0.009**	0.259
Volume of waste diverted from landfill	68.6%	45%	0.023*	0.231

** Statistically significant at 99th confidence interval.
* Statistically significant at 95th confidence interval.

Almost two thirds of the surveyed companies indicated that they take a product life-cycle approach. Concerning the remaining third, 14% of the total assessed the company only from gate-to-gate while the rest also included the most important up- and downstream supply chain partners.

Taking a look at the interview results, around three-quarters (30) of the respondents stated that their company conducts some form of circularity assessment. These respondents provided examples of various indicators, metrics, tools and strategies which they utilised for circularity assessment (Table 4). This list highlights the diverse range of assessment approaches used and how companies are applying and integrating ‘existing assessment approaches’ within their CE assessment. Particularly, various assessment approaches designed for broader sustainability assessment are applied to assess circularity practices. Many companies have stressed that they would like to become more active in assessing CE in particular. Besides CE assessment approaches, companies also provided further insights into tailormade indicators and assessment methods in the survey, which were not always clearly attributed to either CE or sustainability assessment. Yet it emerged that CE indicators were mostly related to either waste (e.g. kg of food saved from waste or waste reduction), material use (e.g. trees saved by use of alternative material or material inputs and outputs), and the R-hierarchy (e.g. design for recycling, reassembly, reuse), while those considered sustainability indicators more often concerned energy-use (e.g. energy saved), CO_2 emissions (e.g. CO2 emissions reduced) and social aspects (e.g. number of people benefitting from a product/service).

Table 4. Approaches applied to assess CE practices by interviewees (n = 30).

Assessment approach	Times mentioned
Material inventory and mass balance	7
External approach developed by consultancy	6
LCA	4
Waste production and/or waste prevention	4
EMF Circulytics tool	2
General business performance- increased business means increased circularity	2
Linking CO_2 impacts of circular economy strategies	2
World Business Council for Sustainable Development (WBCSD) Circular Transition Indicators (CTI)	2
Ladder Van Lansink ranking of materials	1
Volume of products developed with CE strategies sold	1

4.1.2 Distinguishing between CE and sustainability assessment

Survey results (Appendix D) showed that most approaches were considered useful to both assess CE as well as sustainability. This general finding was most prominent in the single indicators included in the list, while life-cycle based/footprint approaches and reporting frameworks had a higher association with sustainability only. In particular, CF was highlighted as the approach associated most often with sustainability assessment. Indicators designed to strictly measure CE (SD CEI direct, SD CEI indirect, MCI) were naturally more frequently linked to CE assessment. Meanwhile, MFA, GRI, S-LCA and MCI were the approaches that the respondents were least familiar with.

The survey results and explicit comments by survey respondents on the need for a clarification between CE and sustainability assessment motivated analysing the difference further within the interviews. Through inductive coding, we identified two groups of respondents: the first group (two-thirds of the respondents) considered CE and sustainability assessment to be different. Within this group, the most important differentiation was that the scope of sustainability assessment was characterised as wider, including more elements that would be listed under the social dimension of sustainability. In the same group, interviewees indicated that CE assessment would therefore form part of sustainability assessment. Furthermore, CE assessment was considered to be more straightforward, since it is more directly linked to material use, which is relatively simple to monitor. Moreover, it takes place in the context of industrial processes, which are generally more measurable. Other differences were that CE assessment is mainly linked to resource management, that it is less verifiable because of its novelty, and that it is focused on high-value reuse of resources.

The second group, composed of approximately one-third of the interviewees, highlighted that CE and sustainability assessment are the same. They, for example, considered CE to be a new version of sustainability, with the existing sustainability assessment tools applicable to CE as well. Social aspects were also considered a central part of CE by a few interviewees, while others mentioned that, to them, "*something cannot be circular if it is not sustainable. So in the measurement, there is no difference*" (micro company, accommodation & food service activities sector). Finally, some considered CE and sustainability to be integrated so densely that any differentiation in terms of assessment was not necessary.

4.2. Development of CE and sustainability assessment approaches

4.2.1. Stakeholder involvement

The companies answering the survey indicated that 39% of them did not create their own assessment framework, 24% have developed their framework internally, and 27% worked with external partners (Figure). Slightly less than half of those external stakeholders were consultancies (16), followed by universities (12) and other partners (11); also, several survey respondents involved more than one of these stakeholder groups. We further addressed the assessment development process and the inclusion of stakeholders in the interviews.

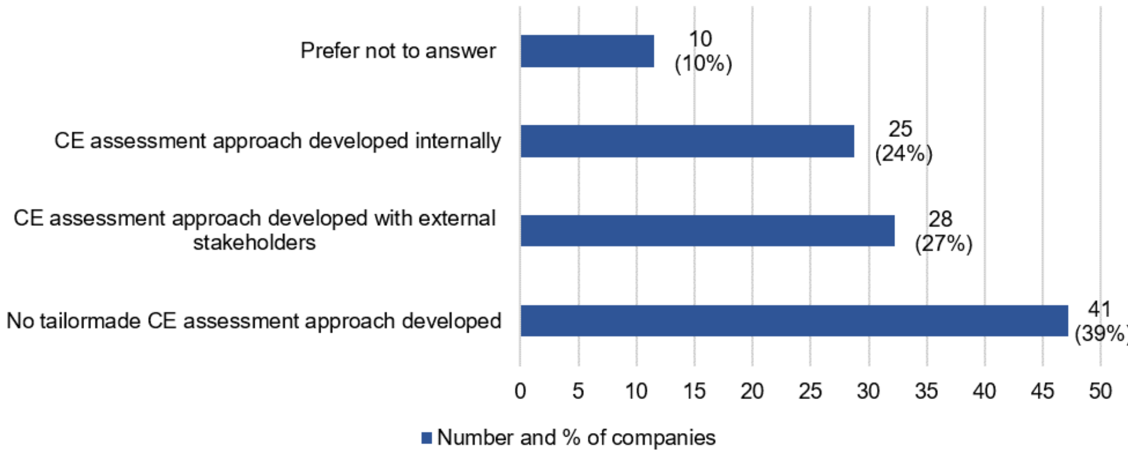


Figure 7. Involvement of external partners in development of tailor-made CE and sustainability assessment framework (n = 104).

In a first step, interviewed companies mostly consulted internally with their employees. Frequently, they created cross-departmental focus groups to develop a sustainability or circularity assessment in line with their own corporate strategy pillars. This assessment was often based on existing industry standards, such as those from the GRI, as well as the sustainability reports of other companies. Several respondents mentioned that they did not develop specific tools for CE assessment but instead relabelled some of their existing environmental sustainability indicators as CE indicators. Upper management engagement was crucial to starting the assessment development process. However, in order to become more circular or sustainable, assessment development should be diffused through the whole company to create a better understanding of sustainability and CE amongst employees. After internal consultation, three-quarters of all interviewees also involved external stakeholders; those who did not involve external stakeholders refrained from doing so mostly in relation with the CE assessment, which was considered technical, and they perceived little benefit of stakeholder feedback. A few micro companies also simply did not have the resources to involve external partners.

Overall, external stakeholder engagement was seen as essential by a large majority of the interviewees. Non-technical stakeholders played a central role in determining companies' strategic sustainability priorities, supporting and approving corporate activities in their respective communities. The assessment was then adapted to these strategic goals through, for example, stakeholder workshops or a materiality assessment by means of a stakeholder survey. Such surveys were a frequently used tool, mostly by large companies, to collect feedback, with practitioners highlighting the need for common understanding of the issues at hand in order to correctly allocate priorities. Our findings demonstrate that for companies engaged with CE, these stakeholder surveys are being utilised within the context of CE assessment. For example, for large companies, shareholders and investors are putting CE on the strategic agenda, driving the inclusion of CE in the assessment process.

Frequently included stakeholder groups were suppliers with which companies had close relationships, clients and universities. Companies had different forms of collaboration with these groups. The initiative to create assessments usually came from larger companies in the supply chain. Their collaboration with the "preferred suppliers" was sometimes based on joint method development, but more often on delivering data regarding the sustainability impacts of upstream production steps. Companies' clients were the second largest group that influenced corporate assessment practices by e.g. stipulating certain certifications or indicators to be reported in the tenders the respondents were bidding for, such as Environmental Product Declaration, SA8000 or ISO 14001. Companies also considered the clients' needs and knowledge of software tools when opting for a certain assessment procedure. Following this, for companies with a larger product portfolio, assessment was described as more complex. Conducting client workshops was a frequent approach to identify their needs with regards to the companies' impact assessment. Finally, universities were often involved to either jointly develop an assessment methodology or to verify the scientific rigour of the assessment process.

Consultants were at times hired to support the assessment process, both through tool development and assistance with its implementation. This collaboration allowed the consultants to continuously adapt and improve their assessment methods. Furthermore, consultants also provided expert knowledge regarding life cycle inventory data of secondary materials used as production inputs.

Finally, larger companies in particular were working on standardising assessment approaches within industry groups such as Factor 10 of the WBCSD or the CE100 by the EMF. While they themselves did not develop the tools, they conducted pilots and provided feedback to the working groups. In contrast, smaller companies often did not assess their activities in a quantitative manner but had an open ear for feedback from their clients and employees, as to allign their activities with their often-idealistic corporate values.

4.2.2. Assessment needs and preferences

Overall, respondents indicated that expert input would be moderately beneficial throughout the assessment phases listed, except for *Internal communication of results*. Even though the need for expertise was similar in both sustainability and circularity phases, Figure 8 shows it was considered slightly more beneficial for the implementation of circularity assessment approaches than for sustainability assessment approaches.

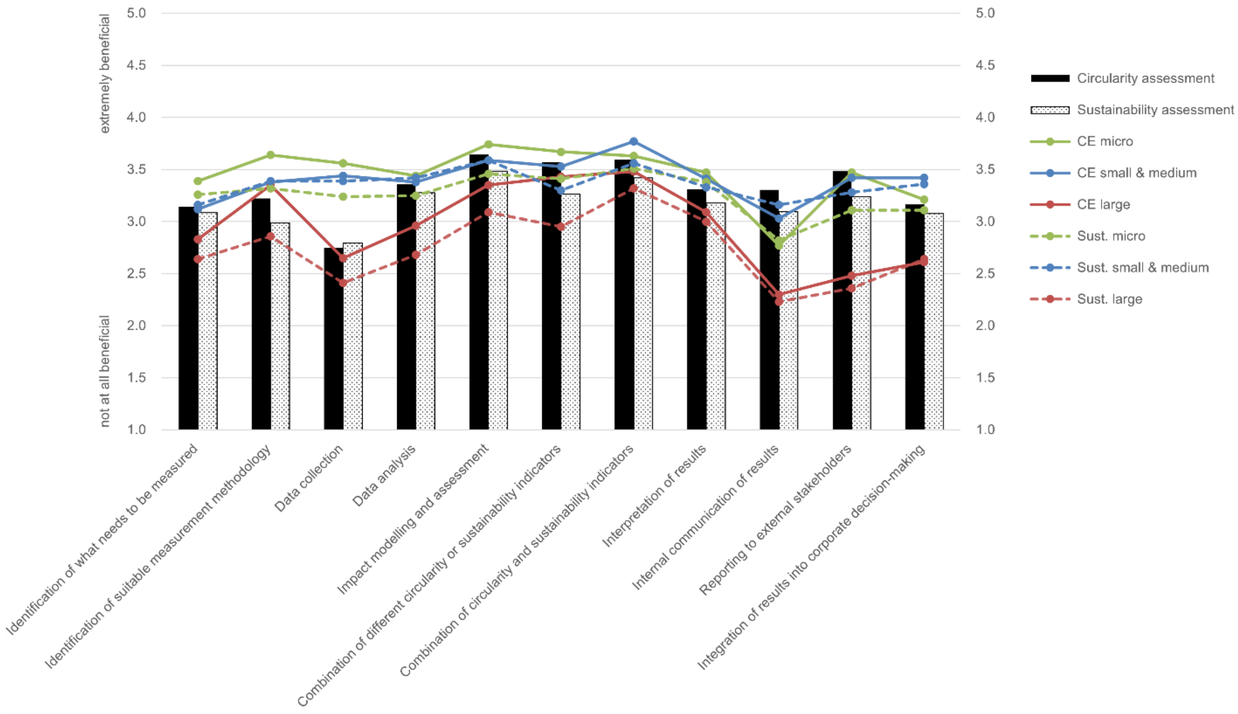


Figure 8. Benefit of expert support for sustainability and circularity assessment, by company size (n = 101).

We also found that large companies had a considerably lower need for expert involvement than SMEs and micro companies. It was further observable that the spread between benefitting from help between circularity (higher) and sustainability (lower) assessment was the highest within large companies, while SMEs and smaller companies seemed to potentially benefit more evenly from both circularity and sustainability assessment support.

When contrasted with the interview findings, it is interesting to observe that micro companies simultaneously form part of the group of companies which seem to potentially benefit the most from external assessment, while also considering assessment in general as superfluous.

With regards to the development of future CE assessment approaches, almost half of the respondents designated the supply chain to be the most suitable level for assessment, given the collaborative nature of CE practices. However, it was also acknowledged that this might be too complex, especially for large companies with an extensive portfolio of products and their respective supply chains. About a third of interviewees proposed that the level of assessment should be adapted to the context. A similar number of respondents advocated for employing an assessment on organisational level, especially if a company provided services or included internal supply chains. Yet, again, it was argued that companies were using several assessment tools on an organisational level, so adding more might not always be favourable nor feasible, especially in the case of a diverging product range. The product level was suggested by about a quarter of companies, with the proposition that metrics should be clearly measurable and not subjective. According to them, it was easier to establish a product's rather than a company's degree of 'circularity', given there was no clear benchmark against which to compare company circularity. Other levels proposed included project level, mainly raised by construction companies, the regional, business group or portfolio level.

4.3. Benefits of - and barriers to - circularity assessment

The 30 interviewed companies which stated that they implemented some form of CE assessment, discussed the perceived benefits they obtain from this assessment. Respondents could mention more than one benefit and through the inductive coding process, each benefit was grouped into one of two domains: (1) external communication and collaboration or (2) internal improvements and insights. The most frequently mentioned benefits are presented in Table 5.

Table 5. External and internal benefits of CE assessment ranked by number of times mentioned by interviewees (n=30).

#	External communication and collaboration	Number of interviewees who mentioned the benefit
1	Marketing and improving reputation of company	6
2	Communicating and reporting to stakeholders	6
3	Communicating to clients	5
4	Providing evidence of activities to increase transparency	5
5	Identifying opportunities and evaluating collaboration	3

#	Internal improvements and insights	Number of interviewees who mentioned the benefit
1	Improving and internal optimising of CE strategies	7
2	Providing insights into broader sustainability performance	5
3	Enabling a learning process and cultural change (employees)	5
4	Developing company strategy and vision (future planning)	4
5	Allowing for comparability and identifying market opportunities	2

Generally, the interview participants discussed how conducting some form of CE assessment has benefited their marketing and external communication processes with stakeholders and clients in particular, as the results demonstrate the value of adopting CE strategies. Internally, responses highlight that for the companies, the entire CE assessment development process resulted in a positive learning experience, rather than from only receiving the final assessment result. Interestingly, investors were only mentioned once with relation to the benefits of CE assessment, suggesting that in its current form, CE assessment approaches are not necessarily integrated within management level decision making. In addition, several participants indicated that although through CE assessment they have been able to improve collaborations, the assessment process always needs an initial goal, *"Are we measuring CE to involve different members of the chain or are we measuring for the sake of measuring?"* (micro company, Other services sector).

The 13 companies which stated that they did not conduct any type of CE assessment then elaborated on the 15 main barriers encountered when considering implementing a CE assessment approach, presented in Figure . Through the inductive coding approach, two key categories of barriers became apparent within the interviews: (1) internal and (2) external. Within this second category, codes were grouped to form a subcategory of methodological barriers. Generally, the nine external barriers relate to the fact that circularity assessment was perceived as too complex. Furthermore, several external barriers are influenced by the current absence of a benchmark or standard for CE assessment, causing difficulty for companies to contextualise their CE assessment results and integrate them within their broader sustainability and/or communication strategies. For the seven internal barriers to CE assessment identified, interviewees commented that the internal capacity of their companies to conduct yet another kind of assessment was limited. This was emphasised by the fact that it was unclear how the assessment results would be used, making it more difficult to justify allocating resources. Within these responses, no correlations were observed between company size, sector or country and their respected barriers and/or benefits.

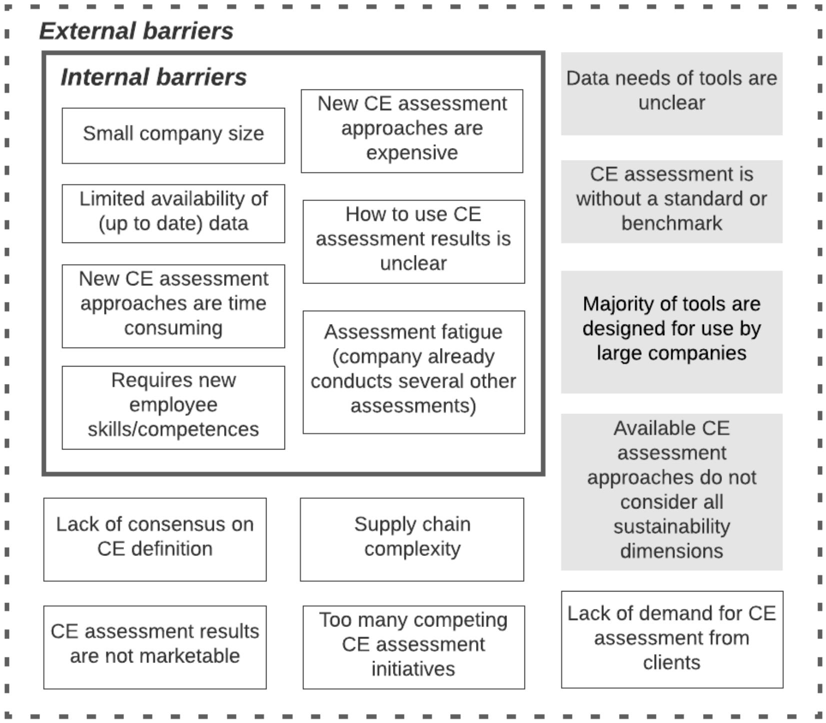


Figure 9. The seven internal and nine external barriers to CE assessment identified by companies not conducting any form of CE assessment. The four external barriers shaded in grey form the subcategory of methodological barriers (n = 13).

5. Discussion

Overall, around a third of the companies in the survey sample do not conduct any CE or sustainability assessment. Also, as previously identified in literature, a low uptake of the CE assessment approaches proposed in academic literature (Stumpf et al., 2019; WBCSD, 2018) was found. Within this study, this is likely influenced by the composition of the sample, consisting mainly of micro companies (45%) and SMEs (33%). The survey results further show that a slight majority of companies engaged with CE assess their practices on a company, rather than a product level. When inquiring about their preferred level of assessment, the supply chain and organisational level are, despite their complexity, indicated as most valuable. Previous inventories of CE assessment approaches find product-level assessment approaches to be most commonly proposed (de Oliveira et al., 2021; Roos Lindgreen et al., 2020) and signal the need for methodological development of supply chain and organisational approaches (Harris et al., 2021; Walker, Vermeulen, et al., 2021). For company level assessment, respondents mainly rely on tailor-made indicators. On a product level, however, the most frequently used tool is LCA, a standardised methodology. This finding is in line with research and industry efforts to align LCA and CE assessment (Ávila-Gutiérrez et al., 2019; Niero et al., 2021). Recently, MFA has been promoted as an apt approach for circularity assessments (Kalmykova, Sadagopan & Rosado, 2018); however, within our sample, there was both a low application of and familiarity with MFAs from companies, irrespective of their size or sector. However, a significant correlation was observed between company size and the application of three out of 22 assessment approaches: GRI indicators, CF and LCA. This might point to both institutional conditions (e.g. the increasingly obligatory nature of sustainability reporting and rise in industry reporting initiatives) and resource availability as drivers for the uptake of assessment approaches by large companies (Di Maio & Rem, 2015). We also found that companies in the production sector were significantly more likely to implement LCA and three single indicators related to resource flows (RR, RC and VWdL) which could be explained by the higher importance of such flows in companies which are transforming materials into products. In contrast, companies in the service sector, which are more often working with intangible products, might apply different CE strategies, subsequently resulting in different impact assessment needs (Blomsma et al., 2019).

With respect to CE and sustainability assessment, findings here show that for companies, the distinction between the two is not clearly defined. This is in line with the persisting blurred perspectives of the two paradigms from both companies and academic literature (Schoeggl et al., 2020; Walker, Opferkuch, et al., 2021). Most assessment approaches were considered by survey participants to be useful to assess CE as well as sustainability. Yet, from the interviews, two-thirds of respondents perceived CE assessment as a part of a wider sustainability assessment, where the latter encompasses the social dimension as well as certain environmental aspects which interviewees considered being not directly related to resource use (e.g. CO_2 emissions and energy use). Some companies with CE 'in their DNA' equated their general performance assessment with CE performance. However, as various authors have indicated, CE practices do not always lead to improved sustainability impacts (Blum et al., 2020; Corona et al., 2019). While our research demonstrates the confusion companies have regarding the differences and similarities between CE and sustainability assessment approaches, the majority of interviewees agreed that sustainability takes precedence over CE, as is promoted in other studies (Kristensen & Mosgaard, 2020). Regarding tailor-made approaches, a small majority of companies in our sample that developed assessment approaches have collaborated with external parties, primarily consultancies, but also universities or supply chain partners. In such collaborations, consultancies and universities often provide knowledge, in line with Pereira and Vence (2021). Consultancies often help companies to adapt existing assessment approaches to corporate realities and to generate information for decision-makers. Furthermore, the consultancies also use their assignments to improve their tailor-made methodologies. Meanwhile, supply chain partners are mainly involved for data collection. This draws attention to the ability of CE strategies to increase collaborations along the supply chain (Brown et al., 2019). At the same time, closer collaboration is needed to address the existing disconnect between research and practice with respect to assessing (the sustainability of) CE practices (Harris et al., 2021).

In the development process, larger companies often make use of available frameworks which support mandatory reporting, such as the GRI as well as tendering requirements made by their governments or clients. While using existing frameworks can be considered a top-down approach to developing assessment approaches, the involvement of stakeholders enables a bottom-up co-creation of assessment approaches, potentially resulting in enhanced assessment capabilities. This reflects two established findings from sustainability assessment literature: (1) Tailor-made assessment approaches better reflect companies' business realities, and (2) the involvement and participation of stakeholders is crucial for the development and application of assessment methodologies (Maas et al., 2016; Sala et al., 2013). Regarding the requirements for external assistance when developing CE and sustainability assessment approaches, we find that the company's expectations are similar for both CE and sustainability assessment. This indicates there is a similar level of understanding of the two concepts, although some tendencies stood out. Primarily, companies indicated they need the most external support when deciding how to combine circularity and sustainability indicators as well as to model the impacts of their CE practices. The latter is also one of the most challenging phases documented in literature, especially for SMEs not experienced with impact assessment methods of life cycle-based/footprint-based assessment approaches (Chevalier, Reyes, Laratte, 2011). Interestingly, external expertise was considered least beneficial for internal communication within the survey, whereas internal improvements and insights were established as major benefits of CE assessment in the interviews.

This study, to our knowledge, is the first to identify the benefits of and barriers to CE assessment within the private sector. Within the interview sample, three quarters of companies declared that they conducted some form of CE assessment, whilst the remaining one quarter did not. The latter group pointed to seven internal and nine external barriers to CE assessment; a categorization of barriers that has previously been found in literature on sustainability assessment. Some of those barriers were categorised as methodological issues, related to the current absence of any standard or benchmark for CE assessment. Companies explained that this has resulted in a lack of demand or general awareness for CE assessment from clients, as similarly found by Dröge et al. (2021b). Interestingly, for the companies that had implemented some form of CE assessment, the primary benefits concern the internal optimisation of CE strategies and the use of CE assessment results within marketing and external communication. This result highlights the value companies obtain from the overall learning process associated with developing and implementing CE assessment, as companies were able to further integrate CE within their corporate sustainability and strategic management processes, as is expected by Skærbæk and Tryggestad (2010) and Lozano (2015). Additional benefits of CE assessment, such as increasing transparency and identifying opportunities for collaboration, were in line with the general benefits of sustainability assessment a company will experience, as described in Bae & Smardon (2011).

With respect to most of the internal barriers to CE assessment we identified (e.g. small company size), our findings suggest that they are consistent with general barriers to sustainability assessment approaches, as seen in Johnson & Schaltegger (2016) and Jaramillo et al. (2019). This suggests that ongoing efforts to develop a single standard for CE assessment, e.g. by the ISO/TC 323 (ISO, 2020), will not remove all barriers to CE assessment. This highlights the continued importance of acknowledging existing barriers to assessment within sustainability research; future CE assessment approaches must consider them in order to increase the accessibility of sustainability assessment in general as opposed to amplifying assessment fatigue (Khalid et al., 2020). Our study also reveals the limited assessment capacities of SMEs, as already established in previous studies (Johnson & Schaltegger, 2016) and stresses the benefits of CE assessment with the hopes that SMEs and micro companies can be informed and supported to allocate resources for this endeavour.

Finally, the results of this study call for a reflection on a long-discussed paradox associated with assessment: standardisation vs. tailoring of assessment approaches. First, as already mentioned, our results showed a key barrier for companies to conduct CE assessments was a lack of relevant benchmarks or standards, prompting a call for some form of standardisation of CE assessment and reporting. However, we have found that companies obtained numerous benefits through the process of developing tailormade CE assessment approaches, benefits which would be potentially reduced, if standardisation was to occur if standardisation was to occur in an overly prescriptive way. At the same time, it is important to acknowledge that companies selecting their own CE indicators opens the doors for incidences of greenwashing, as observed in recent studies on CE assessment and reporting guidelines (Pauliuk, 2018; Opferkuch et al., 2021). These studies indicated that companies are able to cherry-pick CE indicators, reporting more on aims and intentions rather than actual performance. In response to this, we refer to the suggestions of previous studies including Kühnen and Hahn (2018), who discussed this paradox within the context of social sustainability assessment. The authors suggest that while a normative consensus is emerging on what kind of indicators are to be included, decision makers have to accept that at least part of the assessment results will remain incomparable, but are adapted to the respective context (Kühnen & Hahn, 2018). Similarly, in 2001, Veleva et al., noted that lists of environmental performance indicators provided by global sustainability frameworks (e.g., GRI) offer very little insights into how a company may annually select, revise and re-select indicators they deem more accurately measure sustainability. To potentially overcome the standardisation vs. tailoring paradox, Veleva and Ellenbecker (2001) suggest the use of core and supplemental indicators, facilitating both comparability of performance as well as flexibility for context-specific aspects, a suggestion which could be utilised within the context of assessing CE practices.

5.1 Recommendations for academia

While academia was swift to propose a ubiquity of assessment approaches designed to assess circularity, sometimes explicitly identifying their relation to sustainability, less robust knowledge has been developed on the topic of assessment benefits. How the assessment process and results are used for strategic decision making should be further investigated to direct the development of assessment practices. Secondly, such assessments often require expert knowledge and data that might not be readily available in the private sector. Therefore, we recommend that scholars should attempt to create CE assessment approaches with benefits that are validated by their end-users (companies), as to facilitate their uptake. For this, a clearer picture of company needs and capabilities is required to design assessment approaches that match business realities, as has been the case for sustainability assessment. For example, companies expressed they would appreciate if CE assessment were to include the whole life cycle or product supply chain, which implies the involvement of a wider set of stakeholders. When designing CE assessment approaches, it is thus essential to include not only the immediate stakeholders of companies, but to ideally involve the actors involved throughout the entire life cycle of the companies' products. While this has also been advocated for in sustainability assessment (Sala et al., 2013), the life cycle perspective inherent in CE provides a comprehensible and accepted rationale for the co-creation of CE assessment approaches. It could be the role of scholars to facilitate the joint development of assessment approaches that help to identify and involve such stakeholders, promoting the integration of participatory processes, whilst ensuring that interests beyond the businesses' stakes are covered (Keeble et al., 2003). Future studies could also integrate such participatory processes for assessment development in fields not directly related to CE such as innovation and strategic management studies.

Finally, we recommend that academia should be clear in disseminating the message that CE is best used as a means to achieve sustainability and that assessing circularity in itself would not serve this purpose. While circularity and sustainability indicators tend to overlap in some instances, assessment should be able to reveal whether a CE practice will make a company and its partners more sustainable or not. Nevertheless, we argue that CE assessment can still provide companies with insights valuable to managing their resources; it could be seen as a precursor of and not a substitute for sustainability assessment. After all, to assess the impact of resource flows on sustainability, these flows first need to be identified and quantified. For this, we recommend incorporating the use of existing assessment approaches such as MFA-based methodologies, instead of promoting the development of new assessment approaches from scratch (Birat, 2015 Kalmykova et al, 2018). Instead, more academic attention could be paid to understanding assessment capacities of companies and aligning their needs with the existing methods, thus reducing assessment fatigue. This should be done considering the requirements and developments of international environmental standards, tools and labels such as the proposed Corporate Sustainability Reporting Guidelines (EC, 2021).

5.2 Recommendations for practitioners

Corporate ambitions that go beyond profit maximisation are commendable; however, assessment is needed to ensure whether these ambitions can also be transformed into practices that result in the desired impacts; preferably prior to implementing such practices. For impact assessment, stakeholder involvement is recommended for setting priorities, given the strong context dependency of the impacts which CE practices can have on CS. Whereas external experts can help during this process, corporate learning associated with the process of assessment will facilitate cultural change. This requires cross-sectional involvement of employees as well as close collaboration with suppliers and clients. The scope of the assessment should be determined by the life cycle of a product or a cumulation of different products, where in a first step, the resource flows are to be mapped - e.g. through the application of MFA-based approaches. Then, in line with recent research, only in a second step the related impacts in the three sustainability dimensions can be established through application of life-cycle impact assessment methods (see Kalmykova et al., 2018; Maga & Thonemann, 2021; Schulte et al., 2021; Rufí-Salís et al., 2021). It should be noted that traditional MFA-based methods do not, in contrast to tools such as the CTI, provide insights into the different recovery options inherent in material or product flows (WBCSD, 2020). Transparency on the recovery options of resource flows can offer information on suitable CE strategies to take. It needs to be underlined that existing data on resource flows can be used for both assessment steps, thus streamlining the data collection efforts. Further guidance on design strategies, setting up assessment processes for manufacturing companies and balancing the trade-offs when making decisions based on assessment results are covered by Diaz et al. (2021) and Kravchenko et al. (2020; 2021).

6. Conclusion

In this article, we collected empirical evidence on the development and application of assessment approaches by European frontrunner companies engaged with CE practices. The results show that despite ample assessment propositions from the academic realm, only few are implemented by companies. Instead, companies most often develop their own tailor-made assessment approaches to assess sustainability and

CE, frequently in collaboration with consultancies and universities. The applied assessment approaches are either based on direct impact or life cycle-based methods, such as LCA. In addition, our results suggest that the majority of companies engaged with CE are aware of the importance of assessment and are applying assessment approaches that are life cycle based.

The distinction between sustainability and CE assessment is seldom explicit, but the results show that companies perceive sustainability assessment to have a wider scope, notably also including the social dimension. While CE assessment is often understood to fall under the environmental dimension and mainly concerns material use, it provides pertinent information on resource flows, the impacts of which can then be assessed from a sustainability perspective. The companies that conduct such a CE assessment use the results to support external communication and provide strategic insights into resource use. Yet, several of the interviewed companies have abstained from conducting a CE assessment, because of a lack of an assessment standard, limited client demand as well as having only moderate assessment capabilities and capacities.

We are aware that the results of this article are subject to some limitations: the majority of both the survey and interview respondents are micro companies, asking for the results to be generalised with caution. However, given that the majority of companies in the EU are either micro companies or SMEs, the population to which the findings are relevant could be considerable nevertheless. Furthermore, we received several comments in the survey that pointed out that the questionnaire seemed to be designed for large companies, with questions covering a rather extensive list of topics. Therefore, we paid special attention to inclusively addressing, for example, the distinction between CE and sustainability assessment and the benefits and barriers to CE assessment in the interviews. Additionally, we acknowledge the overlapping nature of various assessment approaches described within this study (e.g. MCI, MFA and single indicators) which may have distorted some of the results, potentially further complicated by companies' lack of familiarity with assessment approaches.

The empirical insights into the assessment practices of frontrunner companies engaged with CE, as identified in this article, can support the design of assessment approaches that are (1) adjusted to company needs, increasing their applicability and (2) able to accurately assess sustainability impacts of CE practices. This sustainability assessment could in part be informed by the quantification of resource flows, making circularity assessment a precursor and not a substitute for assessing sustainability. Furthermore, future research could build on the presented findings by analysing the general usefulness and suitability of assessment processes and results in facilitating transformative sustainable change. As mentioned, we recommend both academia and practitioners to drive the involvement of various stakeholders to co-create assessment approaches, which, by improving company capabilities, may have the potential to accelerate private sector initiatives towards SD. Ultimately in the future, clients and other stakeholders will probably more frequently request companies to communicate their contribution of their CE practices to the SDGs in a transparent and systematic manner, for which assessment approaches are essential.

Appendix A: List of included CE networks

Table A1. CE networks by country.

Italy	Netherlands	International[a]
• Atlante Italiano dell'Economia Circolare • Italian Circular Economy Stakeholder Platform (ICESP) • Circular Economy Network • Mercato Circolare	• Circulair ondernemen • Ontertekenaars van Grondstoffakkoord • Circle Economy • Holland Circulair Hotspot • Circulaire Coalitie	• Ellen MacArthur Foundation CE 100 • Circular Economy Club

[a] Included companies needed to have primary business operations in Italy or the Netherlands.

Appendix B: Interview guidelines

1. Why does your company assess circularity? If not applicable, why not?

(1) If does assess CE: What benefits does your company get from assessing circularity?

(2) If does not assess CE: is the reason for this linked to the characteristics of assessment methodologies available for Circular Economy or linked with internal capacity(barriers)?

(3) If does OR does not assess CE: There are various CE assessment approaches available on various scales (i.e. material, product, organizational, supply chain). In your opinion, if we were to develop an assessment approach for circularity, what scale/level(s) should be the focus and why?

2. How does your company approach sustainability assessment and circularity measurement?

(1) If company does assess: In your opinion, what is the difference between the two?

(2) If your company does not do circularity assessment: do you think there is a difference between sustainability assessment and circularity measurement?

(3) If company does assess CE: Within your company, what was the process for creating the assessment approach for circularity?

(4) If company does assess either: How have you included stakeholders in creating a circularity or sustainability assessment process? Does this internal process differ for Circular Economy and sustainability assessment?

Appendix C: Application of assessment approaches

Table C1. Complete results of application of approaches on product and company level (n = 98). CF: Carbon Footprint. EF: Ecological Footprint. PEF: Product Environmental Footprint. E-LCA: Environmental Life Cycle Assessment. LCC: Life Cycle Costing. MFA: Material Flow Analysis. S-LCA: Social Life Cycle Assessment. WF: Water Footprint. EA: Environmental Accounting. GRI: GRI Standards. TCEI (life cycle): Tailormade circularity indicators based on a life-cycle approach. TCEI (direct): Tailormade circularity indicators based on direct impact. TSI (direct): Tailormade sustainability indicators based on direct impact. TSI (life cycle): Tailormade sustainability indicators based on a life cycle approach. MCI: Material Circularity Indicator (by Ellen MacArthur Foundation). MD: Material durability. RC: Recycled content. RR: Recycling Rate. TfD: Time for disassembly. VNRRne: Volume of non-renewable resources not extracted. VVMp: Volume of virgin material production prevented. VWdL: Volume of waste diverted from landfill.

Category	Abbreviation	Yes, on company level	Yes, on product level	Not yet, but planned	No
Life-cycle based/footprint	CF	39%	17%	16%	28%
	E-LCA	18%	42%	13%	27%
	EF	16%	16%	15%	54%
	WF	14%	10%	11%	65%
	MFA	13%	11%	4%	72%
	PEF	11%	16%	15%	58%
	LCC	7%	17%	10%	66%
	S-LCA	5%	1%	16%	78%
Reporting framework	EA	32%	10%	13%	45%
	GRI	27%	5%	9%	59%
Single indicators	VWdL	38%	20%	8%	34%
	RR	36%	22%	5%	37%
	VVMp	29%	22%	12%	38%
	RC	23%	32%	4%	40%
	VNRRne	20%	14%	11%	54%
	MD	16%	30%	1%	53%
	TfD	9%	13%	5%	73%
	MCI	7%	6%	12%	76%
Tailormade indicators	TSI (direct)	46%	14%	12%	27%

TSI (life cycle)	27%	26%	10%	37%
TCEI (life cycle)	24%	19%	8%	49%
TCEI (direct)	21%	24%	7%	48%

Table C2. Complete results of application of approaches by company size (n = 98). CF: Carbon Footprint. EF: Ecological Footprint. PEF: Product Environmental Footprint. E-LCA: Environmental Life Cycle Assessment. LCC: Life Cycle Costing. MFA: Material Flow Analysis. S-LCA: Social Life Cycle Assessment. WF: Water Footprint. EA: Environmental Accounting. GRI: GRI Standards. TCEI (life cycle): Tailormade circularity indicators based on a life-cycle approach. TCEI (direct): Tailormade circularity indicators based on direct impact. TSI (direct): Tailormade sustainability indicators based on direct impact. TSI (life cycle): Tailormade sustainability indicators based on a life cycle approach. MCI: Material Circularity Indicator (by Ellen MacArthur Foundation). MD: Material durability. RC: Recycled content. RR: Recycling Rate. TfD: Time for disassembly. VNRRne: Volume of non-renewable resources not extracted. VVMp: Volume of virgin material production prevented. VWdL: Volume of waste diverted from landfill.

Category	Abbreviation	Yes (micro)	No (micro)	Yes (SME)	No (SME)	Yes (large)	No (large)	Stat. significance
Life-cycle based/footprint	E-LCA	46%	54%	56%	44%	87%	13%	0.004**
	CF	36%	64%	60%	40%	83%	17%	0.001**
	EF	32%	68%	70%	30%	33%	67%	0.986
	PEF	26%	74%	21%	79%	35%	65%	0.561
	MFA	26%	74%	23%	77%	14%	76%	0.97
	LCC	23%	77%	19%	81%	33%	67%	0.499
	WF	21%	79%	27%	73%	26%	74%	0.806
	S-LCA	3%	97%	7%	93%	10%	90%	0.586
Reporting framework	EA	33%	67%	50%	50%	45%	55%	0.35
	GRI	20%	80%	17%	83%	70%	30%	0.000**
Single indicators	MD	50%	50%	43%	57%	41%	59%	0.758
	RC	49%	51%	61%	39%	68%	42%	0.543
	VWdL	49%	51%	61%	39%	70%	30%	0.255
	RR	49%	51%	62%	38%	67%	33%	0.315
	VVMp	45%	55%	56%	44%	52%	48%	0.621
	VNRRne	35%	65%	37%	63%	30%	70%	0.888

	TfD	21%	79%	34%	66%	9%	91%	0.093
	MCI	11%	89%	21%	79%	5%	95%	0.221
Tailormade indicators	TSI (direct)	61%	39%	48%	52%	77%	23%	0.100
	TSI (life cycle)	52%	48%	52%	48%	54%	46%	0.982
	TCEI (life cycle)	44%	56%	45%	55%	46%	54%	0.994
	TCEI (direct)	37%	63%	43%	57%	52%	48%	0.502

** Statistically significant at 99th confidence interval.

Table C3. Complete results of application of approaches by company sector(n = 98).

Category	Abbreviation	Yes (production)	No (production)	Yes (service)	No (service)	Stat. significance
Life-cycle based/footprint	E-LCA	69%	31%	49%	51%	0.043*
	CF	63%	37%	46%	54%	0.099
	EF	35%	65%	28%	72%	0.467
	PEF	24%	76%	30%	70%	0.560
	MFA	21%	79%	28%	72%	0.444
	LCC	23%	77%	26%	74%	0.768
	WF	24%	76%	24%	76%	0.923
	S-LCA	4%	96%	8%	92%	0.444
Reporting framework	EA	48%	52%	34%	66%	0.182
	GRI	35%	65%	27%	73%	0.427
Single indicators	MD	43%	57%	49%	51%	0.574
	RC	67%	33%	40%	60%	0.009*
	VWdL	69%	31%	45%	55%	0.023*
	RR	67%	33%	47%	53%	0.046*
	VVMp	58%	42%	40%	60%	0.077
	VNRRne	41%	59%	27%	73%	0.164
	TfD	28%	72%	16%	84%	0.192
	MCI	11%	89%	15%	85%	0.512

Tailormade indicators	TSI (direct)	62%	38%	59%	41%	0.717
	TSI (life cycle)	57%	43%	48%	52%	0.383
	TCEI (life cycle)	47%	53%	43%	57%	0.675
	TCEI (direct)	44%	56%	41%	59%	0.828

** Statistically significant at 99th confidence interval.
* Statistically significant at 95th confidence interval.

Appendix D: Attribution of approaches to sustainability or CE

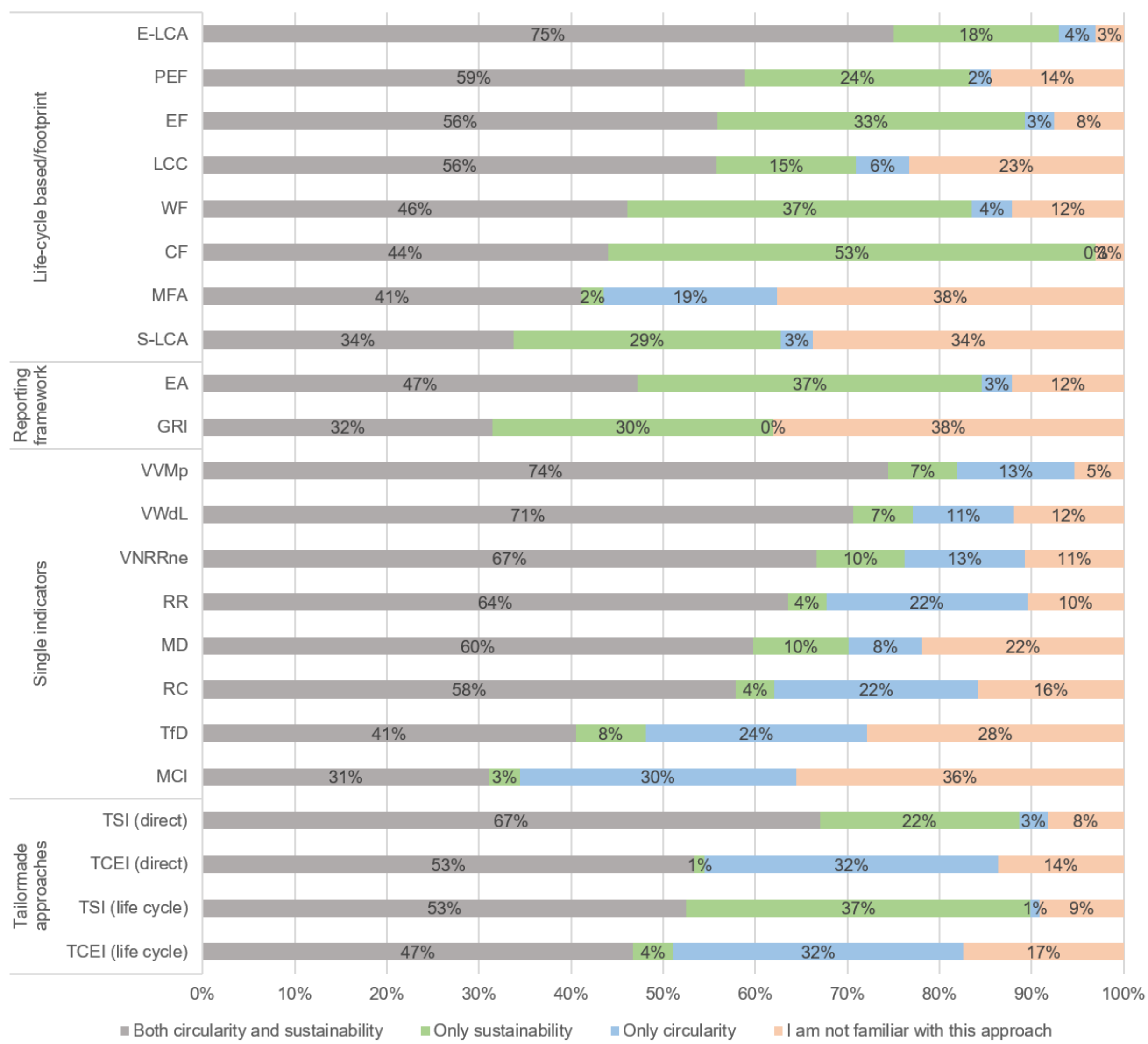


Figure D1. Attribution of approaches to CE- and/or sustainability assessment (n = 97). CF: Carbon Footprint. EF: Ecological Footprint. PEF: Product Environmental Footprint. E-LCA: Environmental Life Cycle Assessment. LCC: Life Cycle Costing. MFA: Material Flow Analysis. S-LCA: Social Life Cycle Assessment. WF: Water

Footprint. EA: Environmental Accounting. GRI: GRI Standards. TCEI (life cycle): Tailormade circularity indicators based on a life-cycle approach. TCEI (direct): Tailormade circularity indicators based on direct impact. TSI (direct): Tailormade sustainability indicators based on direct impact. TSI (life cycle): Tailormade sustainability indicators based on a life cycle approach. MCI: Material Circularity Indicator (by Ellen MacArthur Foundation). MD: Material durability. RC: Recycled content. RR: Recycling Rate. TfD: Time for disassembly. VNRRne: Volume of non-renewable resources not extracted. VVMp: Volume of virgin material production prevented. VWdL: Volume of waste diverted from landfill.

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Chapter 5. Assessing the impact of circular strategies at the company level: design and validation of the SCEIA framework (Strategic Circular Economy Impact Assessment)

Erik Roos Lindgreen, Roberta Salomone, Tatiana Reyes

Abstract

Companies require assistance in assessing the sustainability of circular solutions prior to strategic decisions on their introduction. This article proposes and validates an ex-ante, holistic circular economy (CE) assessment framework SCEIA (Strategic Circular Economy Impact Assessment) at company level, using a mixed-methods approach. First, the framework's normative core and objectives are formulated. A critical literature review method is used to position this article's view that CE, as a concept, is valuable only when contributing positively to all three dimensions of SD. Secondly, a descriptive literature review of previously applied methods in CE assessment is used to design the framework's basic methodological structure, matching its previously defined normative core and objectives. The selected methods comprise a combination of the existing methods of Life Cycle Assessment (LCA), Life Cycle Costing (LCC), Social Life Cycle Assessment (S-LCA) and Material Flow Analysis (MFA). The number of resulting indicators can subsequently be tailored to the company's goals through a materiality assessment (MA). A Multi Criteria Decision Analysis (MCDA) TOPSIS approach is optional to assist in decision-making. Thirdly, the procedure of using the framework in a decision-making process at the strategic level is made explicit by connecting it to existing strategic decision-making frameworks and specifying its application routine. As a final step, the framework is validated through a dual triangulation process, consisting of an expert panel survey and online practitioner focus groups with companies. The expert panel consists of eleven CE assessment experts both from the academic realm as well as the private sector. Their input functions mainly as validation of the framework's objectives and methodological setup, while focus groups with five companies provided insights into its practical feasibility. The triangulation process leads to various revised characteristics, which are reported on together with any potential contrasting inputs. The final SCEIA framework is designed to deliver valuable insights into the impacts of company-level CE activities. It has a modular structure and is applicable to companies with different levels of experience with assessment while preventing trade-offs and burden shifting,

Keywords

Circular Economy, corporate sustainability, resource management, sustainability assessment, participatory research.

1. Introduction

The Circular Economy (CE) has increasingly been discussed as a solution to resolve the sustainability issues associated with society's current linear economic development model (Hartley et al., 2020; Kristensen & Alberg Mosgaard, 2020). CE comprises an extensive umbrella of ideas and strategies that are characterized by their aim to strive for increased resource efficiency through the closing of resource loops (Ghisellini et al., 2016; Blomsma & Brennan, 2017). These strategies have been implemented on different levels: the macro level (city, country and beyond), meso level (industrial symbiosis networks), and micro level (products, firms) (Geng et al., 2012). With respect to the latter, private sector companies have been described as particularly influential in the CE transition, primarily due to their intensive resource- and energy use and, thus, strong influence on resource life cycles (Blomsma et al., 2019; Pieroni et al., 2020). While CE promises profitability through e.g. cost reduction and increased resilience to resource price fluctuations, the uptake of its principles by manufacturing companies is still limited (Pieroni et al., 2020; Howard et al., 2019).

The contribution of CE strategies to realizing sustainability goals is ambivalent; various examples in which higher resource efficiency does not lead to benefits in the environmental, economic or social domains of sustainability are available (Blum et al., 2020; Kravchenko et al., 2019). While CE practices have the potential to contribute positively to several of the globally accepted Sustainable Development Goals (SDGs), various SDGs appear to have no relation to CE practices (Schroeder et al., 2018). Additionally, while the inclusion of positive social aspects as a result of CE would be necessary to support Sustainable Development (SD), the social dimension is commonly overlooked in CE strategies (Calisto Friant et al., 2020; Kirchherr et al., 2017; Schöggl et al., 2020). In the context of the accelerated climate emergency and persisting global socioeconomic inequalities, the need for the assessment of the sustainability impacts of CE strategies before their introduction becomes pertinent (Corona et al., 2019). The finding that the extent of the positive impacts of CE business models remains uncertain for many companies also points to a need for the increased uptake of assessment approaches (Das et al., 2021).

In the past few years, a new research field has dedicated itself to how CE assessment tools could contribute in assisting firm-level decision making process (Vinante et al., 2020). However, thus far, no scientific consensus or standardized approach exists on how to assess an organization's degree of circularity (Kristensen & Alberg Mosgaard, 2020). CE assessment approaches seem to be used relatively rarely by organizations (Stumpf et al., 2019) and recent reviews on current assessment methods indicate methodological shortcomings that might lead to undesirable burden shifting from reduced resource use to increased environmental, economic or social impacts (Corona et al., 2019). Furthermore, structured guidance in strategic decision-making is considered particularly relevant as CE experimentation appears to be largely based on intuitive judgements and decisions, instead of on specific decision criteria (Konietzko et al., 2020). Decision-makers are said to recognize the importance of integrating corporate sustainability in a company's strategy, but still rarely do so (Engert et al., 2016). Integrating sustainability in strategic decision-making is still challenging due to the complexity of environmental and social criteria added to the already complex business, technical, and legal requirements (Kravchenko et al., 2021).

With these issues in mind, the aim of this article is to design the foundations of a new company-level CE assessment framework, providing an assessment solution that prevents unwanted burden shifting. The framework is designed to assist in the strategic decision-making process of selecting a certain CE solution. Strategy is here interpreted as a way forward to achieving SD and its objectives (Waas et al., 2014). This level of decision-making was selected because of the apparent lack of including sustainability considerations in strategic decision making, as well as the need for fundamental (i.e. strategic) changes to conducting business to be able to reach the UN SDGs, among other global sustainability targets (Bonn & Fisher, 2011; Vermeulen, 2018). Non-strategic but incremental or marginal changes could be considered counterproductive, as they "lock up resources that could be used in a strategically smarter way" (Holmberg & Robert, 2000). It is furthermore stated that corporate sustainability can succeed only if embedded in the company's vision and strategy (Azapagic, 2003). The development and implementation of integrated sustainability and circularity assessment methods by companies has been indicated to foster strategic decision-making from a sustainability perspective (Schöggl et al., 2020).

The proposed methodology of this chapter consists of two research phases: design and validation of the framework. In the first research phase, the content of three foundational elements of the framework is designed. First, debate around the contribution of CE to SD is discussed briefly through a critical literature review, and a normative core of the assessment framework is formulated. Then, a descriptive literature review of earlier applied methodologies in company-level CE and sustainability assessment is used to collect the methodologies in line with the previously formulated normative core. Their key methodologies properties are extracted and incorporated in the framework. Also, the collected methodological elements are structured accordingly to existing strategic decision-making frameworks.

The second research phases consist of validating the framework using a dual triangulation approach. This approach consists of a panel survey with CE assessment experts and a series of virtual focus group sessions with practitioners in order to gather their inputs on, respectively, the framework's methodological aspects and feasibility. Both forms of triangulation lead to various revised characteristics, which are reported on together with any potential contrasting or unresolvable inputs.

2. Research methods

A mixed-method research design is used throughout this study. The first research phase, in which the preliminary framework is designed, includes a literature-based approach, consisting of both a critical literature review as well as the use of literature on strategic decision-making. In the second research phase, this preliminary framework is validated, using both an expert panel survey and qualitative practitioner focus groups. The second research phase is characterized as a triangulation step: the means by which different perspectives are fed back into the preliminary framework to challenge and / or validate its initial methodological setup (Turner & Turner, 2017). A schematic presentation of the research design is shown in figure 1.

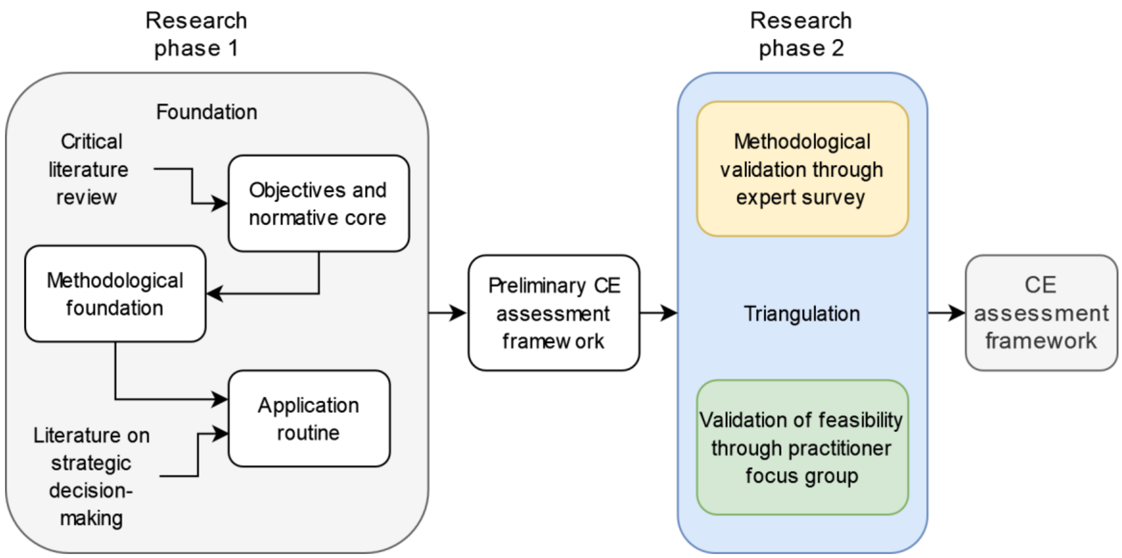

Figure 1. Schematic overview of research design.

2.1. Research phase 1: designing the framework foundation

The foundation of the framework consists of three elements: its normative core (i.e. framing the ideal outcome of applying CE strategies), its methodological aspects to assess progress towards the ideal outcome, and the structure of the framework (i.e. its application routine). Formulating the normative core is based on positioning the framework in the context of the connections between CE and Sustainable Development (SD). To synthesize the primary characteristics of this debate and substantiate our view on the links between CE & SD, a critical literature review approach is applied. The goal of this approach has been described to "assess, critique, and synthesize the literature on a research topic in a way that enables new theoretical frameworks and perspectives to emerge" (Snyder, 2019).

After developing an understanding of the objectives and desired eventual outcome of CE and the framework, fitting methodological properties of the framework are formulated. They are discussed through the application of a descriptive literature review, using CE assessment frameworks that are already applied by practitioners (Paré et al., 2015). A descriptive review seeks out to find patterns among literature on a certain topic with respect to pre-existing propositions, theories, methodologies and has the aim to ensure generalizability of the results. First, existing frameworks are reviewed based on whether they (1) are applied in practice or (2) show to have an approach that responds to at least one of the objectives as formulated previously. From these frameworks, methodologies are extracted that are matching the previously formulated objectives. Next, strategic decision-making literature is consulted to further structure the framework. Different models and procedures for strategic decision-making are used to align the identified core elements with the context of strategic decision-making. This results in a framework consisting of a step-by-step described routine, which is followed by the triangulation steps.

2.2. Triangulation

The preliminary framework is validated through two forms of collecting qualitative data on its practical usefulness through dual triangulation, enhancing its effectiveness (Cornwall & Jewkes, 1995): an expert panel survey and focus groups.

2.2.1 Expert panel survey

First, a survey is designed to collect feedback from a specific group of knowledgeable participants; in this case, an expert panel consisting of private sector and academic experts in CE assessment at company level (Blessing, 2002; Kravchenko et al., 2021). The feedback process focuses on the methodological setup of the framework. The structure of engaging with an expert panel is inspired by the expert panel validation steps as described in Beecham et al. (2005). It consists of: (1) defining the objectives and preliminary setup of the assessment framework; (2) designing the validation instrument (a survey), which explains the framework and allows the participants to provide feedback to its methodological elements; (3) composing an expert panel relevant to company-level CE assessment; (4) providing the participants with the survey and additional explanatory documents (an ‘information package’); (5) collecting and analyzing the responses, determining whether a second round of interviews with the participants is deemed necessary; (6) relating the expert survey results to the success criteria to gain an impression of strengths and weaknesses of the framework, and adjust the framework accordingly.

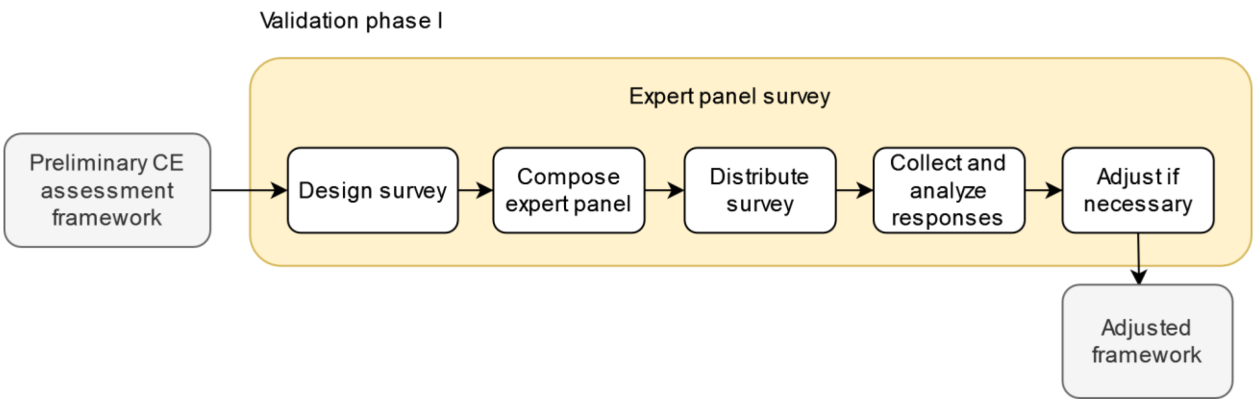

Figure 2. Schematic overview of methodological validation through expert survey.

The identified private sector experts have experience with designing and applying CE assessment frameworks for companies, while the university experts have been involved with building the scientific foundation of CE and sustainability assessment, through the publication of scientific articles. The composition of the list of selected experts and their particular expertise are summarized in Table 1.

Table 1. Expert panel for survey.

Number of experts	Type of organization	Reason for selection
7	University	Working on CE and sustainability assessment, having published relevant articles.
4	Consultancy	Experience with designing and applying CE and sustainability assessment frameworks with companies.

The expert survey itself consisted of three parts. First, a cover letter explained the research objective of the project and the expected role of the expert survey participants. Then, the CE assessment framework itself was detailed in the 'information package' PDF, describing the framework's objectives, methods and application routines. The survey was presented in Microsoft Excel and send by email. It contained open fields to collect expert's comments or amendment proposals related to the proposed methodology for each of the application steps. The closing part of the survey was designed to collect feedback to the five objectives of the framework, asking whether it fulfills the objective or needs amendments. All collected feedback was then evaluated, and suggestions (for e.g. methodological revisions) were incorporated when indicated by a majority (>50%) of participants.

2.2.2 Focus groups

In the second triangulation step, the revised framework was validated on the basis of feedback by its envisioned end-users: a selection of five companies (see table 2) motivated to assess the sustainability implications of their current -or planned - CE activities. They delivered their considerations to the different parts of the framework through various online focus group sessions (O.Nyumba et al., 2018). This method can be considered a form of 'consultative participation', as practitioners are asked for their opinions and consulted by researchers before interventions are made (Cornwall & Jewkes, 1995). The focus group approach was conceived as a strategy to bridge scientific research and 'local' knowledge, with local referring to companies that might be interested in applying the framework (O.Nyumba et al., 2017). The companies that were selected are both European (Italy and France) and African (Tanzania, Ghana). They are composed of a mix of low- and high experience with CE and sustainability assessment. For practical reasons, the online focus groups were divided over different sessions, each with 1-2 participating companies. In advance, the participating companies were provided with documentation to ensure a smooth rollout. Before each focus group, 30 to 60-minute interviews were held with each company to better understand their business context and assessment experience. The focus group consisted of the following parts: (1) 15 mins introduction and context, (2) 5 mins explanation of the objectives of the framework, (3) 20 mins providing details on the framework's application steps + test case example, (4) 15 mins clarification questions (5) 15 mins discuss the objectives of the framework (6) discuss the framework's feasibility (7) roundup and conclusion.

The sessions were recorded and viewed afterwards to complement the coding notes taken during the focus groups. The results were obtained through a grounded theory approach, applying thematic analysis on two levels (Guest et al., 2014; Massey, 2011): using (i) articulated data and (ii) emergent data. The first level of data is acquired through asking the participants direct questions related to the framework. These questions were focused on the framework's clarity, its ability to respond to the set objectives, and the company's barriers to application of the framework – and of CE and sustainability assessment in general. The answers to these questions were addressed directly and then coded for analysis. The second level of data, emergent data, was acquired through analyzing and interpreting the information provided by the companies "in between" the direct questions that were asked – through e.g. stories and anecdotes. Emergent data therefore captures themes that are important to the participants, but invisible prior to the study (Massey, 2011).

Table 2. Focus group participants.

Type of organization	Country	Experience with CE and sustainability assessment
Wine producer	Italy	Experience with carbon footprinting.
Refurbished electronics	Italy	Knowledge of LCA.
Automotive	The Netherlands and France	Extensive knowledge of CE and sustainability assessment.
Drinking water provider	Tanzania	Knowledge of LCA.
Plastics recycler	Ghana	Assessment of resource flows.

3. Framework foundation and objectives.

3.1. Objectives and normative core – critical literature review

Formulating the normative foundation of the envisioned CE assessment framework aims to answer the question: what should the outcome of CE be for the concept to be valuable? The current debate about the relationship between SD and CE is complex and dynamic, and a clear understanding has yet to be defined (Calisto Friant et al., 2020; Geissdoerfer et al., 2017; Millar et al., 2019; Schöggl et al., 2020). Formulating the desired impacts of CE is crucial to assessing the impacts of CE practices; at the same time, companies show to have different views on how CE and sustainability are connected (Walker et al., 2021)

Both CE and SD are subject to numerous interpretations, complicating the interpretation of their connection (Kirchherr et al., 2017; Sauvé et al., 2016). Various authors describe this connection: Geissdoerfer et al. (2017) identify the different interpretations of the relationship, and notice that parties that have been particularly influential in shaping and popularizing the concept interpret the relationship differently. Kirchherr et al. (2017) find that definitions are heterogeneous and only 13% of the analyzed CE definitions applies a holistic perspective. Evidence of the lack of consensus on the topic of what a CE leads to – or should lead to – is also reflected in studies that investigate the assessment of CE. When zooming in on reviews of micro-level CE indicators and assessment approaches, Kristensen & Mosgaard (2020) collect 30 micro level indicators for a CE and find a variety of types of alignment with SD dimensions. Similar results are found in assessment reviews by Roos Lindgreen et al. (2020) and Moraga et al. (2019).Various authors see the lack of inclusion of all dimensions of SD as a shortcoming of current CE metrics (Corona et al., 2019; Pauliuk, 2018).

In fact, the unclear nature of CE’s envisioned outcome and subsequent potential to drive change towards a more sustainable and equitable society has sparked an increasing amount of criticism to CE. Millar et al.

(2019) explicitly challenge the proposition that implementing CE is driving positive impacts in terms of SD. Sauvé et al. (2016) find that both CE and SD are subject to various epistemological problems, complicating research and obscuring academic discussions. Giampietro & Funtowicz (2020) even consider CE an example of socially constructed ignorance, indicating CE's disregard of previous decades of sustainability science, and urge serious *"(…) ideological and scientific discussion about the biophysical and political constraints limiting the current pattern of economic growth"*. Along the same lines, Calisto Friant et al. (2020) warn that when actors will continue to use a framing of CE that does not consider systemic socio-ecological implications, the term could become a tool for greenwashing. Several other studies point towards the risk of trade-offs or even distractions from solving real-world issues when interpreting CE as a resource-management model only (Djuric Ilic et al., 2018). A related general concern is also that social issues are generally underrepresented in CE discourse (Kirchherr et al., 2017; Schöggl et al., 2020).

Other studies offer more solution-driven input to the debate and propose new interpretations or modifications of CE, for example by recommending to consider all three dimensions of SD as the desired end goal of CE strategies (Corona et al., 2019; Vermeulen et al., 2018; Kravchenko et al., 2019). SD has many definitions and a long history of scientific- and policy debate, and is generally considered to satisfy a range of social, environmental and economic goals to ensure that the needs of the present are met without compromising the ability of future generations to meet their own (Azapagic, 2003; Broman & Robèrt, 2017). The specific goal-setting for each of these three SD dimensions is here considered to be determined by the context; SDs objectives change with time and values are determined by a temporary representation of our desired (future) world (Villeneuve et al., 2017). At the same time, the urgency of developing and implementing solutions to the variety of pressing issues associated with our current global development model is not debatable.

From the discussion above, the foundation of the framework consists of assessing the impact of CE strategies to three interrelated SD dimensions: environmental quality, economic prosperity, social well-being (see figure 3). This is in line with previous interpretations of corporate sustainability, which is achieved at "the intersection of economic development, environmental protection and social responsibility" (Engert et al., 2016). The resource-efficiency dimension impacts all SD dimensions; this follows the viewpoint that CE strategies could be seen as a pathway to reaching sustainability goals. The resource-oriented dimension has a unique position in the framework and is therefore marked by a dotted line; positive impacts on the three dimensions of SD can also be reached by introducing solutions that are not resource-efficiency focused. Therefore, it is not a dimension of 'impact', but comprises various CE strategies selected by the company, which then lead to particular impacts to the dimensions of SD. This is explained in following sections.

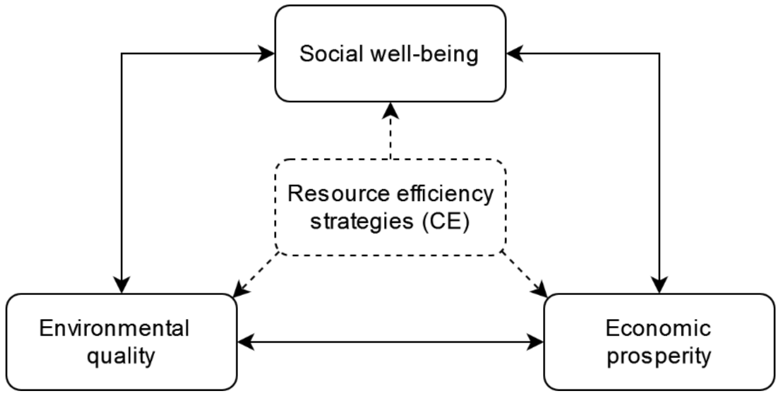

Figure 3. Proposed normative core of the CE assessment framework.

Each of the impact domains requires a brief explanation on its interpretation. For environmental quality, scientific evidence confirms that global climate change and various other interrelated ecological crises, such as the biodiversity crisis, require urgent society-wide transformative change (O'Connor et al., 2020). Businesses carry responsibility for lowering their impacts on the environment; multiple decades of research cover various strategies for businesses to do so (Jones, 1980). The history of the field of realizing positive impacts in the social dimension is younger, even though the social impacts of any business are wide-reaching. They include impacts on local communities, consumers, value chain actors, employees, and society (Kühnen & Hahn, 2017). The concept of social well-being and the fair distribution of resources and wealth fall under the umbrella of the social dimension, and is generally considered to be central to sustainability (Villeneuve et al., 2017). Social well-being is probably the most abstract and complex of the included dimensions and, perhaps for this reason, also not often included in CE assessment (Corona et al. 2019; Kristensen & Alberg Mosgaard, 2020). However, since avoiding trade-offs in the social dimension that have the potential to exacerbate global inequalities even further is considered paramount, it should be considered in the evaluation of CE impacts (Kravchenko et al., 2020; Walker et al., 2021, Padilla-Rivera et al., 2020).

The 'economic dimension' of SD is more contested (Broman & Robèrt, 2017). Recent research deconstructs the idea that our growth-centered capitalist development model is a given and provide post-growth or de-growth substitutes in which different (non-monetary) metrics replace well-known indicators such as GDP (Kallis, 2011; Schneider et al., 2019). In addition, it is worth noting that a company's successful financial performance enables realizing its mission, which, on its own, might contribute positively to either the environmental- or social domains of SD. Therefore, while we acknowledge that alternatives are available and that no clear boundary between the economic- and social dimension exists, the economic dimension is included in the foundation of the assessment framework.

3.2. Framework's objectives

The overall goal of the framework is to assist strategic decision-making processes that involve the consideration of whether to implement CE solutions. Below, its five objectives and a short justification for each are presented.

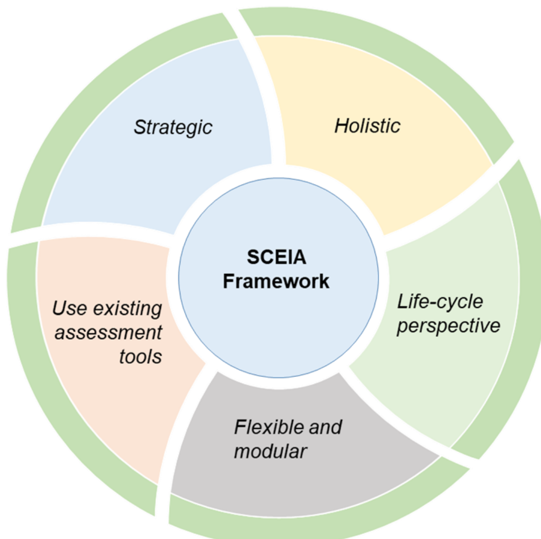

Figure 4. SCEIA framework objectives

A. Enable holistic (multi-dimensional) assessment

The lack of including a holistic perspective on sustainability – or sustainable development – has been signaled as a shortcoming of CE and its assessment, and several studies recommend to consider all three dimensions of SD as the desired end goal of CE strategies (Corona et al., 2019; Kravchenko et al., 2019; Vermeulen, 2018). Current resource-focused metrics might lead undesirable burden shifting from reduced resource use to increased environmental, economic or social impacts. The foundation of the framework aims to avoid this by inclusion of the of three interrelated SD dimensions: environmental quality, economic prosperity, and social well-being. CE is interpreted as a toolbox of resource-efficiency strategies to achieve positive impacts on these three SD dimensions (see figure 3). It takes the position that CE (or resource-efficiency) should not be a goal in itself. This proposition is fundamental to the framework and is reflected in its methods.

B. Prevent burden shifting to other parts of supply chain or life-cycle (life-cycle perspective)

To avoid burden shifting to other parts of the supply chain, a holistic, life-cycle perspective on corporate sustainability is promoted. Companies are complex entities with globalized supply chains: the environmental, economic and social impacts of an organization's operations occur in different stages of the production process, which are often undertaken by different companies (Bianchini et al., 2018). The field of Sustainable Supply Chain Management (SSCM) emphasizes the awareness of upstream and downstream supply chain operations, ensuring that the responsibility of organization is not limited to on-site improvements (Carter & Easton, 2011). The CE assessment framework underlines this system-thinking driven vision (Lozano, 2015). It is also central to the more established concept of Life Cycle Thinking (LCT) to which the framework also adheres. LCT considers the whole product system life cycle from the "cradle to the grave", hereby preventing environmental burden shifting to different part of the life cycle (Finkbeiner et al., 2010)

C. Provide flexibility in terms of (1) scale and (2) sustainability maturity

The scale on which the framework can be applied is flexible. Company-level sustainability contains a variety of sub-scales and no scientific consensus on its definition exists (Corona et al., 2019; Roos Lindgreen et al., 2020). The SCEIA framework adopts the view that the scale of assessment depends on an organization's goal of evaluation and decision-making context (Ávila-Gutiérrez et al., 2019). Product, product-line, plant, division, or entire organization are all considered potential units of analysis within the framework, depending on the end user's goals (Ceschin & Gaziulusoy, 2019).

With respect to company sustainability maturity, sustainability assessment methods are generally characterized by complexity and their large number of impact indicators. This has been described as a barrier to sustainability assessment, especially for companies with lower sustainability maturity or less available resources, such as SMEs (Álvarez Jaramillo et al., 2019; Johnson & Schaltegger, 2016). The SCEIA framework intends to make its application more feasible for companies with low sustainability maturity through being adjustable to the sustainability maturity of the applying firm, by limiting the number of indicators. When a company has more experience, the number of indicators can be increased; depending on data availability. This is particularly relevant for social indicators, and explained in more detail in the next section on the selected methodologies (see section on Materiality Assessment).

D. Build on existing assessment tools

To assess the impact of circular activities on SD, the proposed framework emphasizes the use of existing sustainability impact assessment methods. Such methods have been designed in order to avoid burden-shifting and trade-offs and provide a holistic representation of the real-world impacts (Pauliuk, 2018). Also, the use of methods such as LCA to assess CE has been explored and recommended by various authors (Niero & Rivera, 2018; Roos Lindgreen et al., 2021; Scheepens et al., 2016; Walker et al., 2018). Global standardization organizations such as ISO also promote its use in CE assessment (ISO/TC 323, n.d.). While some methodological adaptations are still necessary, research seems to settle on the conclusion that existing methodologies such as LCA, but also Material Flow Analysis (MFA), Life Cycle Costing (LCC) and Social Life Cycle Assessment (S-LCA) provide an appropriate starting point for assessing CE activities (Kristensen & Alberg Mosgaard, 2020; Moraga et al., 2019a; Niero & Rivera, 2018).

E. Assist strategic decision-making processes.

As described in the introduction, the integration of sustainability into company strategy levels is still a challenge for firms of various sizes (Kravchenko et al., 2021) Strategy has been described as the creation of a unique and valuable position, involving a different set of activities (Porter, 1996). Strategic decisions in firms are characterized by high stakes and long-term repercussions, and the role of human judgements in the decision-making process (Bushan & Rai, 2004). Strategic decision-making has been described as a cognitive process that involves the selection of a preferred action among several alternatives; it can be supported by scoring mechanisms or yes/no trees (Kahneman et al., 2019; Waas et al., 2014). Features of frameworks to assist strategic-decision making include techniques to assess situations and methodologies to choose the best among the alternative strategies (Bushan & Rai, 2004). The strategic level of decision making follows from the standpoint that a company’s marginal changes, with marginally better impacts, are not enough and can even be counterproductive (Holmberg & Robert, 2000). The strategic level of decision-making, instead, is here considered more relevant due to urgency to move away substantially from business-as-usual patterns of production and consumption.

4. Methodological aspects of the CE assessment framework

4.1. Methodological basis

The methodological basis of the framework can be divided into multiple levels. First, questions on the scope (i.e.: which elements should be included in the assessment?) and scale (i.e.: what is the desired unit of analysis?) are answered. Then, it is evaluated whether the framework should be designed to enable sector-specific or general assessments. The framework’s incorporation of existing assessment methodologies is detailed next. The methodological basis of the framework draws inspiration from a combination of existing methods that are (1) applied in practice or (2) show to have an approach that responds to at least one of the objectives as formulated previously. The following existing tools form the basis of inspiration of the methodology: Ecotest by FFACT (Ecotest, n.d.), Optimal Scan by Optimal Planet (Optimal Scan, n.d.), Circular Transition Indicators or CTI (WBCSD, 2020), and ISO 323 (ISO, n.d.).

Table 3. Summary of key aspects of relevant existing CE assessment approaches and standards.

Type	Name	Developed by	Evidence of application	Companies involved in design	LCT perspective	Multidimensional	Uses existing methodologies	Scale of application	Adjustable to sector or needs
Assessment approach	Ecotest	FFACT	Yes (various public and private organizations)	Yes	Yes (collects data from supply chain)	Yes (includes environment, resource efficiency and economic dimensions)	Yes (LCA)	Product chain	Yes
Assessment approach	Optimal Scan	Optimal Planet	Yes (various public and private organizations)	Yes	Yes (special attention for procurement)	Yes (includes environment, resource efficiency, economic and social dimensions)	Yes (LCA)	Flexible (from product to organization)	Yes
Assessment approach	CTI (Circular Transition Indicators)	WBCSD (World Business Council for Sustainable Development)	Yes (various private organization)	Yes	Yes (focused on creating value chain discussions)	No (focuses on link between resource and economic performance; does not include environmental and social impacts)	No (recommends complementing material flow insights with existing sustainability metrics)	Company or specific part of company	Yes
Standard / guidance document	ISO 323-3	ISO	No (development in progress)	Yes	Yes	Yes	Yes (LCA, LCC, S-LCA)	Flexible (from product to organization)	Yes

4.2. General methodological aspects

4.2.1. Scope and scale

As stipulated in the objectives, the SCEIA framework aims to evaluate impacts from a life cycle perspective. It has a system-thinking vision and aims to drive change through transparent collaboration (Lozano, 2015). This perspective is found in various other widely used sustainability approaches, such as Scope 3 carbon emission reporting (Moldavska & Welo, 2018). It is also central to Life Cycle Thinking (LCT) and Life Cycle Sustainability Management (LCSM). LCT is applied in the three selected existing CE assessment approaches Ecotest, CTI and Optimal Scan, and recommended in the early-stage ISO documentation.

Next, the scale on which the framework can be applied is flexible. This is in line with the flexibility of life cycle impact assessment tools, which provide the option to select the level of analysis through choosing an appropriate functional unit. Ecotest, CTI and Optimal Scan also allow for adjustability to an organization's needs.

4.2.2. Sector specificity

The field of sustainability assessment science has discussed the value of either sector-specific assessment approaches or more generally applicable methods. Contrasting opinions on the preferred approach are found but, generally, research concludes that this choice also depends on the goal and context of the assessment process. Some authors state that methods should be situation-specific, since "*business realities, values and culture of the organization, and as such their development should not be constrained to prescribed methodologies or standards*" (Keeble & Berkeley, 2003, p. 151). Other authors note that a "*standardized set of sustainability indicators may miss key impacts*" (Veleva & Ellenbecker, 2001, p. 520) and propose a dual approach: a set of generally applicable core indicators combined with supplemental indicators to account for differences between production facilities. Johnson & Schaltegger (2016) acknowledge that companies are diverse, noting that a "*mismatch exists between the generality of sustainability management tools proposed in research and the heterogeneity of SMEs in practice, which seems to require a diverse set of more size and sector-specific tools*" (p. 494). Contrastingly, Saidani et al. (2017) state that circularity measurement tools could preferably work at the scale of 'thousands of products'. In summary, contrasting views on whether to develop sector-specific or more generally applicable approaches exist. It is however clear that companies are highly diverse entities in terms of e.g. supply chain complexity, inherent sustainability, size, etc., making it difficult to envision a rigid non-sector-specific CE assessment approach that can adequately cope with such complexity. Instead, approaches that are adequately tailored to a specific sector or even organization might offer more potential for change. For this, frameworks that offer flexibility and the possibility to be adjusted accordingly to the situation at hand might be more promising than 'static' general frameworks. This is also reflected in the adjustable nature of the existing frameworks Ecotest, Optimal Scan and the recommendation by the CTI to use e.g. sectoral or regional recovery data.

4.2.3. Connection to existing impact assessment methodologies

The proposed framework emphasizes the use of existing sustainability impact assessment methods (Walker et al., 2020). First, it is considered valuable to make use of the knowledge on sustainability quantification that has resulted in the development of widely used tools such as Life Cycle Assessment (LCA). Secondly, such methods have been designed in order to avoid burden-shifting and trade-offs and provide a holistic and accurate representation of the real-world impacts (Pauliuk, 2018). Thirdly, the use of LCT methods such as LCA to assess CE has been explored and recommended by various authors (Niero & Rivera, 2018; Roos Lindgreen et al., 2021; Scheepens et al., 2016; Walker et al., 2018) and it also applied (to varying extent) in existing CE assessment approaches or standards. Global standardization organizations such as ISO also promote its use in CE assessment (ISO, n.d.). While some methodological adaptations might still be necessary, research seems to settle on the conclusion that existing methodologies such as LCA, but also Material Flow Analysis (MFA), Life Cycle Costing (LCC) and Social Life Cycle Assessment (S-LCA) provide an appropriate starting point for assessing CE activities (Kristensen & Mosgaard, 2020; Moraga et al., 2019; Niero & Rivera, 2018).

Environmental quality

The intention of LCA is to quantify the potential environmental impacts of a product system throughout its life cycle (Dieterle et al., 2018). It is the most widely used and most well-developed environmental impact assessment method available, and companies are already using the methodology to uncover – and subsequently reduce – the environmental impact of their operations (Kjaer et al., 2019). It has previously been promoted in CE literature as an appropriate tool for assessing the environmental impacts of CE actions for its rigor and maturity (Pauliuk, 2018).

Economic prosperity

Literature that discusses assessing this the economic dimension in the context of LCSM proposes both tools that allow for estimating costs and revenues in a more traditional way (such as cost-benefit analyses), as well as using Life Cycle Costing (LCC) to establish insights in the total costs of a product, process or activity discounted over its lifetime (Halog & Manik, 2011; ISO, n.d.) The proposed framework incorporates only the first interpretation, aiming to provide insights into the changes in life cycle costs through the introduction of CE activities. LCC is a technique to assess the total costs associated with the life cycle of a product system, or over a selected period of time, that supports decision making processes during the development stage of products (Wouterszoon Jansen et al., 2020). While different versions of LCC exist, environmental LCC (E-LCC) is considered most appropriate since it is used to complement

LCA with cost assessments. The Society of Environmental Toxicology and Chemistry (SETAC) has published a code of practice for E-LCC, which is used as a blueprint for conducting the assessment in the proposed framework (Swarr et al., 2011). The methodology of E-LCC has been adopted and described for circular solutions by Wouterszoon Jansen et al. (2020), in which for each of the R-strategies available, the relevant actors and cost calculations are presented. For the application of E-LCC, the proposed framework refers to Table 2 of this work.

Social well-being

The development of methodologies that enable the assessment of the social impacts of organizations are still under development, and its application among organizations is not widespread (OECD, 2015). The Global Reporting Initiative (GRI) considers the social dimension to consist of topics such as employment, labor/management relations, occupational health and safety, and more (GRI, n.d.). The field of Social Impact Assessment (SIA) sees social impact to be mostly related to the consequences of any planned intervention such as policies, programs, plans, projects (Vanclay, 2003). The methodology that is selected for application to the social dimension of the framework is Social Life Cycle Assessment (S-LCA). S-LCA is designed to facilitate companies operate in a socially responsible manner by providing data about the potential social impacts on people caused by the activities in the life cycle of their product (Dreyer et al., 2006). While its predecessor is SIA, the history of the methodology is still relatively brief, with the first S-LCA guidelines from UNEP/SETAC being published in 2009, while being updated recently in 2020 (Fauzi et al., 2019; UNEP Setac Life Cycle Initiative, 2020). The impacts of S-LCA are site-specific and include a high level of stakeholder involvement. While the methodology carries several methodological- and practical challenges, it is generally considered the most advanced method to obtain accurate insights into social impacts while accounting for trade-offs. It is mentioned in the upcoming ISO TC 323 standard as the recommend method to assess the social impacts of CE practices.

Resource-oriented (‘circular’) dimension

A well-used existing methodology to obtain insights into resource and energy flows of products, processes, services is Material Flow Analysis (MFA). This method analyses the material throughput (often in kgs of material) of process chains, including extraction, chemical transformation, manufacturing, consumption, recycling and disposal of materials (Bringezu & Moriguchi, 2019). It consists of building an inventory of material and energy in- and outputs of a certain system under review. This results in a (graphic) representation of the mass- and energy flows, usually in kgs for materials or the relevant unit such as kWh or MJ of energy consumption, coupled with an overview of this information in table format. This is also referred to as a mass balance process flow diagram, or mass balance sheet, in which the mass balance can be used to control for the accuracy of the MFA (i.e. to see if the overview is complete). The approach is not standardized like the LCA methodology: applying a certain type of MFA depends on the eventual goal of the analysis. However, the application of MFA is often combined with LCA, as it can serve as the foundation on which to build a more comprehensive system of analysis (Corona et al., 2019). MFA has also been recommended by several authors as part of the set of tools appropriate for assessing CE (Graedel, 2019). However, while providing details information on resource flows, the methodology does not provide information on how a certain system could become more resource-efficient. For this, the proposed framework incorporates the views that selecting the CE strategy most fitting to the company depends on a number of factors that fall outside of the scope of this assessment framework (sector, geographical location, market conditions, etc.).

The ‘blueprint’ of company-level resource data following from MFA will subsequently be coupled with both the resources’ sustainability impacts; this recommended procedure is explained in more detail in chapter 5.

4.3. Indicator selection process – materiality assessment

Most of the described methodologies for assessing the impacts of CE will all result in a large number of indicators. For example, when applying the impact assessment method ReCiPe in LCA, the result will consist of impacts on 18 diverse midpoint impact categories, ranging from particulate matter to freshwater ecotoxicity, expressed in different units. While normalization and weighting steps to process this information and facilitate interpretation are optional, they have been criticized for bias and being based on value choices (Pizzol et al., 2017). For S-LCA, five stakeholder categories are included which each carry various subcategories, eventually leading to 32 impact subcategories, from child labor to cultural heritage. Various ways to contextualize and process this intricate set of information to facilitate decision-making are still being researched (Siebert et al., 2018). For the economic domains, the output is different; applying the LCC methodology results in the total costs of certain activity, detailing the distribution of these costs over the lifecycle of this activity. The costs are expressed in monetary terms, avoiding the issue of still needing to aggregate and contextualize many diverse indicators.

Table 4. Simplification process for different SD domains.

Dimension	Applied method	Output	Processing
Environmental quality	LCA	Impacts on 18 midpoint categories (using ReCiPe)	Apply materiality assessment (MA)
Social well-being	S-LCA	Impacts on 32 subcategories	Apply materiality assessment (MA)
Economic prosperity	LCC	Overview of lifecycle costs, expressed in €	N/A

Since the complexity of sustainability tools such as LCA and S-LCA has been indicated as a barrier to company-level implementation, the SCEIA framework aims to enable the selection of indicators that are most material to an organization (Johnson & Schaltegger, 2016). This selection process is recommended for three key reasons: first, it is recognized that every organization will have different sustainability issues, responding to different relevant sustainability indicators (Azapagic & Perdan, 2000; Warhurst, 2002). Second, decision-makers are more likely to make informed decisions if the information relevant to the organization has been critically analyzed and prioritized (Kravchenko et al., 2020). In other words, the development, selection and use of indicators is a dynamic process that informs decision making rather than being an end in itself (Keeble & Berkeley, 2003). Third, reducing the amount of complex information facilitates the decision-making process, increasing the chance of agreement to a solution within an organization (Rahdari & Anvary Rostamy, 2015).

In order to facilitate the process of indicator selection, the aspects of each sustainability domain that are most important (or 'material') to the organization and its stakeholders are determined (Whitehead, 2017). Materiality assessments have been documented and promoted in detail by the GRI, to determine which economic, environmental and social issues are most important to both the company as well as to its stakeholders (Calabrese et al., 2017). The materiality assessment approach is used freuqently in consultancy- or accountancy settings – particularly in intergrated reporting (IR) (Reverte, 2015). It involves a materiality matrix, placing issues on a spectrum from less to more important. It will remain the choice of the organization – and its stakeholders – to determine how many indicators will be taken into account in the assessment- and subsequent decision-making process; this also depends on data availability and the sustainability maturity of the organization, since previous experiences with sustainability impact assessment is likely to allow for a higher number of indicators to be included (UNEP Setac Life Cycle Initiative, 2020)

4.4. Multi Criteria Decision Analysis (TOPSIS)

When multiple CE strategies show to be favorable, decision support might be needed to explicitly analyze emerging trade-offs in light of contextual settings (Kravchenko et al., 2021). Applying Multi Criteria Decision Analysis, sometimes also refered to as Multi Criteria Decision Models, can address multiple conflicting objectives in sustainability assessment to facilitate decision-making processes (Cinelli et al., 2014; Varsei et al., 2014; Buchert et al., 2015). MCDA allows to aggregate complex qualitative and quantitative data in a transparent way, facilitating the communication between various stakeholders by creating a common language (Domingues et al., 2015; Munda, 2016; Varsei et al., 2014). It provides practitioners a tool to compare different objectives and different dimensions, and it has been applied in the combined use of CE indicators and sustainability assessment, or in LCAs (Niero & Kalbar, 2019; Domingues et al., 2015). Various types of MCDA exist, such as Multi attribute utility theory (MAUT), Analytical hierarchy process (AHP), Dominance-based rough set approach (DRSA), etc. (Cinelli et al., 2014). In the CE assessment framework, the so-called Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) is recommended. This technique has been described as simple, rational and comprehensible, and has been applied to sustainability decision-making in CE before (Roszkowska, 2011; Niero & Kalbar, 2019). TOPSIS allows for selecting the alternative with the shortest Eucledian distance to an ideal solution and farthest from the negative ideal alternative; it is built on a decision matrix, normalisation and weighting procedure, with the opportunity of providing a visualization. It's step-by-step procedure is described in more detail in (Roszkowska, 2011).

4.5. The framework's application routine

Here, the step-by-step application routine of the SCEAI framework is described. The framework's strategic purpose requires embedding it in a strategic decision-making context and management literature, particularly from Azapagic (2003), Mintzberg et al. (1976) and Porter (1996).

Strategic positioning of firms has been described in detail by Porter (1996) describing strategy as the creation of a unique and valuable position, involving a different set of activities. It involves making decisions on what activities *not* to do as an organization, and involves the ways a company's activities interact and reinforce one another. Other elements that are connected to making strategic decisions in firms are high stakes and long-term repercussions, and the role of human judgements in the decision-making process (Bushan & Rai, 2004). Practically, strategic decision-making has been described as a cognitive process that involves the selection of a preferred action among several alternatives; the distillation of a large set of complex information into a single choice is often supported by methods that involve scoring mechanisms or yes/no trees (Waas et al., 2014; Kahneman et al., 2019). Different perspectives on strategic decision-making in the context of sustainability in a variety of firms have been proposed in i.e. Hallstedt et al. (2010) and Coteur et al. (2016). Features of frameworks to assist strategic-decision making have been described by Bushan & Rai (2004) and include, among other elements, techniques to assess situations and methodologies to choose the best among the alternative strategies.

To provide strategic decision-makers with more than just a set of existing tools to aid in assisting their choice for certain circular solutions, the framework is structured accordingly to the proposed structure of “unstructured” decision processes by Mintzberg et al. (1976). Their framework has been modified accordingly to the context of CE decision-making. The proposed structure is also in line with the 4-step (ABCD) operational procedure of the framework for strategic sustainable development as proposed in Broman & Robèrt (2017), the three consecutive phases of sustainability decision planning along supply chains by Stindt (2017), and Azapagic’s systems approach to corporate sustainability (2003).

5. Preliminary SCEIA framework

5.1. Structure of preliminary framework.

The resulting preliminary framework’s structure consisted of five phases, of which some are iterative: (1) point-of-departure: recognize need for decision, develop vision (2) identification phase: scoping and identification of resource / energy flows and stakeholders; (3) diagnosis: tailored impact assessment (4) development phase: develop CE strategy to target priority resources; (5) selection phase: decide on optimal solution. Each of these steps contains sub-steps that comprise the methodological elements as described in chapter 4; the identification phase included the use of MFA, the diagnosis phase makes use of MA and LCA, LCC and S-LCA, the development phase refers to the existing CE toolboxes listed in table 12, and the selection phase recommends the use of the TOPSIS MCDA technique for decision support.

In the next subsections, each step of the preliminary framework is explained, with the inclusion of the inputs and outputs necessary and each step’s integration into the organizational structure. This is then followed with a summary of the expert panel’s feedback to this version of the framework, and the resulting amendments to the framework.

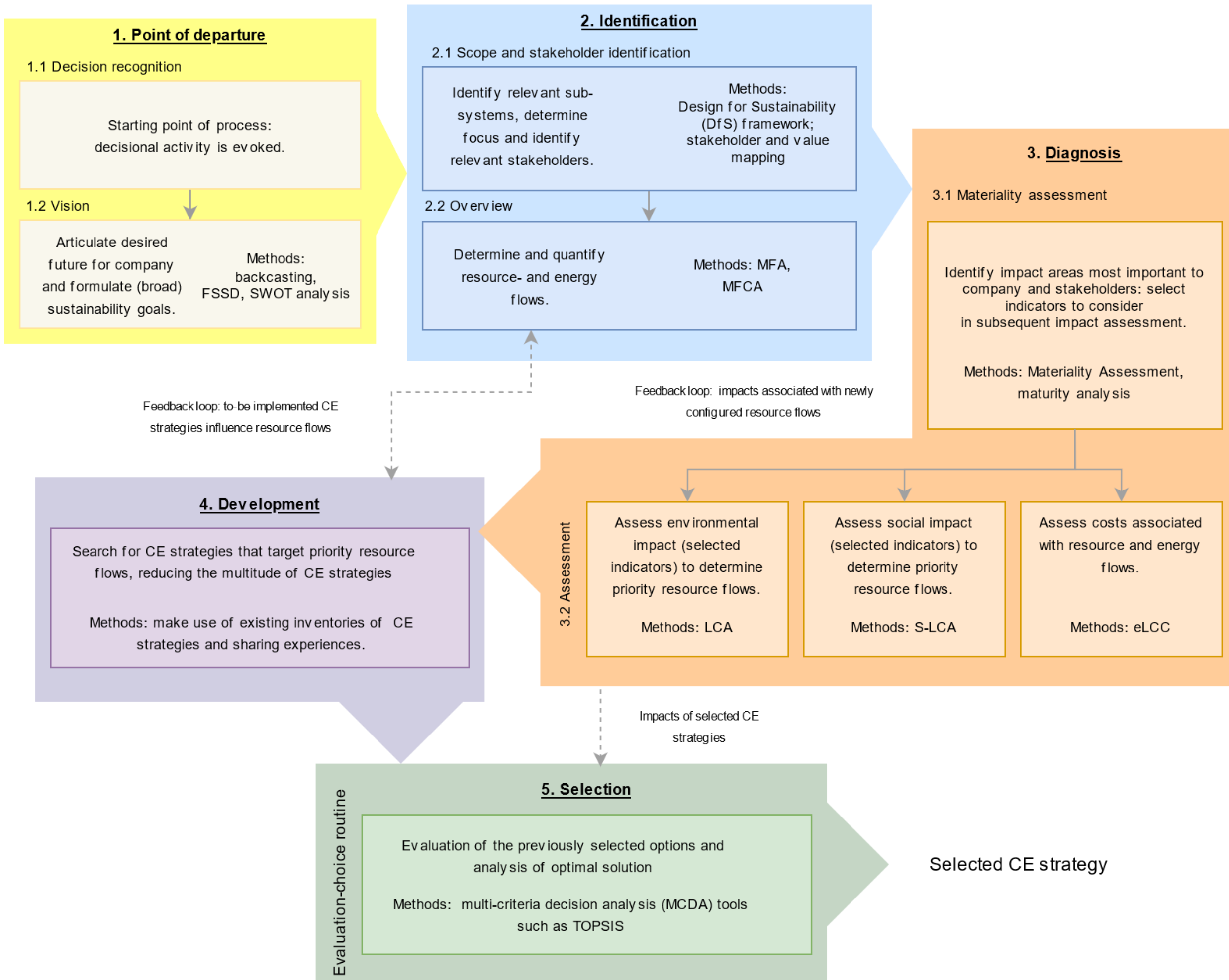

Figure 5. Application routine of preliminary framework.

5.2. Point of departure

5.2.1. Decision recognition

The first phase of the strategic decision-making process is the decision recognition phase, in which strategic opportunities, problems and crises which evoke decisional activity are recognized (Mintzberg et al., 1976). Translating this to the context of CE as a potential pathway to a more sustainable society, drivers can consist of external stimuli such as increasingly stringent environmental legislation or customer demand and expectations, or internal reasons such as leadership or the business case for sustainability (Epstein & Roy, 2001; Lozano, 2015). The external drivers and actors involved are highly diverse; internally, the decisional activity will likely be driven by management level employees. Monitoring the external environment, whether or not in collaboration with other firms, to ensure the company's activities are answering to a changing worlds has been described as central to identifying threats and opportunities (Azapagic, 2003).

Table 5. Decision recognition.

Step	Description	Internal stakeholders involved	External stakeholders involved	Input	Methods	Output
1.1 Decision recognition	Start of process. Decisional activity is evoked.	(Management) employees	Community Clients Government Investors Other	Various (internal/external events)	-	Starting point of process

5.2.2. Vision

After recognizing the need for decisional activity, the development of a sustainability vision by the company's management, and potentially other internal- and external stakeholders, follows. This step articulates a vision for the future of the company, and provides an intellectual framework for company strategy; according to some authors, a conceptual map with steps from the company's current reality to a desired future state is included (Mirvis et al., 2010). Others note that the vision could also be a statement, underlining the firm's core purpose and end-goals. It is considered an essential prerequisite before starting with any strategic decision-making process related to sustainability (Broman & Robèrt, 2017). Participation of a diverse range of both internal as well as external stakeholders has been described as a success factor for vision development (Mirvis et al., 2010). This vision should then be translated into (general) sustainability objectives on a strategic level; for more operational decisions, it is recommend to formulate more specific targets (Kravchenko et al., 2021). Backcasting and the FSSD are recommended as appropriate approaches to move from a sustainability vision to arriving at a strategic plan (Broman & Robèrt, 2017; Mendoza et al., 2017). Additionally, a sustainability SWOT analysis could be carried out to obtain a more formalized picture of the company's strategic fit through identification of its strengths and weaknesses, as well as relevant threats and opportunities (Azapagic, 2003).

Table 6. Vision.

Step	Description	Internal stakeholders involved	External stakeholders involved	Inputs	Methods	Output
1.2 Vision	Articulate desired future for company and formulate (broad) sustainability goals.	(Management) employees	Community Clients Government Investors Other	Dependent on selected method.	Backcasting FSSD, SWOT analysis.	Vision and sustainability objectives

5.3. Identification

5.3.1. Scope and stakeholder identification

This step is related to determining the scope and relevant stakeholders as described in chapter 4.2. In addition to realizing the need to engage in 'decisional activity', the scope and scale of such a decision needs further definition; i.e. the relevant sub-systems and their inter-related nature should be identified (Broman & Robèrt, 2017). In practice, this could still be adjusted after continuing with the following steps, as most parts of the framework are intended to be applied iteratively, modifying the scope of the study while the study is being conducted as additional information is collected (ISO, 2006). This step is highly context-dependent as both the scope and scale are determined by the specific nature of the recognized decision at hand; it provides flexibility to zoom in on a certain product, product category, business division, geographic location, or process most relevant to the company.

Table 7. Scope and stakeholder identification.

Step	Description	Internal stakeholders involved	External stakeholders involved	Inputs	Methods	Output
2.1 Scope and stakeholder identification	Identify relevant sub-systems, set scope and identify relevant stakeholders.	(Management) employees, multidisciplinary team.	External advisors Wide range of stakeholders (Shareholders)	Discussion (management) employees and multidisciplinary team.	Design for Sustainability (DfS) framework; stakeholder mapping.	System boundaries; list of relevant stakeholders

For an overview of different scales of potential innovation towards sustainability, the Design for Sustainability (DfS) framework proposed in Ceschin & Gaziulusoy (2019) is recommended. As formulated previously, the framework is aimed at facilitating fundamental and high-impact change, with a holistic, life-cycle perspective. While the scope and scale are context-dependent, it is recommended to therefore consider the "socio-technical system innovation level" as most appropriate. This level focuses on radical changes in how societal needs (such as nutrition and mobility) are fulfilled, supporting transitions to new socio-technical systems.

Setting the scope and scale of analysis will be undertaken by the responsible management level employees. It could be beneficial to involve external advisors in an early phase of the decision-making process, to ensure appropriate scoping. In the case of both closely held as well as publicly held corporation, while shareholders generally do not control day-to-day business decisions, major decisions require their vote of approval and should therefore also be involved in the process.

With setting the scope and scale for the system primarily influenced by the decisional activity, this step is also used to identify the internal- and external stakeholders belonging to this system. Early and constructive stakeholder engagement is generally described as a prerequisite for a sustainable corporation (Azapagic, 2003; Shrivastava & Hart, 1995). With respect to CE, taking on a system's view, external stakeholders such as supply chain partners play a particularly important role; stakeholder engagement may also positively influence the cultural orientation toward CE principles (Salvioni & Almici, 2020). This process is again iterative, since in the overview step and diagnosis phase, the system's impact hotspots will be identified, which influences which external stakeholders are most relevant to reducing these impacts. With respect to internal stakeholders, it is recommended to form a multidisciplinary team that is adequately equipped with knowledge of sustainability and business model transformation; if possible having different organizational roles, both managerial as well as operational, and from different fields of expertise (Mendoza et al., 2017).

5.3.2. Overview

In the overview step of the decision-making process, the users of the framework clarify and formalize the system at hand. It is the first step in which the CE assessment framework explicitly offers quantification of inputs- and outputs of the system. Since the framework is intended to determine the impacts of introducing CE solutions, an overview of the resource and energy flows that move through the system under study, as defined in the previous step, is essential. For this, the framework recommends the use of MFA, which is a structured approach for depiction of resource- and energy flows along value chain processes within the previously set scope (Stindt, 2017). It will provide the blueprint for any next steps, indicating *where* in the system which *types and quantities* of energy and resources are used. This is a technical and data-intensive exercise, for which external expertise is likely needed. The MFA result will provide strategic-level management with an overview of what is physically happening within the set analysis scope in terms of resource- and energy flows.

Table 8. Overview.

Step	Description	Internal stakeholders involved	External stakeholders involved	Input	Methods	Output
2.2 Overview	Determine and quantify resource- and energy flows.	(Management) employees; operational staff for data collection.	External advisors Supply chain partners	Resource data within set scope.	MFA MFCA	Overview of resource- and energy flows.

While the related tool of Material Flow Cost Accounting (MFCA) has been used to integrate resource efficiency into strategic management (Rieckhof, Bergmann, & Guenther, 2015), and MFA is frequently named in CE assessment, MFA's relevance to strategic-level decision making has not been made explicit. One reason for this could be its intensive data requirements, and relative technical complexity. In order to assemble a complete picture of resource- and energy flows within the system's boundaries, it is required that both operational staff as well as supply chain partners participate closely to the data inventory process. If not available in-house, it is recommended to invite external life-cycle experts to coordinate the process of data collection and present the results to the management. The resulting depiction of resource- and energy flows will be the foundation for both the diagnosis phase as well as formulating appropriate CE strategies, as described next.

5.4. Diagnosis

In Mintberg's proposed structure, the diagnosis phase entails comprehending the cause-and-effect relationship between the "evoking stimuli" relevant to the decision context (Mintzberg et al. 1976). In the current context of understanding the sustainability impacts of introducing CE solutions, this implies understanding the relations between resource- and energy use and their sustainability impacts. Using resource-use expressed in kg's, as emerging from the MFA, as a KPI in decision-making is not sufficient since its relation with sustainability impacts is not linear. Therefore, assessing the sustainability impacts of the resources flowing through the system under study allows to *prioritize* areas for change; i.e. determining which resource flows to target with the implementation of CE strategies. It provides the baseline environmental, economic, and social performance of the system, signaling impact hotspots (Azapagic, 2003).

5.4.1. Materiality assessment

Before determining the baseline impacts of the resource- and energy flows in the system under study, it is recommended to determine priority impact areas through a materiality assessment (MA). The primary reason for this is the need for simplification, driven by the large number of possible impact indicators from the impact assessment methods LCA, LCC and S-LCA. Various interconnected factors play a role in whether to simplify the diagnosis process by reducing the number of decision-making indicators: the 'sustainability maturity' of the firm, data availability and the complexity of the previously defined system. Both academic as well as private sector research has described determining the sustainability maturity, usually depicting the concept as a path from 'compliance', focusing on risk reduction and ad-hoc responses to challenges, to 'leadership', embedding sustainability principles in its long-term strategy (Baumgartner & Ebner, 2010; Baya & Gruman, 2011). For companies that are characterized by low sustainability maturity, it is recommended to include a lower number of indicators from each SD domain when the company has no prior experience with sustainability assessments; this is recommended for reasons of data availability and knowledge and particularly relevant for the social dimension. Vice versa, when the company has a longer history of sustainability assessment and therefore higher sustainability maturity, more indicators can be included. An indicative visualization of this principle is presented in figure 6 below.

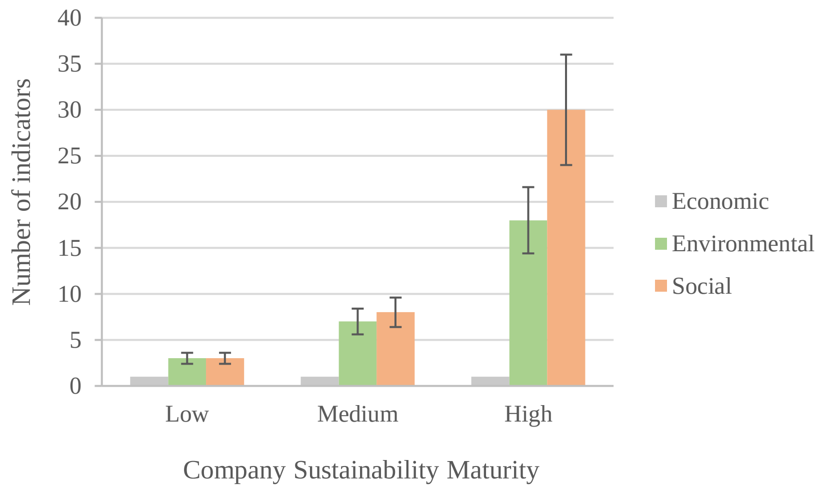

Figure 6. Sustainability maturity level and number of indicators.

The error bars in the figure indicate that the number of indicators to include is not fixed; this depends on the outcome of the MA and other factors. The figure shows that the application of the framework could be seen as a long-term process, moving towards higher sustainability maturity over various years or even decades, depending on the progress and complexity. Also, it is important to highlight that a higher number of environmental indicators will mainly have consequences for the subsequent decision-making phase, since environmental impact assessment methods used in LCA lead to many indicators by default. For S-LCA, the process is more dynamic, and data needs to be collected individually for each indicator. This will in practice be the most challenging domain; not only in decision-making, but mainly in data collection and interpretation.

After deciding on the company's level of maturity and the number of indicators that will be considered, conducting an MA will reveal the aspects of each sustainability domain that are most important to both the company and its stakeholders (Whitehead, 2017). This process, placing sustainability issues on a spectrum from less to more important, is visualized in the figure below. For the selection of stakeholders participating to the MA, examples could be to involve stakeholder groups such as scientific, regulatory, consumer, societal and business/industry (Whitehead, 2017). Next, for determining the complete list of indicators to be used in the analysis, determining the sustainability maturity level is optional, and might already have been undertaken by the company in the past.

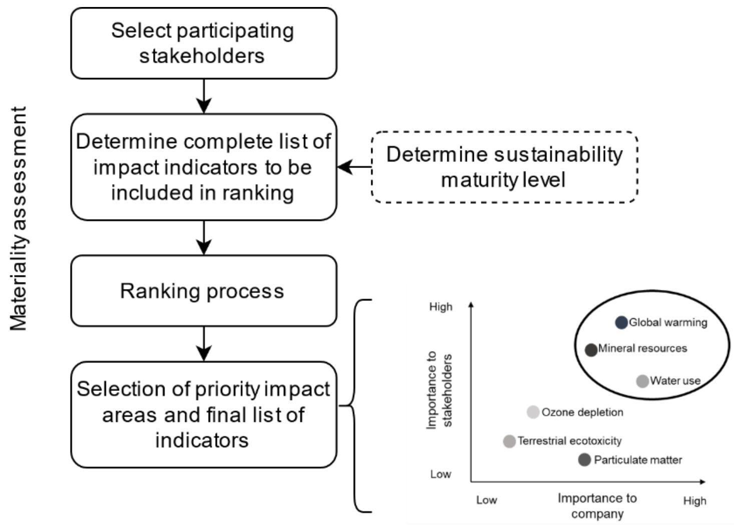

Figure 7. Application steps for MA.

For LCA, an impact assessment method will need to be selected, which will be associated with a certain number of indicators. For example, for the ReCiPe impact assessment method results in 18 diverse midpoint impact categories. This should be done with external advice from an LCA consultant. For S-LCA, although not exhaustive, 40 impact subcategories are available, which are distributed over 6 stakeholder categories (UNEP Setac Life Cycle Initiative, 2020). The availability of information on those indicators will be dependent on the sustainability maturity of the company and previous experience with assessment approaches such as Social impact assessment (SIA), Accountability 1000 assurance standard (AA1000), Social accountability international sa8000 standard (SA8000), Global reporting initiative (GRI), Environmental management systems (EMS), Product environmental footprint (PEF) (UNEP Setac Life Cycle Initiative, 2020).

Table 9. Materiality assessment (MA).

Step	Description	Internal stakeholders involved	External stakeholders involved	Input	Methods	Output
3.1 Materiality Assessment (MA)	Identify impact areas most important to company and stakeholders.	(Management-level) employees, multidisciplinary team, diverse selection of employees	Selected stakeholders	All available indicators.	Materiality assessment Maturity analysis	Selection of indicators to consider in subsequent impact assessment.

5.4.2. Impact assessment

Then, the sustainability impacts associated with the resource- and energy flows of the system are quantified. This is done using methods as proposed in Life Cycle Sustainability Assessment: LCA, S-LCA and LCC (ISO 14040-44; 2006). A few aspects of each these methods are important to highlight. While some methodological adaptations might still be necessary, such existing methodologies provide an appropriate starting point for assessing CE activities. They will be tailored accordingly to the input from the previous MA (i.e. the number of indicators is reduced). This particularly relevant for S-LCA: it will allow data collection for fewer social indicators, making the method more attractive to companies with a low sustainability maturity. eLCC, on the other hand, will only result in a single monetary indicator.

Table 10. Impact assessment.

Step	Description	Internal stakeholders involved	External stakeholders involved	Input	Methods	Output
3.2 Impact assessment	Assess current impacts to enable prioritization.	Operational staff for data collection.	External advisors Supply chain partners	Overview of resource- and energy flows	LCA, S-LCA, eLCC	Baseline impact of system; prioritization of resources to target.

5.5. Development: search and screen

The overview- and diagnosis phases produce insights into the connection between the system’s energy and resource use and its related – most material – impacts on the different sustainability dimensions. It provides the baseline impact of the system and it allows for prioritization or ‘targeting’ certain resources. The next step is then to search for solutions to minimize the baseline impact by reducing – or make more efficient use of – resource and energy flows by applying CE strategies. In the strategic decision-making structure proposed by Mintberg’s, this phase includes ‘browsing’ existing ready-made solutions and designing new solutions (Mintzberg et al. 1976). This process of 'search and screen' will be centered around browsing available CE strategies, and choosing which CE strategy is (1) most suitable to the system at hand, (2) most effectively targets the previously determined priority impact domains.

The screen and design phase is the multi-stage, iterative process of selecting a CE strategy; it is aimed at reducing the multitude of CE strategies to a number that can be evaluated and processed by time-constrained decision-makers. According to Mintzberg, the process of screening can be superficial, merely being aimed at eliminating infeasible strategies (Mintzberg et al. 1976). It is the most creative and therefore least structured phase. The CE strategy that is most useful to the company is to a large extent determined by the decision-making context (i.e. sector, internal culture, market conditions, logistics, available human resources, etc.). The framework recommends to arrive at a few potential CE strategies to be selected before assessing their impacts.

The process of introducing CE strategies and accompanying business models is highly complex and has been the topic of recent research in the field of CE business model innovation (CE BMI) (Pieroni et al., 2020). It goes beyond the scope of this framework to formulate business model innovation pathways for manufacturing companies; CE BMI frameworks have been presented in (Antikainen & Valkokari, 2016; Bocken et al., 2018; Santa-Maria et al., 2020), among others, and potential barriers in (Guldmann & Huulgaard, 2020; Linder & Williander, 2017). Instead, we highlight that when selecting a CE strategy from the previously described inventories, the focus should be on eliminating – or minimizing - resource flows that are associated with high environmental and social impacts. This allows for making radical choices that have the potential to fundamentally lower sustainability impacts.

In figure 5, the process box of 'screen' feeds back into the 'overview' step; any (hypothetical) CE strategy that will be selected influences the energy- and resource flows within the defined system. Therefore, the previously constructed MFA-based overview is modified on the basis of the hypothetical new CE strategies that are introduced. This will involve analyzing the (estimated) reduction or elimination of certain resources, while potentially adding others. Also, certain new transport movements might be introduced, or, in cases of disruptive innovation, entirely new production chains. In turn, the impacts on the SD domains associated with the company's energy- and resource flow will be different. Modelling the consequences of CE strategies on resource flows is not straightforward; again, external expertise is likely needed in determining this relationship and the new hypothetical overview of resource flows. In reality, ex-ante LCAs carry inherent variability and uncertainty, which has however also been described to "not nullify the effort" (Cucurachi et al., 2018)

In the context of CE strategies, many available categorizations of CE solutions or 'CE toolboxes' have been developed by various authors and organizations to inspire CE interventions. While they might not provide ready-made, ‘tailored’ solutions, such overviews provide the company with an overview of the many CE strategies on different levels that are available.

Table 11. Development.

Step	Description	Internal stakeholders involved	External stakeholders involved	Input	Methods	Output
4. Development	Search and select CE strategies that target priority resource flows and are applicable to the respective business context.	(Management-level) employees; multidisciplinary team.	External advisors Supply chain partners	CE strategies inventory.	CE toolboxes available in literature (see: CE strategy inventory).	Selection of one - or more - CE strategies.

Table 12. Overview of inventories of CE strategies proposed in literature.

Reference	Approach	Level	Categorization	CE strategies included
(Allwood et al., 2011)	Provides various product-level material efficiency strategies.	Product	Energy- and material efficiency options in context of typical material supply chain	Energy- and carbon efficiency: (1) energy efficiency, (2) more recycling, (3) carbon capture. Material efficiency: (4) longer life, more use, repair and resale, (5) product upgrade, modularity, remanufacturing, (6) component re-use, (7) less metal, same service, (8) yield improvements.
(Blomsma et al., 2019)	Proposes 'Circular Strategies Scanner' framework that introduces a taxonomy of circular strategies for use by manufacturing companies engaging in CE.	Company level; including materials, products, business models.	Categorized according to drivers and area of application.	See figure 5 in (Blomsma et al., 2019)
(Reike et al., 2018)	Proposes 10R strategies: single model encompassing different CE strategy typologies.	Product	Presents hierarchy of resource value retention options, including connection to different steps in product production and use life cycle.	R0 Refuse, R1 Reduce, R2 resell, reuse, R3 Repair, R4 Refurbish, R5 Remanufacture, R6 Repurpose, R7 Recycle materials, R8 Recover energy, R9 Re-mine.
(Kalmykova et al., 2018)	Provides a CE strategies database, applicable to different part of a company's value chain.	Company's value chain	Categorized according to part of value chain (materials sourcing; design; manufacturing; distribution and sales; consumption and use; recycling and recovery; remanufacture; circular inputs).	See table 2 in (Kalmykova et al., 2018)
(Henry et al., 2020)	Proposes a typology of CE start-ups, defining several archetypes.	Business model	Categorized into five archetypes: design-based, waste-based, platform-based, service-based and nature-based business models. Innovation type, R-cluster and CBM strategy also considered.	See figure 5 in (Henry et al., 2020)
(Konietzko et al., 2020)	Presents the Circularity Deck: an extensive set of CE principles for product, business model and ecosystem innovation.	Product, business model, ecosystem	Based on circular strategies: narrow, slow, close, regenerate, inform.	See table 1 in (Konietzko et al., 2020)
(Circle Economy, 2020)	Presents the Disrupt Framework, containing 80+ CE strategies for product development.	Product	Based on various key elements of CE: design for the future, incorporate digital technology, etc.	See DISRUPT Tier 2 and Tier 3 in (Circle Economy, 2020).

5.6. Selection

5.6.1. Evaluation-choice routine

In the decision-making model proposed by Mintzberg (Mintzberg et al. 1976), the evaluation-choice routine is considered to be the evaluation of the previously collected options and can use three modes: judgement, bargaining and analysis. Analysis is characterized by a focus on factual evaluation as opposed to evaluation through less-formalized, or even individual judgements, and is therefore considered most relevant to the context of ex-ante sustainability assessment of CE strategies.

When a small number of CE strategies is selected, and an equally small number of SD indicators, the evaluation-choice routine (i.e. selecting the preferred CE strategy) might be straightforward. However, it is likely that conflicting results or trade-offs emerge that are not resolved easily without additional decision support. This additional support is offered in the forms of the MCDA approach, and, more specifically, by recommending TOPSIS. This relatively simple technique offers to select the alternative (i.e. CE strategy) with the shortest Eucledian distance to an ideal solution.

In Mintzberg's framework, the last step 'authorize' describes how the decision must follow a certain approval routine throughout the company's hierarchy. While this is indeed an important phase, it is not considered to be within the scope of this framework's goal.

Table 13. Selection

Step	Description	Internal stakeholders involved	External stakeholders involved	Input	Methods	Output
5. Selection	Evaluation of the previously collected options and analysis of optimal solution.	Management	External advisors Supply chain partners	Impact assessment results	Multi-criteria decision analysis (MCDA) - TOPSIS	Decision on CE strategy

6. Validation results

6.1. Expert panel

As described in chapter 2, an expert panel survey approach is applied to validate the methodological structure of the preliminary SCEIA framework (Cornwall & Jewkes, 1995). Its different steps have previously been summarized in figure 2. The experts provided their input to each of the steps of the framework, commenting on the proposed methods. Additionally, they reflected on whether the framework succeeded in reaching its objectives. In this chapter, we describe the main feedback themes and show how the framework has been revised based on the experts' comments.

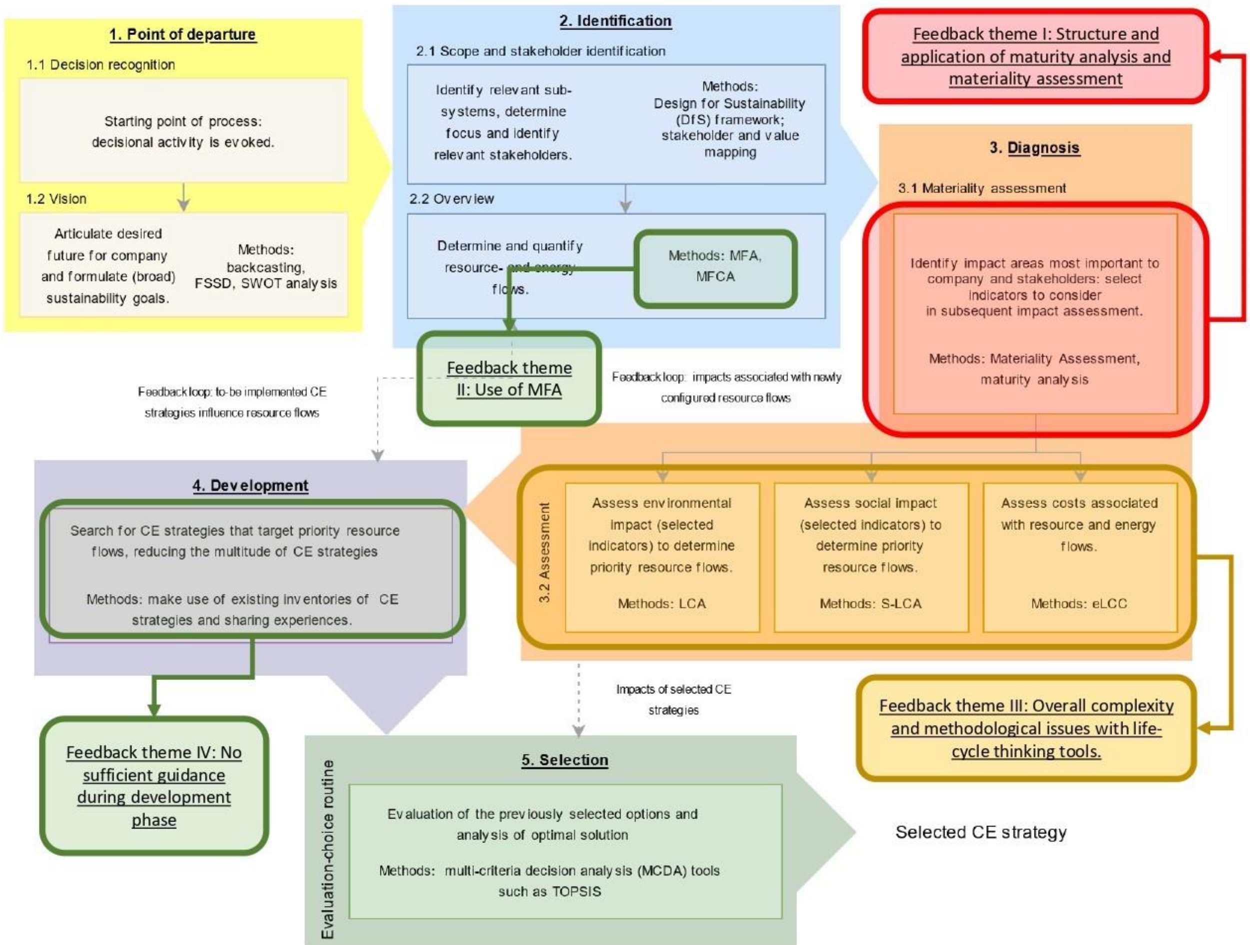

Figure 8. Summary of expert feedback to the preliminary SCEIA framework. Only feedback theme I (in red) was confirmed by >50% of the participants, and has therefore led to changes. Feedback theme III, in orange, was adjusted through emphasizing the framework's modular nature, but no structural changes were deemed necessary. For feedback themes II and IV, no changes were made – for justification, see text below.

6.2. Feedback themes

I. Structure and application of maturity analysis and materiality assessment

This theme was considered most relevant, since 6 out of 11 participants had questions related to both the maturity analysis step and the application of the materiality assessment. Some of the issues were concerned with the purpose of both steps, while others were connected to the order of application. For example, one expert commented "*it seems that 'materiality assessment' is the selection of LCA's impact categories. If the framework intends to apply the ISO14040/44 procedure, selecting impact categories is in the goal and scope definition phase*". This was reiterated by an expert who recommended to move both the maturity as well as the materiality assessment to an earlier phase of the process. Three experts were not sure why the maturity analysis and materiality assessment were grouped in one step, stating that the difference between the two methods was unclear, and that the connection how one method feeds into the other should be specified. Lastly, one expert asked for specification on the input required to determine the sustainability maturity level of the company.

Amendments to the framework

Following the suggestions above, the maturity analysis and materiality assessment steps were separated and taken out from the 'diagnosis' step. The maturity analysis was added to phase 1 (point of departure). More context on the role of maturity self-assessment was provided, following ISO standard 9004:2018 on Quality Management. For the materiality assessment, it was made clearer that this step is used to identify the impact areas most important to both the company as well as its stakeholders. It was added to phase 2 (identification). To highlight that the framework should also be useful to companies with less experience in CE assessment, the modular nature of the framework has been underlined in its documentation.

II. Use of MFA

5 out of 11 experts noted some doubts considering the application of MFA: the method could be considered too ambitious and "complete", especially for smaller companies with little or no experience related to assessment. According to some, MFA could be considered superfluous when the next step is to conduct an LCA. With respect to the method's complexity, one expert stated that "*this step may become impractical in small companies*". Highlighting both the challenging nature of MFA as well as the importance of considering resource flows, another expert mentioned that "*most companies are not aware of their resource flows, so there are big efforts being made in this space by pioneering companies to identify their resources. Quantifying them is a whole other challenge on top of this*." Some experts provided alternatives to conducting a full MFA, such as application of the CTI or a "*relatively overarching screening/analysis rather than such a detailed MFA*". Comments around the overlap of MFA and LCA included one expert who suggested that MFA could also be positioned under the diagnosis phase, as an LCAs inventory phase is similar to conducting an MFA. Similarly, another expert commented: "*Because LCA's are following, is a quantitative measurement really necessary here? Additional quantification only consumes time which in practice is not favored*." Additionally, the MFAs inability to capture social impacts was mentioned once.

Amendments to the framework

The doubts around the complexity of conducing a full MFA are justified. However, when discussing CE solutions, which are primarily centered around resource efficiency, an overview of current resource flows is crucial. Only limited tools are available to establishing this overview, and MFA is the most well-used.

The OECD has previously stated that an MFA at company level is "relatively easy to compile" (OECD, 2008). Following the experts' comments, a 'screening' of resource flows is proposed as a solution in case the company has no previous experience with assessment. Here, an 80/20 rule could be applied: creating an overview of the bulk resource and energy flows, which should generally be feasible since these would also be the resource flows related to the highest costs. This has been taken up in the maturity table as well. While the CTI has been proposed as an alternative to MFA, the mass-balance method presented in CTI is very closely related to – if not the same – as conducting an MFA. The CTI method has now been included in the framework as well. With respect to the overlap between MFA and LCA, we have purposefully kept those steps separate to highlight that kg's of materials do not equal environmental impacts. Also, when designing CE solutions, the overview of resource flows can help to formulate matching strategies.

III. Overall complexity and methodological issues with life-cycle thinking tools.

4 out of 11 experts highlighted that the proposed life-cycle thinking tools could be (1) too complex and (2) pose methodological challenges in relation to their connection to CE. One expert stated that "*not all companies would be able to apply the presented methods, harming the results and, consequently, the decision-making*", while another phrased this issue as follows: "*in terms of practicality, this framework may face challenges. Organizations are unlikely to be willing to spend an excessive amount of time (therefore money) on measurement methods such as MFA, MA and three types of LCAs. Currently, one LCA or MFA study is for a company already quite something and action can be based on that already.*" Other comments revolved around the life cycle methodologies' ability to deal with 'circularity', particularly when including closed loop systems, and cutoff/allocation issues. Another critical perspective was that an LCA might reveal impact hotspots that are outside of a company's direct sphere of influence. Lastly, it was commented that the participants to the materiality assessment might not be aware of all impact categories relevant to both LCA and S-LCA, since they will most like not be experts in these methodologies.

Amendments to the framework

The concerns about the complexity of LCA are valid, but no alternative methods are offered by the experts, or available on the market at this point in time. One solution to the issue of complexity is, similarly to the issues with MFA, to give a larger role to the maturity self-assessment in the framework. This implies that if a company is just starting their assessment journey, a full LCA is indeed too complicated: instead a 'screening-LCA' using a low number of indicators could offer a solution. With respect to the methodological issues of LCA not being able to capture certain traits of circular solutions, while this is a valid remark, methodological improvements to the method are currently in development (Pena et al., 2020).

IV. No sufficient guidance during development phase

The development phase of the framework is purposefully the least ‘guided’ phase of the framework: it presents an extensive list of CE strategies to inspire companies, but does not offer a pathway to CE BMI. This has led to some questions from the experts, for example related to the extensive nature of the list of strategies, and the proposed method for selecting an appropriate strategy. One expert stated “*it is nice that you reviewed so many strategies; it looks pretty complete. However, many authors will have different definitions about strategies (e.g. reuse of product or reuse of material). Here maybe you should simplify things a bit*”. Another remark was: “*This is still a huge list of strategies to choose from. How does one choose? Also, when is one CE Toolbox preferred over the other? There is quite some guidance required in this step*”.

Amendments to the framework

The process of selecting a CE strategy from the 100+ available strategies is indeed not an easy task. The reason for this mainly lies in the heterogeneity of businesses and the high context dependency: a CE solution that might be applicable to a bike repair shop might not work for an industrial methane plant. It is considered beyond the scope of this framework to formulate BMI pathways for manufacturing companies, to be able to implement CE strategies: instead, this framework is only concerned with the assessment of the impact of such strategies. As described previously, several other studies provide guidance to the question of which CE strategy to apply in which business and decision-making context (Diaz et al., 2021).

V. Other small additions and useful comments

Various suggestions by the experts were taken up in the framework or its documentation after their feedback. Please see the table for a summary, structured accordingly to the framework’s different phases.

Table 14. Smaller suggestions and comments to the different phases of the SCEIA framework by the participating experts.

Phase	Suggestion or addition following the experts' feedback.
1. Point of departure	• Add PESTEL tool to understand drivers for CE. • Specify that the framework could also be applied to existing CE solutions. • Clarify that it is recommended to use existing sustainability goals (vision). • Clarify that the framework is not made to be used for external comparison, but for internal decision-making.
2. Identification	• Specify that stakeholder mapping is used for stakeholders, and DfS for scoping. The stakeholder list is then used in the materiality assessment (MA) later. • Remove MFCA.
3. Diagnosis	• For LCA: specify which impact assessment should be used, and whether this is consequential / attributional. • Highlight that results will lead to prioritization: i.e., targeting the current (baseline) resources with the highest impacts.
4. Development	• Specify that input to this step is the output of last step (i.e., prioritized resource use), based on which the CE strategy are identified. • CTI might also contain suggestions for CE strategies.
5. Selection	• Link the selected (or rather the process of selection of) optimal CE strategy to the defined goals and sustainability objectives in step 1 point of departure • Include the use of scenario analysis.

6.3. Achieving its objectives

The experts were also invited to provide their feedback to on whether the framework reaches its objectives. These synthesized results are presented in the table below, in which the approval rate indicates the % of experts that considered the objective to be reached.

Table 15. Summary of the experts' critical feedback to each of the framework's objectives.

Objective	Approval rate	Critical feedback
Holistic (multi-dimensional)	82%	• Be more explicit in definitions of CE and sustainability used. • Estimate how many man-hours and financial cost it would require a company to do this exercise with various scopes. • Managing trade-offs between different dimensions is key: MCDA should be required.
Life-cycle perspective	73%	• Despite the wide adoption of these methods, it has been shown that they might not be sufficient to address the complexity of systems beyond products. • Make sure that the framework can prevent burden shifting to other parts of supply chains. • Boundary setting will be key.
Flexibility in scale and maturity	54%	• The framework acknowledges different maturity profiles, however does not take it into account when providing examples of assessment methods; neither MFA, or LCAs are for low maturity profiles. • This framework seems to require a lot of data for methodology which many organizations do not own. • High effort, would require a certain maturity in sustainability. Also, the costs and effort of conducting an LCA might be high, feasibility could be difficult in a certain time frame.
Build on existing assessment tools	82%	• LCT methods are not the easiest to apply to a variety of different companies. • To ensure this framework is used it should maximize the amount of work that companies have done through their regular sustainability reporting and disclosure processes (e.g. materiality assessment, calculations, methodologies, strategies, etc.)
Strategic	82%	• This framework as is, requires too much effort to be used by SMEs (too cumbersome and costly). • Scenario analysis and taking into consideration the dynamics are key for strategic decision making, which might not be well enough reflected in the tools like LCA.

As presented in the table 15, the approval rate for each of the objectives was higher than 50%. However, the objective 'flexibility in scale and maturity' showed to be the most controversial among them. This is in line with the previously identified primary feedback theme (I. Structure and application of maturity analysis and materiality assessment), in which these concerns also appeared. Therefore, the proposed changes following this research theme (moving the maturity analysis, and emphasizing the framework's modular nature in its documentation) are also considered to resolve these doubts regarding this critical feedback.

6.4. Focus group results

The focus groups with five companies provided articulated data insights into the framework's usefulness to their assessment ambitions, the framework's objectives and its feasibility (including company barriers). The collected emergent data provided additional insights.

6.4.1 Clarity and usefulness

After explaining the framework in detail during the focus groups, all companies indicated the procedure was clear to them and no additional explanation was needed.

Generally, the framework was positively received, with companies confirming different examples of how it could benefit their assessment practices. One company indicated it could contribute to obtaining an *"impact picture of a certain investment strategy*", using the results in institutional communication outputs. Two other companies indicated that a similar procedure that the framework describes has been – or is currently - used in their company context. For example, the automotive company indicated that a materiality assessment is indeed used to determine the areas of importance in its assessment procedure. Another company stated that the identification of impact hotspots has driven the development of their operations, and that the framework could have been useful to guide this process. The prioritization of interventions based on their ability to reduce impact was appreciated, and the framework was said to provide sufficient decision support to this process.

The holistic nature of the framework was additionally indicated as valuable by three out of five companies, who considered a "360-degree perspective" or "comprehensive view" on sustainability to be crucial. According to one participant, the framework was useful to their business through its ability to "*avoid declaring something that is not true*" – even though the LCA method might pose some challenges (see 6.4.3).

6.4.2. Emergent insights and challenges (objectives and feasibility)

While no direct critical feedback to the framework's objectives was provided, several insights and challenges emerged from the focus group sessions.

Sphere of influence and external constraints

All companies indicated challenges that were often related to their specific business context, and perhaps to a lesser extent to their assessment practices. A recurring theme was the limited influence companies might have on realizing their sustainability ambitions. As a more concrete example, if a certain input material is associated with high impacts, it's not always possible to replace it. One company indicated to be highly dependent on its suppliers. It was prevented to have the possibility to switch to other suppliers that offered services that matched their sustainability aspirations, simply because the market did not offer it. This was also true for a company in the East-African context, which had experienced availability challenges when considering low-carbon transportation options. The participant highlighted that the country in which it operates depends largely on imported goods – with a potentially higher environmental impact. Related to supply-chain dependencies, another company mentioned that >70% of the components used in their final product are not produced by themselves but externally, complicating the decision-making process and the company's influence. Still, due to the company's larger purchasing power, its procurement protocols were able to demand detailed sustainability information to be delivered when changing a material or supplier.

Other company-specific challenges were found in the complexity of production processes, high production standards and associated legal, safety and quality constraints to materials used. For examples, technical feasibility was mentioned as a barrier when increasing the amount of recycled materials, with every new material demanding a strict technical- and safety compliance procedure.

Application context

Two companies had remaining questions related to the application context: (i) whether the framework would be applicable to different sectors, and (ii) whether the framework would allow to investigate impacts resulting from fundamental revisions to company's business models. While the answers to both questions would be yes (see section 3.2), these aspects are somewhat contested in literature and provide ground for further study.

Feasibility

The participating companies addressed various barriers to both their present assessment practices, as well as of those potentially related to the application of the framework. Some of those challenges were related to the LCA method. Two companies, for instance, underlined their worry for the sensitivity of LCA to the assumptions applied. This could lead to replicability issues, or to confusing and contrasting results from different analyses. A potential solution to this issue, individually proposed by two participants separately, was to stimulate sharing assessment lessons within their sector to harmonize the measurement practices.

The high complexity and data-intensity of the suggested life-cycle methods were also addressed. With respect the first element, one company simply stated "*if assessment becomes too complex, companies won't do it*". With respect to the data demands of life-cycle methods, different companies had different perspectives, depending on their context. Data collection issues were in some cases related to supply chain complexity: i.e. in the electronics sector, supply chains are relatively obscure and obtaining reliable information on the social conditions of mining processes is difficult. Another company addressed this complexity through the use of a life-cycle database, while being in the process of acquiring primary data from suppliers. Yet another participant highlighted the challenge of motivating supply chain partners to deliver data, as this would be costly and time consuming for them. This was reiterated by a participant who addressed that several supply chain partners might be less formalized and therefore less likely to be delivering data of the required specificity. According to the participant, an overlooked element of data collection is its mode of communication, and for the tool to be accessible to larger numbers of business leaders, companies need to work within that reality.

Additional insights

Several other relevant insights emerged during the focus group session. One important remark was that the framework is bit oriented too specifically on finding "*unique solutions*", as opposed to a mix of CE and sustainability options. This would require more emphasis on a 'dynamic systems approach', which could be added to a next expanded version of the framework.

One company emphasized that a key barrier for them had been a lack of knowledge: both on assessment methods, but perhaps more importantly on sustainability challenges and their relevance to the company. This had been overcome through several years of learning and training – and element that is not often addressed in academic literature related to company-level of assessment.

A critical perspective was offered by a company that stated that assessment might not always be necessary. In their experience, current investors are not always constrained by the lack of metrics, and telling a story might be sufficient. At the same time, the company described how investors might also use different evaluation frameworks, with different understandings of 'impact'. Therefore, perhaps increased focus should be on how assessment could also be tailored to its eventual use.

In two cases, the increased relevance of sustainability assessment was put forward. One company stated that sustainability assessment would become increasingly imperative, as the company is directly facing the challenges associated with climate change. Another company highlighted the proliferation of sustainability assessment in the decision-making process, particularly due to rapidly developing European regulations.

6.5. Final resulting framework

The final revised framework after the twofold validation process is presented below in figure 9.

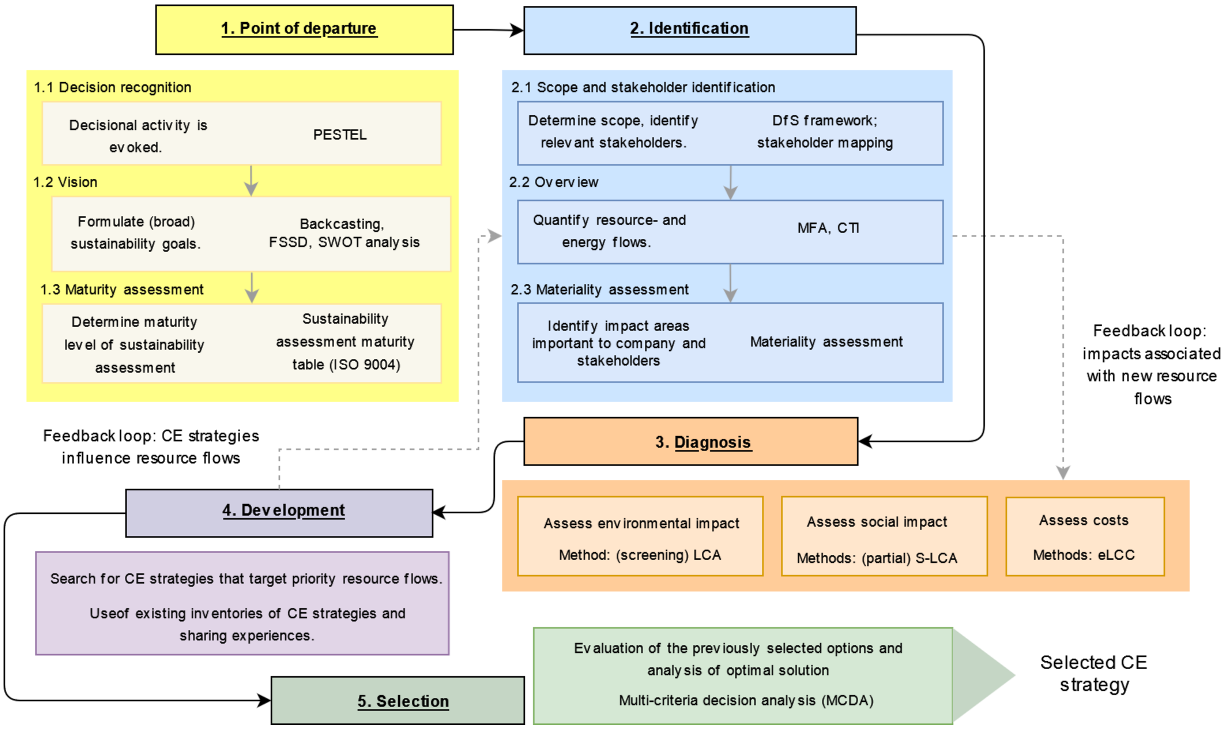

Figure 9. Resulting SCEIA framework after validation steps.

As mentioned, following feedback theme I, changes were made to the maturity analysis and materiality assessment steps. For the recommended maturity self-assessment, the ISO standard 9004:2018 on Quality Management is listed. For the materiality assessment, it was made clearer that this step is used to identify the impact areas most important to both the company as well as its stakeholders. With respect to theme II, the use of MFA, CTI was added as an alternative. The complexity and methodological issues with the LCT methods were addressed through the addition of a screening LCA, using a procedure such as described in (Arzoumanidis et al., 2017). Similarly, it is indicated that a full S-LCA is not considered required; instead, using a selection of (relevant) social indicators from the method will provide more feasibility.

7. Discussion and conclusion

The proposed SCEIA framework aims not to provide a final solution to assessment questions that have been discussed in academic literature for several years. Instead, through integrating lessons from strategic management literature and sustainability assessment practices, it aims to offer guidance to companies with assessment ambitions in a context of decision-making related to CE practices. To contribute to this goal, the framework was designed using a mixed-methods approach. First, the normative core of the framework was formulated, after which its objectives and methodological properties were extracted. Then, a two-fold validation approach was applied to receive external inputs on its methodological structure and feasibility.

Several assessment elements remain topic for discussion and provide ground for further research. A central theme throughout the validation procedure has been the tension between accuracy of assessment (i.e. its reliability) and its feasibility for companies (i.e. aligning its complexity with company capabilities). This discussion relates to external- and internal barriers to assessment, which have been defined previously in literature on sustainability assessment (Johnson & Schaltegger, 2016; Lozano, 2007). Concretely, several experts indicated that sophisticated tools such as MFA and LCA could be considered too time-intensive and complex for companies (Di Maio & Rem, 2015; Elia et al., 2017). This is however contrasted by recent empirical studies showing a high presence of methods such as LCA in companies' assessment experiences (Das et al., 2021). In the selection of focus group participants, several companies confirmed their experience with – or at least knowledge of – LCA. A point for further research could be the use of the results of such sophisticated assessment methods in, specifically, strategic decisions: a larger number of criteria forms a challenge for decision-makers concerned with integrating environmental, economic, and social criteria along with their day-to-day business KPIs (Kravchenko et al., 2021). This might form a barrier to the inclusion of sustainability criteria in strategic decision-making.

It is important to highlight here that it is not expected that companies are immediately proficient to use such available sophisticated tools. As indicated by one of the focus group participants, the process of familiarizing company staff with the LCA method could take years, and is a dynamic and challenging process. This awareness on the need for continuous improvement might be related to the companies' quality management processes and experience with ISO 9004. The dynamic learning process might be exacerbated by the growing number of available assessment approaches, posing the challenge of understanding how they relate to each other, and when to use one (Hallstedt et al., 2010). In this learning process, several 'soft' challenges, i.e. related to the company's culture, might appear along the way (Lozano, 2015). Future research into assessment could dive deeper into such learning processes and associated 'soft' challenges, and evaluate whether the proposed assessment solutions are pragmatic (Walker et al., 2021). This could provide the theoretical foundation of future - collaboratively designed and feasible - assessment approaches.

From a methodological perspective, the proposed methods that the SCEIA framework incorporates might require further research into its application specifically to CE strategies. This was indicated by several participants of both the expert panel as well as the focus groups. While the application of LCA to quantify the environmental impacts of CE strategies appears evident and is recommended in literature (Pena et al., 2020), the methodology is continuously under development and carries some methodological challenges with respect to evaluating CE-related activities. Perhaps most significantly, there's ongoing discussion in the LCA community on how to allocate the credits of CE activities throughout different phases within (open-loop) systems of production (Civancik-Uslu et al., 2019; Corona et al., 2019). Different common allocation methods exist, and while most practitioners appear to use the so-called “end-of-life” method, no consensus on which approach represents reality most accurately has been established. Other remaining methodological gaps deal with using LCA to assess circularity in recycling activities over multiple life cycles, especially when material properties are influenced by this, and how to extend LCA application beyond giving a ‘point in time’ quantification of environmental impacts (Lueddeckens et al., 2020). It is however expected that the method’s continued application will foster scientific- and practical discussions regarding these challenges, further driving the methodological maturity of applying LCA to CE.

Similar to LCA, both the application of LCC and particularly of S-LCA carry several challenges, such as complexity, data availability, required expert knowledge, and associated costs. For LCC, a methodological issue is the inclusion of time in the modelling: cost data is volatile subject to market fluctuations (Swarr et al., 2011). Related to this, taking a longer-term perspective is important in conducting an E-LCC study: if this would be ignored, quick cost reductions would, by default, be considered favorable over long-term value creation (Bradley et al., 2018). The method also offers opportunities: LCC involves extensive participation from the stakeholders involved, which might provide a viable basis for a CE (Wouterszoon Jansen et al., 2020). This also holds for S-LCA, which addresses the main stakeholder groups, employees, local community and society (Dreyer et al., 2006). For S-LCA, its period of development has been shorter, causing it’s challenges are more extensive (Chhipi-Shrestha et al., 2015). It has therefore not yet applied been in practice frequently. However, it is expected that future assessment will increasingly include the social dimension, and S-LCA, selecting a limited number of its extensive list of indicators, is expected to be an appropriate tool for doing so.

Two last and more fundamental points of discussion are (1) the selection of an appropriate CE strategy and (2) the role of CE in realizing sustainable change. For the first topic, most of the focus group participants highlighted that selecting the appropriate CE strategy depends on a large variety of context-specific elements. It goes beyond the scope of the framework to list all available CE strategies and assess the degree to which they are compatible with an organization. However, previous research has provided tools that assist companies with CE business model innovation and selecting the appropriate CE strategy (Konietzko et al., 2020; Antikainen & Valkokari, 2016; Bocken et al., 2019, Diaz et al., 2021), and future works will deepen the understanding of which CE strategy to apply in which situation. With respect to the second issue, the framework adheres to the position that CE should not be considered a goal in itself (Blum et al., 2020; Harris et al., 2021). CE is here considered to offers potential solutions that could contribute to SD. While the impact of CE solutions on certain elements of SD might be identified as positive, CE has no or little relation to a large amount of SDG targets (Schroeder et al., 2018). Other studies even provide examples of CE practices that lead to negative and undesirable outcomes to SD (Blum et al., 2020). Some have called this perspective a 'trade-off' interpretation of CE (Geissdoerfer et al., 2017). Examples of negative impacts of resource-efficiency goals can, for example, be related to rebound-effects (such as in the case of car-sharing provided by Scheepens et al. 2016). In other cases, the environmental or socio-economic burdens of keeping resources 'in the loop' simply do not outweigh the benefits (e.g. highly energy-intensive or expensive recycling processes). While mass- and energy flow inventories provide useful insights in the material consumption within an organization or process, material weight is not a direct steering parameter for sustainability decision-making, since the relation between kgs of material with sustainability impacts is not linear: certain materials might be much lighter but have a much higher carbon footprint, for example. Therefore, assessing the sustainability impacts related to the materials used in the process is considered essential, to determine which resource-efficiency strategy yields the most beneficial results.

A potential limitation of the validation approach is that, for the focus groups, participants were selected that showed interest in CE assessment and, in almost all cases, already had experience with assessment. In subsequent stages, inputs from companies that are earlier in their assessment journey could be included. Related to this is the research gap with respect to company capabilities relevant to CE and sustainability assessment. A more formalized and tested maturity self-assessment process could assist companies in understanding which capabilities to develop further, and how to sketch a dynamic assessment timeline. Lastly, further research could test the application of the framework in practice to study its feasibility. In the future, this could be expanded to different sectors to further refine and revise its application routine and included methods.

8. References

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Chapter 6. Assessment of circular economy scenarios for mineral water production – pilot test case SCEIA framework

Erik Roos Lindgreen, Giovanni Mondello, Roberta Salomone, Tatiana Reyes

Abstract

The mineral water sector is responding to changes in legislation and consumer demand by evaluating the introduction of different circular economy (CE) strategies. In order to assess the (environmental) sustainability impacts of such strategies, the previously designed CE assessment framework SCEIA is tested in a pilot case setting with an Italian mineral water company. The company produces mineral water, packaged in single-use PET packaging, single-use glass and reusable glass bottles. The selected phases of the SCEIA framework are (1) point of departure (decision recognition, vision, maturity assessment), (2) identification (scoping and overview), (3) diagnosis (environmental assessment) and (4) development. Applying the life cycle assessment (LCA) method for the environmental assessment results in the baseline environmental impact of the company and subsequent assessment of four potential CE strategies: (i) the increased use of recycled PET (rPET) in its packaging, (ii) the increased use of reusable glass bottles, (iii) using electric vehicles for distribution, instead of diesel trucks, and (iv) the use of on-site generated electricity from solar PV. The results show that all four CE strategies can lead to significant reductions in greenhouse gas (GHG) emissions, as well as other environmental impact categories. Applying the SCEIA framework shows to lead to useful results, even though challenges in its application remain. The impact results for the CE scenarios should be considered first estimations, and strongly depend on the underlying assumptions. Further research will provide more detailed impact results, and can advance the company's assessment maturity level by incorporating the economic- and social dimensions of sustainability.

Keywords

Sustainability assessment, life cycle assessment, mineral water, scenario analysis.

1. Introduction

Drinking water for human consumption is usually distributed through pipeline systems (i.e. tap water), tanks on vehicles, containers, or glass or plastic bottles. With respect to the latter, Italy is one of the largest consumers of bottled water globally, with total of 13.500 million liters consumed in 2019, amounting to around 225L/year per capita (Statista, 2021). In 1980, this number was 47 L/year per capita: despite growing concerns on the environmental consequences of the use of single-use plastic or glass packaging of bottled water, the market for bottled water is growing (Gambino et al., 2020). Simultaneously, society, businesses and governments are increasingly aware of the environmental burdens associated with inefficient use of resources (Calisto Friant et al., 2021; Masi et al., 2018). One of the drivers of this awareness has been the popularization of the concept of circular economy (CE), which provides an umbrella of strategies aimed at increasing resource efficiency, and thereby contributing to sustainable development (Blomsma & Brennan, 2017).

Both single-use glass as well as single-use polyethylene terephthalate (PET) mineral water packaging are characterized by a low resource-efficiency: the raw material- and energy inputs used in the production process are subsequently attributed a short 'valuable lifetime' (Chen et al., 2021). While plastic packaging recycling rates in Italy have been described as 'promising' (being around 44%), 40% of the collected plastics is still incinerated and around 16% is landfilled (Lombardi et al., 2021). Additionally, it should be noted that recycling of PET has been found to reduce GHG emissions by only around 20% when compared to not recycling (Shen et al., 2011). This however strongly depends on which recycling technology is used (Schwarz et al., 2021). For glass packaging, the recycling rate in Italy is 77% (Ferrara et al., 2021). However, its environmental savings have been debated due to the high energy intensity of the glass recycling process (Krivtsov et al., 2004; Testa et al., 2017).

The CE offers a toolbox of strategies to reduce the aforementioned resource inefficiencies (Reike et al., 2018). However, not all CE strategies result in their expected sustainability impact, and it is therefore recommended to conduct an impact assessment prior to their introduction (Blum et al., 2020; Niero et al., 2021; Roos Lindgreen et al., 2021). To study the environmental sustainability implications of applying CE strategies to the mineral water sector, the previously developed SCEIA (Strategic Circular Economy Impact Assessment) framework is applied (see chapter 4). This is a modular, holistic framework based on existing sustainability impact assessment methods, designed to guide companies in assessing whether CE solutions result in beneficial sustainability impacts. To test this framework in practice, a collaboration with a pilot case study company in the mineral water sector in Italy was set up. The choice for this company was motivated by (1) its motivation to engage with assessment practices, (2) the changing context of its product and increased attention for the CE and sustainability impacts of bottled water, and (3) its relatively low level of assessment experience (assessment maturity), making the company suitable for initial partial implementation of the framework. The SCEIA framework is thus focused on studying (1) the baseline environmental impacts of the production of packaged mineral water (glass and plastic) and (2) the potential of several CE- and sustainability strategies to decrease the environmental impacts currently associated with mineral water production.

Since the SCEIA framework is modular and the company's experience with CE- and sustainability assessment is relatively low, only the environmental dimension of sustainability was selected to include in this analysis. For this, the life cycle assessment (LCA) methodology was used to quantify the current system's environmental impact and the impact of the CE strategies. The LCA method allows the impact assessment over the different life cycle phases of a product or process (Guinée et al., 2011). Following the baseline impact and identifying impact hotspots, the CE and sustainability impact improvement scenarios included are: (1) the increased use of recycled polyethylene terephthalate (rPET) in the packaging of the mineral water, (2) the increased use of reusable glass bottles (3) alternative transportation options (electric trucks instead of diesel trucks), and (4) using on-site generated electricity from solar photovoltaic panels in the production process. More details on the underlying assumptions of these scenarios are provided in section 2.7.

This paper is structured as follows: first, details on the methodology and the analysis' goal and scope are provided. This includes a step-by-step short description of the phases of the SCEIA framework's phases selected in the process, and a condensed description of the production process at the case study company. Then, in section 2.3, the data inventory is described and the most important assumptions are put forward. This is also done for the selected CE and sustainability improvement scenarios. In the results chapter, the current environmental impact of mineral water production at the case study company is presented, and the impacts of the potential CE and sustainability scenarios are highlighted. Sensitivity analyses examine robustness of the results and their sensitivity to uncertainty factors (i.e. data points of lower quality). The feasibility of the scenarios and their concrete implications of the results are presented in the discussion section, as well as brief comparison to results from previous LCA studies.

2. Methodology

2.1 SCEIA framework phases included in the assessment process.

In the previous chapter of this thesis, the SCEIA framework was designed to deliver valuable insights in the impacts of company level CE activities. It has a modular structure, is designed to be applicable to companies with different level of experience with assessment, and aims to preventing trade-offs and burden shifting. It is strongly based on existing sustainability impact assessment approaches. Below in figure 1, an overview of its selected phases in this assessment process are provided in green.

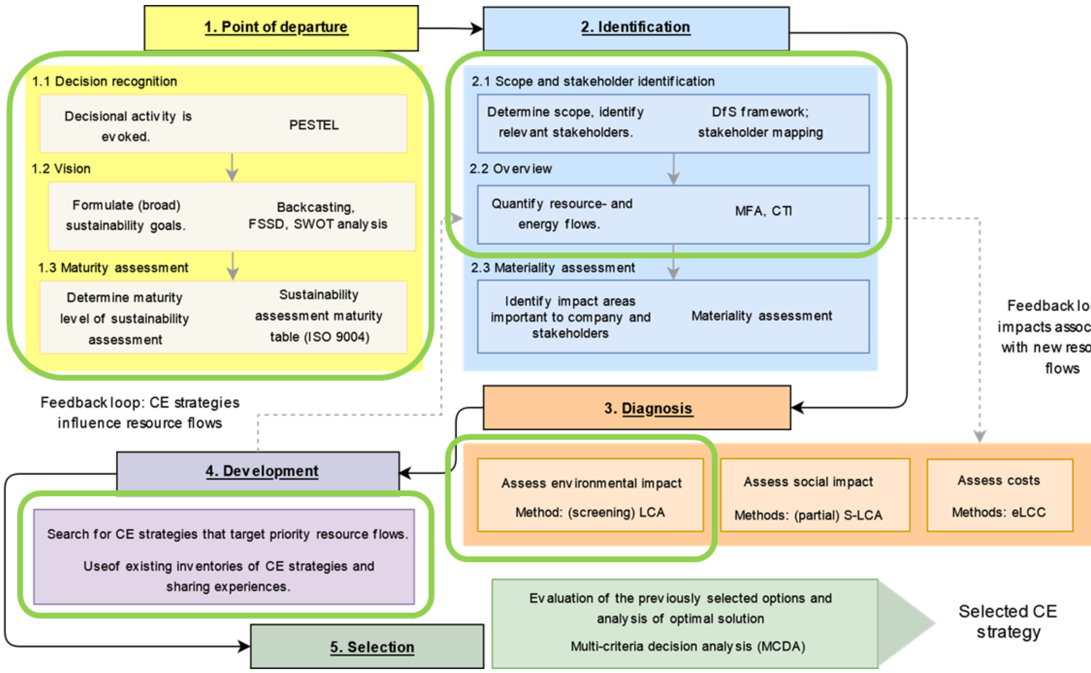

Figure 2. Selected applied phases of SCEIA framework.

2.1.1. Decision recognition

The first phase of the strategic decision-making process is the decision recognition phase, in which strategic opportunities, problems and crises which evoke decisional activity are recognized (Mintzberg et al., 1976). In the case of the mineral water company, various external drivers caused the company to recognize the need for making decisions related to the sustainability of their product. Examples are the planned introduction of a plastic tax by the Italian government, requirements on the inclusion of post-consumer resources in plastic packaging as stipulated by the European Council, and increased customer attention for CE and sustainability.

2.2.2. Vision

The company has a history of sustainable activities, both in terms of the implementation of several solutions as well as in their brand identity and marketing. Their sustainability vision is driven by the notion that the quality of their product, and the low mineral content of their water, can be partially attributed to the untouched environment that is associated with its bottling reservoirs. Therefore, preserving the natural environment will allow the company to continue to deliver its product. This vision has led to the realization of implemented measures to lower the environmental impact of their products, such as the use of electricity generated with an on-site PV system at one of their production plants. The company has also joined a consortium to realize a “bottle-to-bottle” system for the packaging of mineral water. In the next years, the company aims to start the transition to lowering environmental impact through measures focused on packaging.

2.2.3. Maturity assessment

To determine the company's experience with CE and sustainability assessment ('maturity assessment'), the maturity table is used (see table A1 in the appendix). This table is based on self-assessment tables A.21 and A.28 in ISO standard 9004.2008 (Quality management). At the start of the project, the company applied no life-cycle management assessment approaches (LCA, LCC, S-LCA), and no resources flows were quantified – even though a physical accounting system gave insights into the company's purchased resources. The company can therefore be characterized as having a low maturity (level 1) with respect to CE- and sustainability assessment. This has implications for the data collection process and selection of applied methods. For now, the focus of the assessment will be on the environmental domain, while the social and economic domains of sustainability are considered to be evaluated in a second stage.

2.2.4. Scope and stakeholder identification

The mineral water company produces mineral water, both carbonated as well as non-carbonated, packaged in glass and plastic (PET). It has three lines of operation, located at the same plant: two lines for PET bottles of different sizes and one for glass bottles of different sizes. With respect to the latter, a share of bottles is returned back to the company after its consumption. From early meetings with the company's management, the company level was considered to be the most relevant scope for a CE or sustainability analysis. The company agreed with conducting an organizational-level environmental assessment as a first step, identifying hotspots of environmental pressure. Next, future scenarios could be drafted, based on "creative but realistic visions on a more sustainable model of operations". Following this, the goal of the study is twofold: i) to analyze the baseline environmental impact of the company's activities in 2018, with the functional unit of the LCA being: the total production and distribution of mineral water packaged in plastic and glass by the company in 2018, and ii) to quantify the environmental improvements of different CE strategies relevant to the company's operations. The organization also expressed interested in expanding the assessment beyond the environmental domain of sustainability by applying the Life Cycle Costing (LCC) and Social Life Cycle Assessment (S-LCA) methodologies in the future. Since the social impact of the organization is not evaluated in this stage, a mapping of its relevant stakeholders is yet to take place.

With respect to the scope of the study, the system boundaries that were chosen include the extraction of natural resources, transformation and production (i.e. bottling the water), and subsequent distribution to the company's clients: distributors. The use-phase and end-of-life of the bottles are not considered, since these phases are (1) not in the direct scope of influence of the company, while the goal is to propose environmental sustainability improvements that can be realized by the company, (2) strong assumptions would need to be made on the collection- and recycling rate of the water bottles in different regions where the products are consumed. The system boundaries are visualized below in figure 2. For more details on the system boundaries related to the use of reusable bottles, see section 2.3.5.

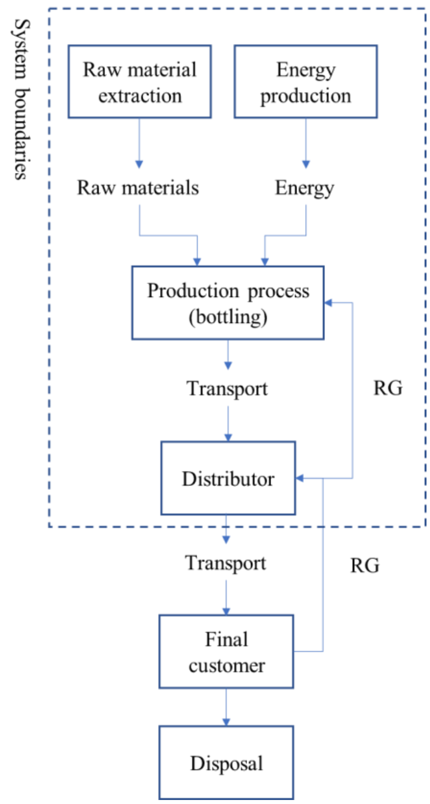

Figure 2. System boundaries selected for the environmental impact assessment. RG stands for the fraction of reusable glass bottles that are returned to the distributor and subsequently to the mineral water company. In line with the system boundaries, only the transport from the distributor back to the company is considered.

2.2.5. Overview

In order to understand the production process and its several physical- and energy inputs, an inventory of its relevant physical flows is established. Since distribution potentially forms a substantial part of the company's environmental impact, detailed information on its distribution process was collected. The data collection process is described in more detail in the life cycle inventory (section 2.3).

2.2.6. Diagnosis

For the assessment of both the baseline environmental impacts of the company's activities, as well as the potential impact reductions due to CE strategies, the methodology used to perform the environmental assessment was the Life Cycle Assessment (LCA) method based on the ISO 14.040 (ISO, 2006) and ISO 14.044 (ISO, 2018) standard. The SimaPro software (version 9.1) supported the data processing and the ecoinvent 3 database was used. The LCA is composed of four main steps: goal and scope definition (chapter 2.2), inventory analysis (chapter 2.3), impact assessment and interpretation (chapter 3: results). The LCA-type is attributional LCA, which was chosen to determine the baseline impact of the system, identifying and describing the environmentally relevant physical flows within the set system boundaries (Finnveden, & Potting, 2014). The analysis focuses on the environmental impact category of greenhouse gas (GHG) emissions. After obtaining the information related to the environmental hotspots in the system, different CE scenarios (see section 2.7) were drafted aimed at reducing the system's overall environmental impact. The ecoinvent 3.2 database and impact assessment methods ReCiPe 2016 (H) and IPCC GWP 2013 100a were used in the analysis, using foreground data where possible. Data and assumptions are presented in more detail in chapter 2.3. and in the supplementary materials.

2.2.7. Development

The development phase comprises searching for solutions to minimize the baseline impact by reducing – or make more efficient use of –resource and energy flows by applying CE strategies. From recent developments related to the production of mineral water, as well as discussions with the company's management, several scenarios in which CE strategies are used for potential sustainability improvements were formulated. Below, these improvement scenarios and their underlying assumptions are presented.

The use of recycled PET (rPET)

Directive (EU) 2019/904 of the European Parliament and of the Council on single-use plastics stipulated targets for the recycled content in plastic bottles in the EU (EC, 2019), and the European Commission has proposed a mandatory EU recycled content target for plastics packaging of 30% by 2030 (Additives for Polymers, 2021). Simultaneously, an Italian plastic tax on virgin plastics was proposed in 2020 Italian "budget law" and is expected to obligate producers of single-use plastic products to pay a to-be-determined price per ton of used virgin plastic materials. In this context, the mineral water company takes part in the CORIPET consortium ("Coripet – Consorzio volontario per riciclo del PET," n.d.): a voluntary non-profit consortium, recognized by the Italian Ministry of the Environment between producers, converters and recyclers of PET bottles. The consortium guarantees the fulfillment of Extended Producer Responsibility (EPR) obligations by its producer members, managing the end-of-life of packaging materials. CORIPET's current activities comprise the realization of a "bottle-to-bottle" system, collecting and recycling PET to become rPET, to be used in the production of new bottles. While the end-of-life phase of the production process is not considered in this analysis, the environmental impact of the CE scenario of using different shares of rPET in the production of the PET lines is evaluated. This is done for the case of 30% rPET in 2025, 50% rPET in 2030, and 100% rPET in 2050. For the production of rPET, the ecoinvent 3 database is used. The results are compared to previous scientific studies on the use of rPET in the beverage sector (Horowitz et al., 2018).

Increasing the use of reusable glass bottles

As mentioned previously, a share of the companies' products is sold in reusable glass bottles. They are returned back to the company after which they are inspected, cleaned and used in the production process. Increasing the share of reusable bottles would be in line with the aim of a CE to increase resource efficiency and avoid waste (Reike et al., 2018). Previous LCA studies have indicated that the use of refillable bottles is preferable from an environmental perspective, although this depends on the number of 'circulations' and the distance covered, and transport mode used for distributing the bottles (Ferrara et al., 2021; Tua et al., 2020). To investigate the potential of reducing the companies environmental impact using an increased share of reusable bottles, this scenario is analyzed.

Transport by electric vehicle

Previous environmental assessments show that the transport emissions, particularly for glass bottles, form a substantial part of several environmental impact categories. After this is confirmed using the LCA method, the scenario of replacing the current mechanism of transportation (diesel trucks) with electric vehicles is considered as a potential solution.

Using renewable energy in the production plant

Lastly, one scenario to improve the environmental sustainability of the production process of mineral water is to install solar PV panels at the plant. This will avoid the generation of electricity through the common average electricity mix in Italy. The environmental impact of this scenario is investigated.

2.3. Life cycle inventory – data and assumptions

Complete data on the company's operations for the glass line and two PET lines was collected in 2019 and 2020. The flowcharts of both lines are presented in figure A1, A2 and A3 in the appendix. Detailed information on the use of raw materials, electricity and transportation were available for every phase of the production process. These are withheld from this chapter due to their sensitive nature. This includes the electricity mix and energy use expressed in kWh, the number of bottles of different sizes produced, the weight of secondary packaging used and the locations of the distributors to which the bottles were sold. For some data, assumptions were made, which are presented below. For the CE scenarios, often, no primary data was available as these scenarios are still hypothetical. In these cases, literature data, where possible from previously conducted LCAs, and ecoinvent 3 processes were used to complement the collected primary data.

2.3.1 Description of production process

The company's three automated production lines produce mineral water packaged in plastic and glass in different sizes (see table 1). NRG signifies 'non-returnable glass' (single use bottles) while RG refers to reusable glass bottles. For each line, the production process is slightly different. Therefore, a short description is provided below.

Table 1. Mineral water products associated with each production line

Line	Products
PET line A	150 CL still, 200 CL still.
PET line B	33 CL still, 50 CL still/sparkling, 100 CL still/sparkling.
Glass line	25 CL still/sparkling (NRG), 50 CL still/sparkling (NRG), 75 CL still/sparkling (NRG), 100c CL still/sparkling (NRG), 92 CL still/sparkling (RG), 100 CL still/sparkling (RG).

PET line A

The PET line A is the least complex production line, since no carbonation of the final product is involved. The line produces larger PET bottles of 150 CL and 200 CL. The production line is largely automated. Preforms are delivered to the production plant. They are intermediate products, produced through injection molding of PET, that are subsequently blown into a PET bottle. This blow molding process uses pressurized air to shape the original preform into a bottle sized plastic shape. After reaching its final shape, a polypropylene label is applied. In a single step using a 'monoblock', the bottle is rinsed, filled with mineral water that originates from the spring, and capped in the next step. In line with food safety standards, a number of bottles undergoes laboratory inspection to guarantee purity. The next steps are related to packaging: packages of six bottles are bundled with PE shrink film, and paper handles are applied to each package. The packages are subsequently placed onto pallets, which are wrapped in shrink film and provided with a unique identification code. They are prepared for distribution, for which diesel trucks are used.

PET line B

PET line B has a layout similar to PET line A, but produces a larger variety of bottle sizes, and includes sparkling mineral water production. Again, the preforms of the bottles, having different weights depending on bottle size and presence of CO_2 in the final product, arrive at the first step. They are subsequently blown into their final shapes in a blow molding step. Subsequently, a premix system mixes separately delivered CO_2 gas (in tanks) with mineral water for the 'frizzante' bottles. This is again followed by a 'monoblock', which rinses, fills and caps the PET bottles. The steps thereafter are equal to PET line A, although no handles are applied to the packs of bottles.

Glass line

The glass line contains a number of additional steps due to (1) the nature of the packaging material and (2) the inclusion of RG bottles, which are returned to the company after their use. The glass bottles are delivered on pallets, which are first unloaded in a 'depalletization' step. Then, the RG bottles, which are carried in crates, are taken out of these crates, the remaining caps are removed and they are washed. The crates are washed as well and circulated again. The NRG bottles do not undergo these previous steps. Then, all glass bottles go through an inspection process. They enter the 'monoblock', in which they are filled with either non-carbonated or carbonated natural mineral water. For the production of this carbonated water, a premix system similar to that of the PET line B is applied. The filled RG bottles of a specific size are than capped in a separate process step, in which a crown cap is applied, while the others are capped in the 'monoblock' process. As a next step, paper labels are applied to the bottles, and they are packed in carton boxes. The RG bottles are packaged in crates again. After the packing step, the boxes or crates are put onto pallets, which are provided with a specific code, and wrapped to be ready for distribution.

2.3.2 Electricity use

The electricity use of every step in the production process was provided by the company: including the electricity use associated to blow molding processes and i.e. operating the internal 'conveyer belts' of the plant. To properly model the electricity mix used by the company in 2018, a combination of company data, ecoinvent 3 data and online information was used. First, the company delivered information on the energy mix of the electricity used in 2018. This is presented in the table below. This information was expanded with online information on the specific shares of renewable energy (Statista, 2018). Next, each category was made more detailed to review the processes present in the ecoinvent process "Electricity, medium voltage {IT}| market for | Cut-off, U". However, since the shares are only valid for 2014, the relative fractions were updated in the newly created electricity process. Full details on the resulting modeled electricity mix are presented in the appendix table A2.

Table 2. Electricity mix company in 2018.

Category	Information from company	Extrapolated from (Statista, 2018).
Renewable sources (hydro, wind, solar, biomass)	36%	
Hydro	Not reported	15%
Wind	Not reported	6%
Solar	Not reported	7%
Biomass	Not reported	8%
Coal	13%	
Natural gas	43%	

Other petroleum products	1%
Nuclear	4%
Other sources	3%

2.3.3 Other energy use

In the received energy documentation, the production plant's energy use is split into:

1. General services: the activities and their associated energy use that have a general character, i.e. not directly connected to the production.
2. Auxiliary services: the activities and their associated energy use with a general character, not strictly part of the production process, but necessary and supportive to the plant.
3. Production processes: the activities and their associated energy use exclusive to the production process, structured accordingly to each of the production steps.

The third type has been included in the model as part of each of the production steps. The first category comprises the lighting for the production lines, the lighting for the offices on-site and general electricity use of the offices. The second category comprises vapor generators (which uses GPL for the PET lines, and electricity for the glass line), electrical pumps, compressors (both for refrigeration as well as for compressed air drying), the fire system, a sterilization system, a transformation system and the waste water treatment. Several processes of these auxiliary processes, were, after discussion with company staff, attributed to the blow molding processes of PET line A and B (see table 1). The energy was subsequently divided using mass allocation, assuming that the volume of liters of water produced presents a proxy for the individual line's energy use.

Table 3. Auxiliary energy processes of the company, as reported for 2018.

Process	Original attribution to category	Revised attribution
Booster (PET line A, PET line B)	Auxiliary services	Blow molding processes of both PET lines. Ratio of quantity of liters/year used to attribute energy to PET line A and PET line B.
Air compressor (PET line A, PET line B).	Auxiliary services	
Cooling towers (PET line A, PET line B)	Auxiliary services	
Electrical pumps	Auxiliary services	N/A
Compressor for air drying	Auxiliary services	N/A
Fire system	Auxiliary services	N/A
Autoclave (sterilization)	Auxiliary services	N/A
Industrial water purifier	Auxiliary services	Attributed to waste water treatment process.
Civil water purifier	Auxiliary services	
Waste water collection tanks	Auxiliary services	
Battery charger trolley	Auxiliary services	N/A
Transformation cabin	Auxiliary services	N/A
Compressor for refrigeration	Auxiliary services	N/A
Vapor generators (GPL and electricity)	Auxiliary services	Vapor generators (GPL use) are attributed to both PET lines, using the ratio of quantity of liters/year used to attribute the GPL use to PET line A and PET line B. Vapor generators using electricity are attributed to the glass line.

For the on-site waste water treatment processes, their yearly energy use was provided, and the company delivered an estimation of the total volume of waste water treated annually. The latter figure was used for the small-scale wastewater treatment process available in the ecoinvent 3 database (wastewater, average {CH}| treatment of, capacity 1.6E8l/year).

2.3.4 Use of raw materials

PET bottles - PET preforms of different weights, corresponding to different bottle size and whether the water is carbonated or uncarbonated, are purchased by the company from a single producer. The transport distance from the producer to the mineral water company is used in the model. No primary data for the production of the preforms was available, but European (RER) processes for PET granulate (bottle grade) and injection molding (shaping the preform) were selected in the ecoinvent database. Bottle caps of PET bottles were made of polypropylene (PP), and a similar modeling approach as the preforms was used. The weight of the PP bottle labels was provided by the company. Their production process was modeled using

PP granulate and subsequent calendaring and, again, the distance from their producer to the mineral water company was used in the model.

Glass bottles - Glass bottles of different sizes, weights and color are bought from a single producer. The distance from the producer to the mineral water plant has been used in the modeling. European (RER without Switzerland and Germany) processes for the production of white or green packaging glass were used. These processes include a mix of primary and secondary materials: around 60% of glass cullets are used, and comprise the resource- and energy inputs associated with a two-stage molding process.

Secondary packaging - Several types of secondary packaging are used for transportation purposes. For all secondary packaging, the production location was provided and used in the model. The PET bottles from PET line A and PET line B are bundled in packs, containing six or twelve bottles depending on their size, using LDPE shrink film. Here, a global ecoinvent process of this packaging material was used. The packaged bundles of the larger bottle sizes, produced in PET line A, also contain handles, which consist of 90% LDPE and 10% paper. The single-use glass bottles are packaged in carton boxes, containing between twelve and thirty bottles, depending on their size. The European (RER) ecoinvent 3 process for corrugated board was used. The reusable glass bottles, on the other hand, are transported in HDPE crates that are washed after arrival at the plant. Their average reuse time was estimated to be approximately five times per year, with an overall lifetime of around ten years. The pallets used for transporting the different packs of water to the distributor circulate among different companies. They are considered to be outside the scope of the company's operations or responsibility, and are therefore outside the system boundaries. All products are, once bundled and placed on pallets for transport, wrapped in linear low-density wrapping film (LLDPE), of the quantities for each product were provided. Since this specific type of wrapping film is not available in ecoinvent 3, the European (RER) process for linear low-density wrapping film is used.

Other physical inputs - Several other physical inputs are used in the production process. For attaching labels to each of the different bottle types, pressure sensitive hotmelt glue is used. While the yearly quantity is known, no process that corresponds to this type of glue is available in the ecoinvent 3 database. Instead, a global process for "chemical product" is used. Another physical input is the use of liquefied CO_2, bought in tanks, used for carbonation of (some of the) mineral water produced in PET line B and the glass line. The total volume of liquefied CO_2 used in 2018 is known; to distribute this over the PET line 4 and glass line, the ratio between liters of carbonated water produced in 2018 by both lines is used. This amounts to 65% PET B, 35% glass line.

Other physical inputs include soap and detergents. To clean the glass RG bottles, hydrogen peroxide is used. The yearly quantity is added to the glass line. For all lines, the cleaning agents include hydrogen peroxide, sodium hydroxide, and peroxyacetic acid. While ecoinvent processes for the first two cleaning materials were available, peroxyacetic acid is modeled using a general soap process.

Two other physical inputs include the use of carton layers between pallets and the top covers of the pallets (made of PE). For both, the total weight and production location was received by the company. Their weights have been attributed over the three lines based on the yearly volume of pallets produced each year.

2.3.5 Transport and distribution

The company's clients are, generally, distributors, who are responsible for the sale of the product to the final consumers. Three types of distributors are identified. Most relevant is the long-chain distribution, which consists of individual distributors, that subsequently sell the water to small independent businesses with surfaces smaller than 100 m^2 (e.g. supermarkets, shops, restaurants, bakeries etc.). These organizations subsequently sell the water to consumers. Short-chain distribution, on the other hand, is the modern retail system composed of a network of large-scale supermarket chains and other chains of intermediaries of various kinds. The third distribution channel is e-commerce, which is mainly aimed at facilitating some small customers that are out of reach of the regular points of sale. In 2018, sales realized through e-commerce were relatively low, and due to the dispersed and complex nature of the distribution, their transport has not been considered.

While determining the exact location of every distributor was deemed impossible due to data availability and the vastness of the distribution network, the locations were estimated using detailed information on the sales of the different products in different regions in Italy. This information was received for 2020, and was subsequently calculated for 2018 using the same ratios between the regions. Next, distances from the production location to the capital of the region, in which it is expected that most distributors are located, were calculated using Google Maps. Transport was confirmed to take place with diesel trucks, but in order to arrive at the final ton-kilometers, some calculations were necessary. Company information provided the information that every truck carried 32 pallets of bottles. The amount of mineral water packs on each pallet depended on the product type; this information was received and used. It was subsequently assumed that one type of product (i.e. bottle size and type) was transported in one truck. The total weight of all transported weight of bottles their packaging materials was then calculated per region and per product type. Based on pallet weight and number of pallets transported for each truck, EURO5 freight lorries of size 16-32 metric tons were selected in the ecoinvent 3 database. This is line with the transportation assumption as followed in Ferrara et al. (2021).

A share of the mineral water bottles packaged in glass are reusable: they are returned and inspected, cleaned and refilled at the production plant. These bottles are almost exclusively sold to clients such as hotels and restaurants, who are supplied by a distributor that is also responsible for the collection of the used bottles. There, to model these so called 'VAR' ('vendere a rendere') bottles, they are assumed to be transported back from the distributors to the production plant, using the same distances. According to company estimates, the re-use time of the glass RG bottles is about twenty times. From literature data, it is assumed that the number of rotations is between three and five per year; therefore, we assume a number of four rotations per year (Rigamonti et al., 2019). This would correspond to an average lifetime of five years for the RG bottles.

Some losses might occur, both in the collection process as well when they are inspected at the company to verify the absence of damages. For both parameters, no primary data was available so literature data is used, setting the average refund rate of empty bottles at 98.7% and a discarding rate of 1.85% after inspection (Tua et al., 2020). These losses are compensated through adding required inputs of new glass bottles in 2018. Since the received data related to the complete sales, transport and energy use in 2018, only the transport of the empty bottles back to the company (four times) was considered in assessing the impacts of reusable bottles.

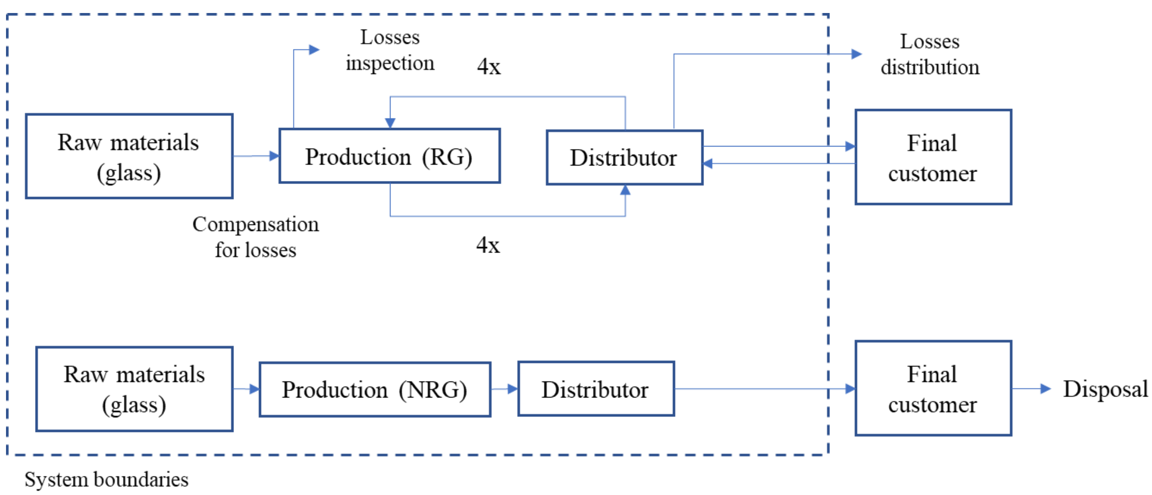

Figure 3. System boundaries related to the model for reusable bottles. A number of four rotations per year was assumed. The losses after inspection are assumed to be part of the received glass waste data (see next section). The losses in the distribution phase fall without the scope of the analysis.

2.3.6 Waste

Information on the total quantities of general categories of waste produced in 2018 were obtained from the company. The data is however less detailed than other part of the production process due to (1) the broad categories of which data was received (i.e. "plastics" instead of which types of plastics) and (2) inaccessibility of primary data by the relevant waste processes companies. For these two reasons, general waste processes in the ecoinvent 3 database were selected for the categories presented below. The choice was made to select global recycling processes over national incineration processes, since the waste is collected separately at the plant and the waste management companies subsequently process it further.

Table 4. Waste categories and selected ecoinvent 3 database processes.

Waste category for which the yearly quantity was received (2018)	Selected process in the ecoinvent 3 database.
Processing of 'mixed materials'	Municipal solid waste {IT}| treatment of, incineration |
Processing of absorbent filters	Hazardous waste, for incineration {Europe without Switzerland}| treatment of hazardous waste, hazardous waste incineration |
Processing of aluminium waste	Aluminum (waste treatment) {GLO}| recycling of aluminum |
Processing of chemical substances from lab	Hazardous waste, for incineration {Europe without Switzerland}| treatment of hazardous waste, hazardous waste incineration |
Processing of glass waste	Packaging glass, white (waste treatment) {GLO}| recycling of packaging glass, white |
Processing of inorganic waste	Municipal solid waste {IT}| treatment of, incineration |
Processing of organic waste	Municipal solid waste {IT}| treatment of, incineration |
Processing of paper and carton waste	Paper (waste treatment) {GLO}| recycling of paper |
Processing of plastic waste	Mixed plastics (waste treatment) {GLO}| recycling of mixed plastics |
Processing of sludge	Raw sewage sludge {CH}| treatment of, municipal incineration with fly ash extraction |
Processing of toner waste	Hazardous waste, for incineration {Europe without Switzerland}| treatment of hazardous waste, hazardous waste incineration |

2.3.7. CE and sustainability improvement scenarios

The use of recycled PET (rPET)

For the replacement of virgin PET with rPET, ecoinvent data is used in the model: the process "polyethylene terephthalate, granulate, bottle grade, recycled {CH}| polyethylene terephthalate production, granulate, bottle grade, recycled" was chosen. For the PET bottles of all sizes, the calculated scenarios are presented in table 5. These numbers are based on company estimates.

Table 5. Assumptions rPET content scenarios.

Scenario year	Virgin PET content	rPET content
2025	70%	30%
2030	50%	50%
2050	0%	100%

Increasing the use of reusable glass bottles

To assess the impact of increasing the share of reusable glass bottles, two perspectives are discussed. First, the analysis focuses on the avoided impacts from keeping these bottles 'in-the-loop', since their production is avoided. This is done by creating a scenario in which the two RG bottle types are modeled to be NRG bottles – used only once. Through this approach, the avoided impact of the average reuse time on the overall impact is calculated. Next, a bottle-to-bottle comparison is made to arrive at an estimation of the avoided impacts when extending the results to the full production process of the glass line, based on the total volume of mineral water produced by this line.

Transport by electric vehicle

No processes for electric trucks are available in the ecoinvent 3 database, and using the data of an electric passenger car is considered too far removed from the situation at hand. Therefore, available literature data is used to estimate the impact reduction potential of using electric trucks (see Table 11 for a detail of this data).

Using renewable energy in the production plant

To investigate the estimated environmental impact reduction through the realization of on-site electricity generation using solar PV, ecoinvent 3 data was used. Specifically, the process "Electricity, low voltage {IT}| electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted" was selected. The total electricity consumption of the three lines was used to calculate the environmental impact reduction.

2.4. Life cycle impact assessment

After creating the baseline model in SimaPro using the inventoried data as described previously, the environmental impact of the production process was estimated with the use of the ReCiPe 2016 (midpoint, H, v.103) impact assessment method. The selected midpoint approach contains 18 impact categories: Global Warming Potential (GWP); Stratospheric Ozone Depletion (SOD); Ionizing Radiation (IR); Ozone Formation, Human Health (OF-HH); Fine Particulate Matter Formation (FPMF); Ozone Formation Terrestrial Ecosystems (OF-TE); Terrestrial Acidification (TA); Freshwater Eutrophication (FE); Marine Eutrophication (ME); Terrestrial Ecotoxicity (TEcotox); Freshwater Ecotoxicity (FEcotox); Marine Ecotoxicity (MEcotox); Human Carcinogenic Toxicity (HCTox); Human non-Carcinogenic Toxicity (HnCTox); Land Use (LU); Mineral Resource Scarcity (MRS); Fossil Resource Scarcity (FRS); Water Consumption (WC). For a full description of all categories, their indicators and categorization factors see Huijbregts et al. (2017).

With respect to the estimated baseline impact, the results are presented for the company in its entirety (all lines), per line and subsequently per packaging type. First, GHG emission results are shown, after which all 18 impact categories follow. A similar approach is used to estimate the impacts of the proposed CE strategies, except for those with data based on literature information. Afterwards, sensitivity analyses are used to study the influence of the type of trucks and the assumption for the reusable glass bottles.

3. Results and sensitivity analyses

3.1. Baseline impact

First, the baseline environmental impact of the company is presented. This is done by showing a carbon footprint analysis of the company's operations, using the IPCC Global Warming Potential (GWP) 2013 100a method, zooming in on each of the individual processes responsible for a significant share of the impact. This is then expanded with the results of the Recipe 2016 midpoint (H) method.

3.1.1. Company level carbon footprint

Overall greenhouse gas (GHG) emissions of the mineral water company in the baseline scenario (2018) are estimated to be ~18,3 kton CO_{2eq}/year. The distribution over its different production lines and general processes is visualized in figure 4 below. The three production lines are together responsible for 98% of the estimated yearly GHG emissions in 2018. The general energy processes (~1,5%) include the lighting for the production lines, the lighting for the offices on-site, general electricity use of the offices, and the auxiliary processes summarized in table 3 that are not attributed to production line. The impact of the waste processing is negligible.

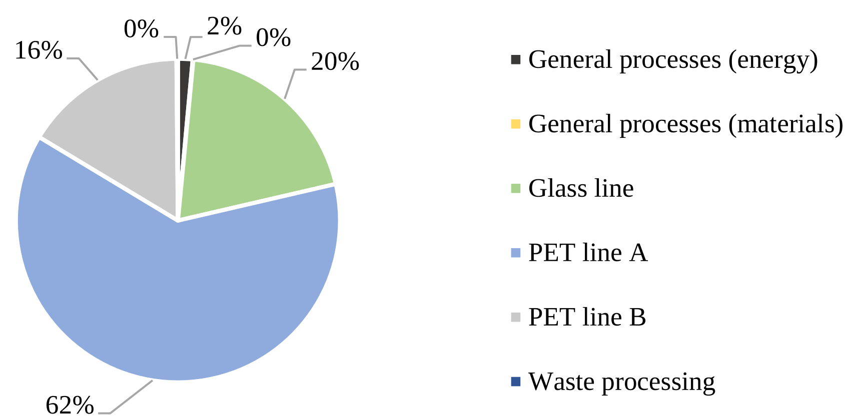

Figure 4. Yearly GHG emission results for the company's production process, under its baseline scenario (2018, IPCC GWP 2013 100a method).

The presented results are largely influenced by the volumes of mineral water that each of the lines produces in one year; PET line A has the largest yearly output and is therefore dominant in terms of yearly GHG emissions. The figure below presents the results normalized for production volume pear year. Accounting for the annual production volume, the glass line is, under the assumptions here described, relatively most carbon-intensive when expressed as GHG emissions per liter mineral water produced.

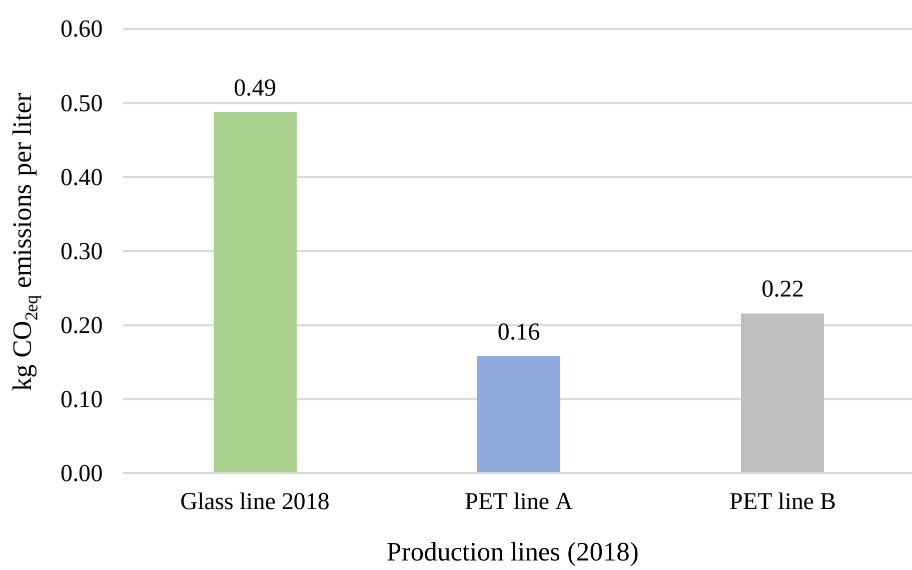

Figure 5. GHG results normalized for production volume pear year in the baseline scenario 2018 (2018, IPCC GWP 2013 100a method).

Comparing the distribution of emissions for each of the lifecycle phases of the lines (see table 6), it is observed that physical inputs are most significant for each line. These physical inputs include the packaging (PET or glass), bottle caps, labels and also the secondary packaging materials. For the PET lines, the production process is responsible for a greater overall share of yearly CO_{2eq} emissions due to the blow molding process used to shape the bottles. In the next sections, the CO_{2eq} impact/year for each of the lines is viewed in more detail to enable a better understanding of the reasons for the results (see section 3.1.3 and onwards).

Table 6. Distribution of emissions over lifecycle phases for each production line.

Line	Physical inputs (upstream)	Production process (core)	Transport (downstream)	Total
Glass line	71%	1%	28%	100%
PET line A	56%	8%	36%	100%
PET line B	72%	8%	20%	100%

3.1.2. Company level assessment – all environmental impact categories

Figure 6 below shows the results for all production processes for the complete set of environmental impact categories, using the ReCiPe 2016 Midpoint (H) method. The results for each of the impact categories seem comparable, with PET line A being responsible for a share of around 60% of each environmental impact category. The greater impact in land use change for the glass line is caused by both the use of packaging glass as well as the paper labels used for the glass bottles.

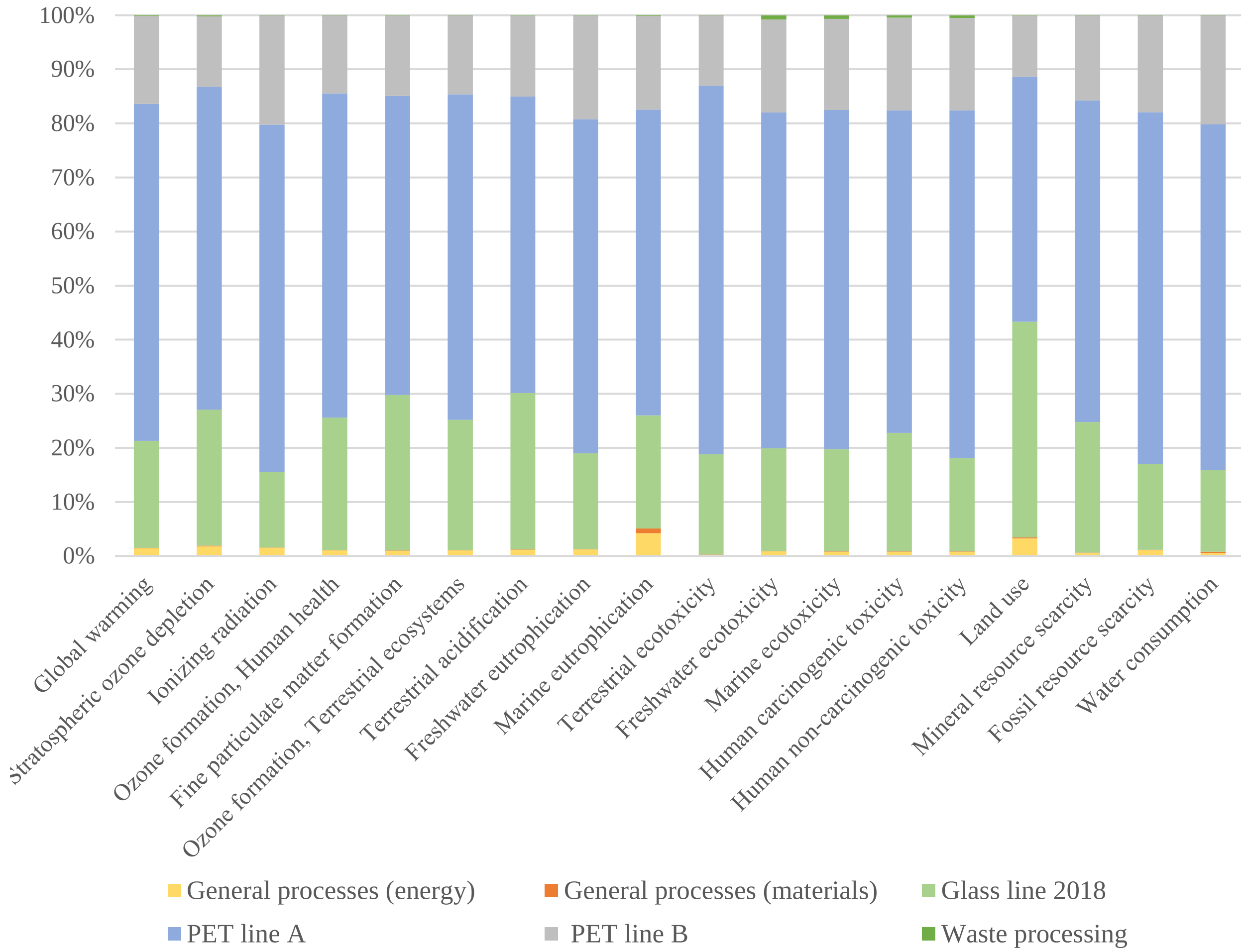

Figure 6. ReCiPe results for the total of all three production lines in 2018 (ReCiPe 2016 Midpoint (H) method).

3.1.3. Glass line impacts

As presented earlier, the distribution of CO_{2eq} emissions over the different life cycle phases of the glass line are mostly concentrated in its physical inputs (71%), followed by its transport (28%) and finally the energy use in the production process (1%). This distribution is slightly different for different bottle sizes and fundamentally different for reusable bottles, under the assumptions presented in 2.3.5. In the table below, the results of the GWP analysis are shown for each type of bottle produced in 2018.

Table 7. Distribution of emissions over lifecycle phases for each glass product.

Bottle size and type	Physical inputs (upstream)	Production process (core)	Transport (downstream)	Total
25 CL still/sparkling	92,2%	0,7%	7,1%	100%
50 CL still/sparkling	90,8%	1%	8,4%	100%
75 CL still/sparkling	88,6%	1%	10,4%	100%
1000 ML still/sparkling	87,9%	1,1%	11,1%	100%
920 CL still/sparkling (VAR)	26,9%	1,7%	73,1%	100%
1000 ML still/sparkling (VAR)	33,6%	1,4%	64,2%	100%

Zooming in on the physical inputs, the emissions associated with glass production are dominant. Taking a 50 CL NRG bottle, for instance, the production of packaging glass is responsible for 78% of the CO_{2eq} emissions of all physical inputs, while the aluminum bottle cap makes up 15%. Similar results are found when zooming in on the use of physical inputs for the other bottle formats. This signals that reducing this primary production impact through i.e. reusing glass bottles could potentially drive a substantial GHG emission reduction. Another relevant remark is that, in all cases, the share of GHG emissions from secondary packaging materials (carton box as packaging material, stretch film for pallets, etc.) is small (~3% of all physical inputs).

For the reusable bottles, the transport process is dominating. The 73,1% impact of GHG emissions is divided over the distribution of the full bottles to the distributor (44%) and the transport of the empty bottles back to the production plant (27%). Under the current assumptions, the latter takes place four times in the baseline production year (2018); the effect of this assumption – and of the overall reuse time of bottles – on the overall impact is investigated in section 3.3.1. When displaying the results for all environmental impact categories of the glass line (figure 7), the large impact of transportation on impact category ‘terrestrial ecotoxicity’ becomes apparently. This is likely due to the high brake wear emissions associated with heavy transport vehicles – the EURO5 freight lorries of the selected size.

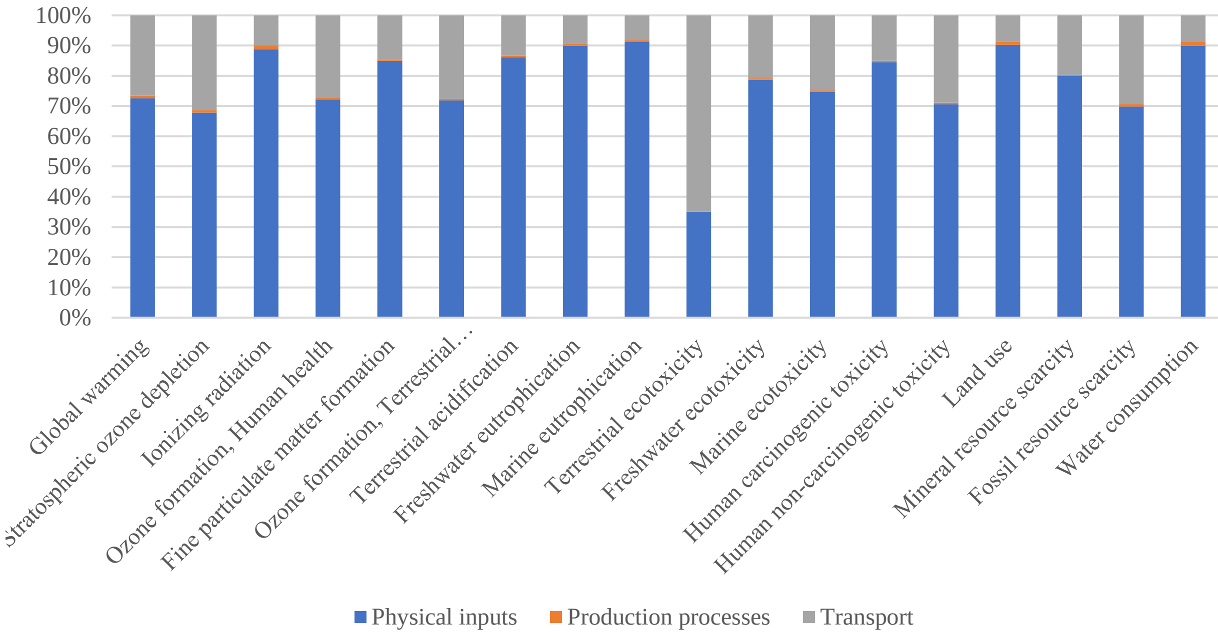

Figure 7. ReCiPe results for the total of all three production lines in 2018 (ReCiPe 2016 Midpoint (H) method).

3.1.4. PET line A impacts

Showing the results of the GHG emissions of PET line A per bottle type, the results show a higher share of the impact in the transport phase of the life cycle. This is not caused by heavier materials – the transport of plastic bottles has a lower weight per liter compared to the weight of glass packaging – but due to the lower impact associated with the production of the lightweight plastic packaging materials. For example, the glass packaging of a one-liter bottle weighs 450 grams, while the PET packaging of a two-liter bottle weighs around 30 grams.

Table 8. Distribution of emissions over lifecycle phases for each product of PET line A.

Bottle size and type	Physical inputs (upstream)	Production process (core)	Transport (downstream)	Total
150 CL still	59,1%	7,3%	33,6%	100%
200 CL still	55,0%	7,6%	37,4%	100%

Zooming in further on the different elements included in the life cycle of the PET production line A (see figure 8), it is observed that the bottle cap and label are both responsible for around 2% of the overall impact for both bottle sizes. Secondary packaging (packaging film, pallet shrink film, bottle pack handles, sheets and pallet covers) are responsible for 5% (150 CL) and 7% (200 CL). When zooming in on the production process, a share of 78% is caused by the electricity use of the blow molding process, and another 12% is due to the electricity use of the bundling of the bottle using PE shrink film packaging. For the PET bottles of both sizes, most of the GHG emissions are caused by the use of raw materials: bottle grade PET granulate are responsible for 74% of the carbon emissions, while the production and transport of the preform account for 23% and 3%, respectively.

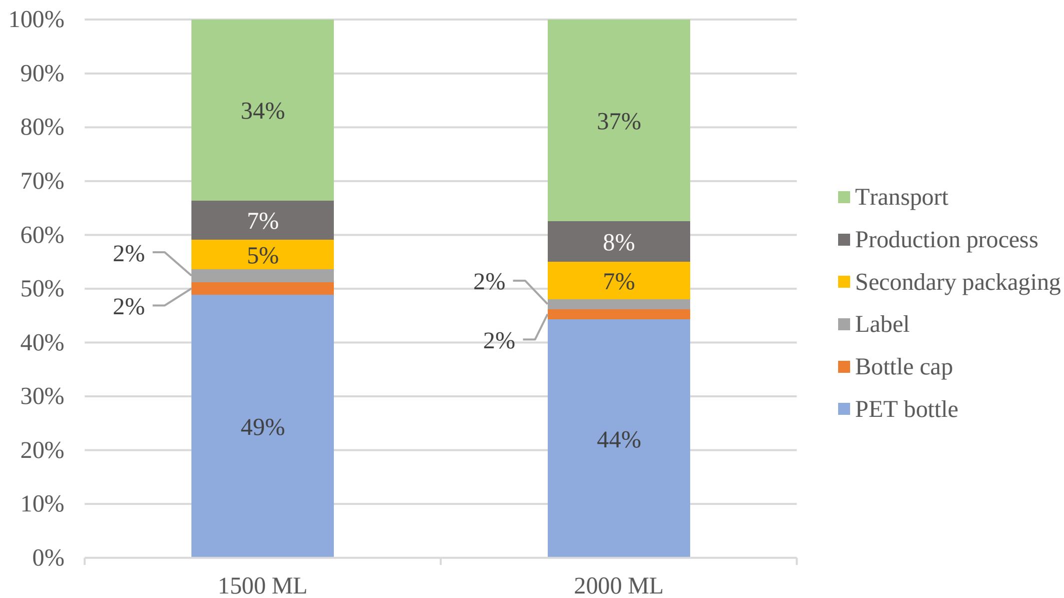

Figure 8. Detailed GHG emission results for production line PET line A, for the baseline scenario 2018 (2018, IPCC GWP 2013 100a method).

3.1.5. PET line B impacts

The average contribution of the different life cycle phases to PET line B is visualized in figure 9 below. Again, the upstream processes are dominant.

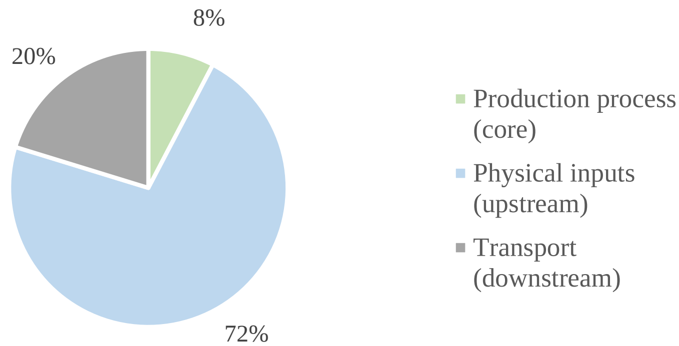

Figure 9. GHG results normalized for production line PET line B, for the baseline scenario 2018 (2018, IPCC GWP 2013 100a method).

Showing the different bottle types (table 9), the results show similar results as the results of PET line A, albeit with a slightly higher contribution of GHG emissions caused by the primary packaging material. This is mainly due to the somewhat higher weight of the packaging in comparison to the water content. It can also be observed that carbonated water bottles have a slightly higher GHG impact in their production phase. This is due to the use of liquified CO_2 in their production process.

Table 9. Distribution of emissions over lifecycle phases for each product of PET line A.

Bottle size and type	Physical inputs (upstream)	Production process (core)	Transport (downstream)	Total
33 CL still	84%	8%	8%	100%
50 CL still	74%	8%	19%	100%
50 CL sparkling	76%	9%	15%	100%
100 CL still	71%	7%	22%	100%
100 CL sparkling	71%	11%	19%	100%

3.2. CE scenarios

3.2.1. The use of recycled PET (rPET)

The first CE scenario that is evaluated is the increased use of recycled PET (rPET) in the production process of the company's plastic products. The results for each of the scenarios are previously detailed in section 2.3.7. are shown below for PET line A (figure 10). For this line, it is estimated that a reduction in GHG emissions of 30% will be reached when using 100% rPET. This represent a reduction of more than 50% in terms of the impacts associated with the physical inputs used in the production process. It is assumed here that the production processes and transportation remain equal.

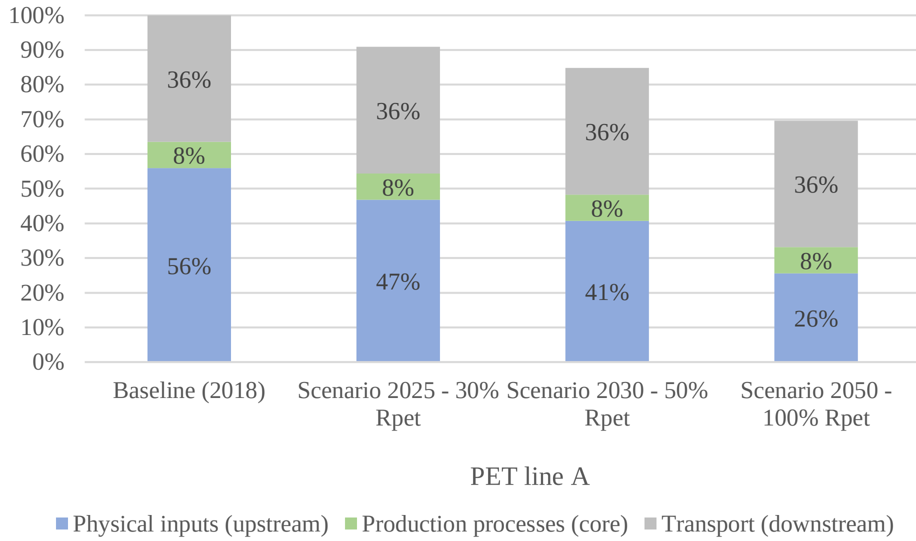

Figure 10. GHG results of CE scenario 'increase use of recycled PET' for PET line A (IPCC GWP 2013 100a method).

Analyzing the results for PET line B shows more significant reductions in GHG emissions, since the overall contribution of the raw PET material is higher for this line (see table 9). This results in an overall estimated reduction of 39% with respect to GHG emissions, again reducing the GHG impact of the physical inputs to the production line B with more than half.

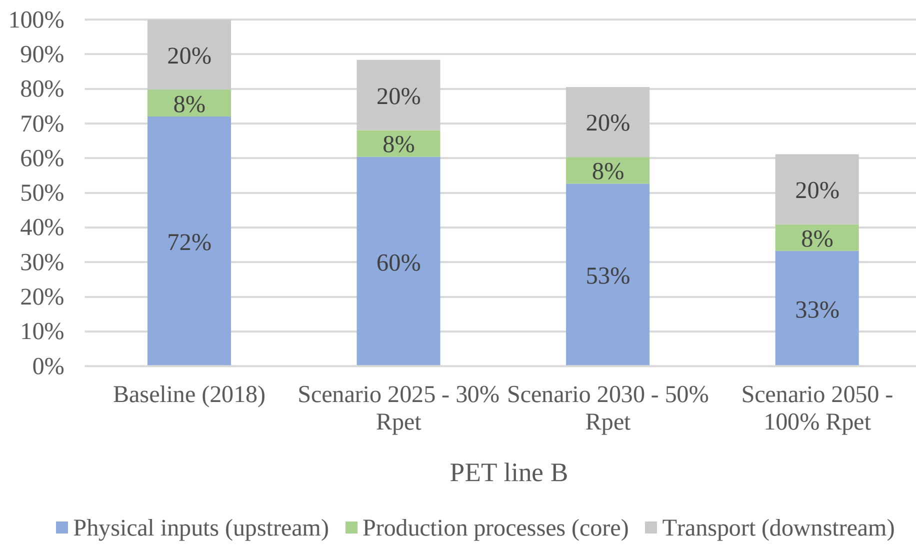

Figure 11. GHG results of CE scenario 'increase use of recycled PET' for PET line B (IPCC GWP 2013 100a method).

The table below shows the results of examining the impact these different scenarios have on the overall GHG emissions of the company.

Table 10. Overall GHG emissions reduction for each of the rPET scenarios.

Scenario	GHG emission reduction
Scenario 2025 (30% rPET)	92%
Scenario 2030 (50% rPET)	87%
Scenario 2050 (100% rPET)	75%

3.2.2. Increasing the use of reusable glass bottles

To investigate the environmental impacts of re-using a share of the produced glass bottles, two analysis approaches are used. The first analysis focuses on the avoided impacts from keeping these bottles 'in-the-loop'. This is done by creating a scenario in which the two RG bottle types are modeled to be NRG bottles – used only once. The avoided impact of the average reuse time, as provided by the company, is visualized below (see figure 12). The results show the impact compared to the baseline scenario of the glass line, in 2018.

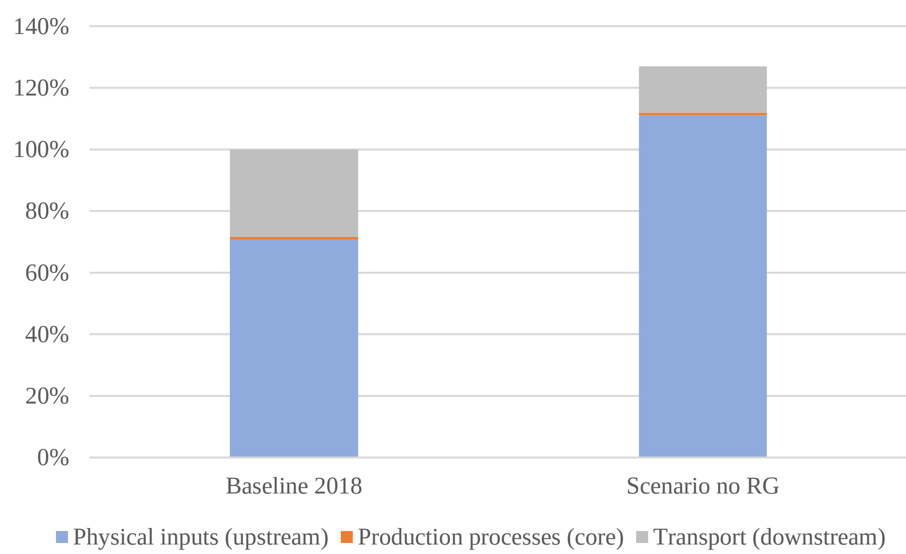

Figure 12. GHG results of CE scenario 'increasing the use of reusable glass bottles' for the glass line (IPCC GWP 2013 100a method).

As can be seen in figure 12, the overall impact of the baseline scenario is ~27% lower than when no NRG bottles would be sold by the company. Interestingly, the impact of the associated transportation decreases with ~7%. This is due to the avoided transport movements of empty bottles from the distributor to the production plant (assumed to take place four times per year). However, the largest observable change is that the GHG emissions associated with the upstream physical inputs grow steeply, with 40%. This is a direct effect of the extended lifetime of the glass bottles, avoiding the use of raw materials and production processes needed to produce glass packaging.

Zooming in on the bottle level, two bottle types of the same size are compared: 100 CL NRG and 100 CL RG. The total GHG emissions associated with the first are estimated at 0,62 kg CO_{2eq}/liter, while that of the latter are less than half of that, with 0,29 kg CO_{2eq}/liter. As can be seen in the detailed overview in figure 13 below, it is again observed that the emissions from transport increase, while the impact of the glass itself decreases steeply. While dependent on bottle size, these results indicate that the increase in reusable bottles has the potential to decrease the emissions of the glass line with roughly 50%. Since in the baseline scenario, the glass line is responsible for around 20% of the company's GHG impact, this would be a reduction of roughly 10% overall. The effect of the underlying assumptions is studied in more detail in section 3.3.2.

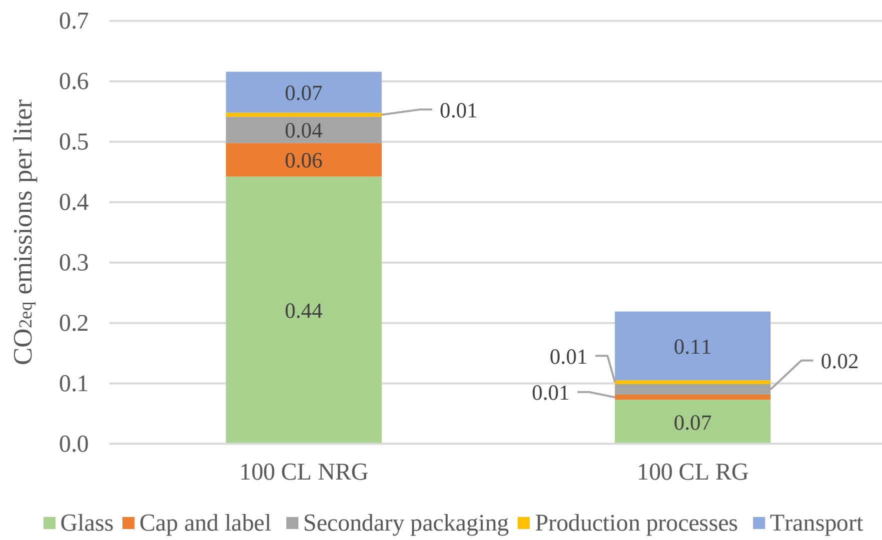

Figure 13. GHG results of CE scenario 'increasing the use of reusable glass bottles', comparing the bottles 100 CL NRG and 100 CL RG (IPCC GWP 2013 100a method).

3.2.3. Transport by electric vehicle

As expressed previously, the overall footprint of the mineral water company is estimated to be ~18,3 kton CO_{2eq}/year in 2018. Roughly 30% of this amount (~5 kton) is related to the transport of the mineral water bottles (and their secondary packaging) to the distributors. Lowering the carbon emissions related to the distribution mechanism could therefore play a significant role in lowering the overall carbon emissions of the company.

No processes for electric trucks are available in the ecoinvent 3 database, and using the data of an electric passenger car is considered too far removed from the situation at hand. Therefore, literature data is used to estimate the impact reduction potential of using electric trucks. Due to methodological differences between literature studies and for reasons of simplification, only GHG impacts are considered.

Table 11. Literature review for electric truck scenarios.

Reference	Summary	Estimated emission reduction	Range
(Elangovan et al., 2021)	Compares diesel truck and electric truck in specific scenario. Considers manufacturing of both. Focus on energy consumption and GHG emissions.	40% greenhouse gas emission reduction with the use of electric trucks as compared to diesel trucks.	40%
(Sen et al., 2017)	Applies hybrid LCA and LCC methods to compare impacts of different fuel technologies of heavy-duty trucks in the US.	Battery electric trucks emit around 25% less GHGs emissions at than the diesel trucks (see figure 3). This includes (negligible) vehicle manufacturing.	25%
(Lee et al., 2013)	Compares electric and diesel urban delivery trucks in terms of life-cycle energy consumption, greenhouse gas (GHG) emissions, and total cost of ownership (TCO).	In a scenario with less frequent stops and high average speed (more relevant to the situation at hand), electric trucks emit 19−43% less GHGs than diesel trucks.	19-43%
(Bachmann et al., 2015)	Estimates fuel and GHG reductions of hybrid electric vehicles used by a Canadian courier company, as compared to their previous use of diesel trucks.	Hybrid diesel trucks reduce GHG emissions by an estimated 23% (city scenario) and 8% (highway scenario).	8%-23%
(Zhou et al, 2017)	Compares life cycle GHG emissions of class 6 medium-duty battery electric truck with a class 6 medium-duty diesel truck in Canada, using different scenarios for temperature, driving cycle and payload.	While GHG reductions can be obtained, even around 80%, this strongly depends on the scenario. For a 100% payload, in the highway scenario with infrequent stops, for example, no GHG reduction is achieved.	N/A

From the above, it becomes clear that a reduction in GHG emissions could be expected from the use of electric trucks, but the extent is highly dependent on a variety of factors (stops, distance, payload, and even temperature). Future research could investigate the distribution of mineral water in more detail to consider which electric transportation setup would be most feasible and result in lower GHG emissions – and other environmental impacts.

3.2.4. Using renewable energy in the production plant

In the baseline scenario of 2018, the production processes are modeled to use electricity with accordingly to the Italian national grid mix (see section 2.3.2.). To investigate the estimated environmental impact reduction through the realization of on-site electricity generation using solar PV, ecoinvent 3 data was used.

The GHG emissions associated with the company's total electricity use form around 17% of the overall GHG impacts. When generating electricity with on-site solar PV, the estimated reduction of impacts of that share is close 100% when applying the IPCC GWP 2013 100a method. This results also holds true when using the Recipe 2016 midpoint (H) method to expand to other environmental impact categories: all are reduced between 99,99% and 99,5%.

3.3. Sensitivity analyses

3.3.1. Reusable bottle assumptions

As indicated by Ferrara et al. (2021) and Tua et al. (2020), among others, the reuse time of glass bottles is an important determining factor when calculating their environmental impact. In the case of the mineral water company, the assumptions on the average number of rotations or 'circulations' of the RG bottles per year is considered to be potentially important, as this determines the number of times the bottles are transported back to the production plant. Different reuse rates are found in literature; for example, according to the PEF guide, an average reuse rate of 30 for glass bottles is recommended (Zampori and Pant, 2019). The effect of the reuse time and rotations is investigated through a sensitivity assessment for the 100 CL bottle size. Please see table A3 in the appendix for the underlying assumptions on the reuse time, bottle lifetime and bottle recirculation.

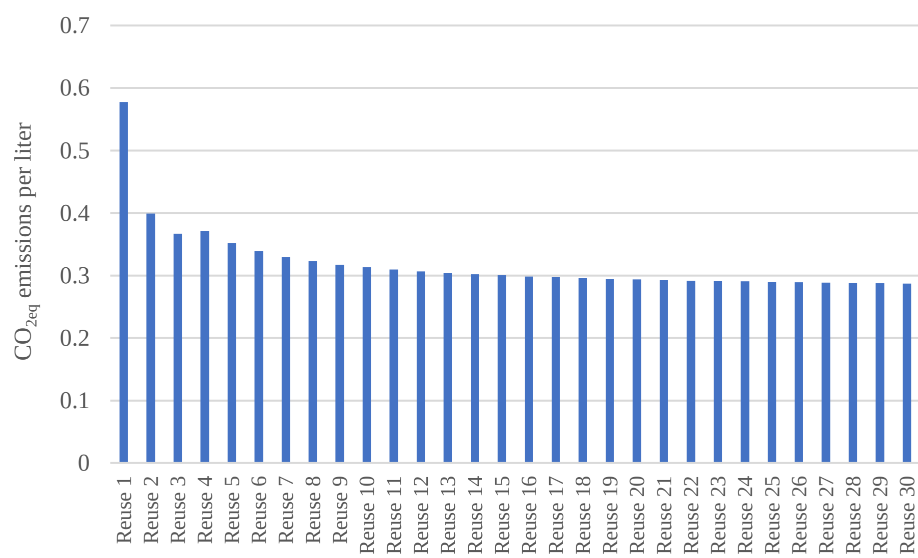

Figure 14. Results for sensitivity analysis on bottle reuse and rotation times (IPCC GWP 2013 100a method).

As can be observed in figure 14 above, the results of the sensitivity confirm that the largest gain in terms of GHG emission reduction takes place during the first few numbers of reuse times. As mentioned earlier, a reduction of around half of the GHG emissions is achieved through the reuse of the bottle. This is achieved after around 10 reuse times. While specific for the situation at hand, particularly with respect to the distribution distance, these results are in line with similar sensitivity analyses presented in (Tua et al., 2020).

3.3.2. Assumptions for truck types

GHG emissions from transportation of the mineral water bottles form a substantial part of overall GHG emissions (around 30%). While the size of the truck could be determined through the known weights of the pallets and the number of pallets per truck, the specific emission standard was not known. Therefore, the effect of changing the emission standard on the overall GHG emissions was tested in a sensitivity assessment. The results below show that the expected result change is small.

Table 12. Sensitivity analysis different truck types.

Emission standard	Expressed as percentage change compared to 16-32 EURO5
16-32 metric ton, EURO6	98,1%
16-32 metric ton, EURO5	100,0%
16-32 metric ton, EURO4	99,2%
16-32 metric ton, EURO3	100,0%

4. Discussion and conclusion

4.1. Environmental analysis

Using an environmental impact assessment approach, the baseline impact of a mineral water company was investigated. Afterwards, the expected impacts of applying CE strategies were estimated. The primary environmental impact category used in the analysis was the emission of GHGs. The analysis of the baseline impact showed that the upstream, core and downstream production processes of the glass and PET lines were responsible for 98% of the estimated yearly GHG emissions in 2018. Without accounting for production volume, PET line A showed to be responsible for around 62% of the overall GHG emissions annually. However, when accounting for the production volumes per line, the glass line showed to carry higher GHG emissions per liter of mineral water produced. Zooming in, this was mainly due to the use of the raw materials (glass) in its primary packaging.

The assessed CE strategies all led to lower GHG emissions: using 100% rPET could lead to an overall decrease of 25%, increasing the use of reusable glass to an additional 10%, and, assuming that electricity generated by on-site solar PV could power all production processes, another 17% reduction could be expected from changing from grid electricity to solar PV. The effect of using electric transport is yet unclear, as literature indicates a range of improvements. While the results of the current study present a first indication of the environmental impact of the to-be-applied CE strategies, potentially providing sensible insights to the company and the mineral water sector, it should however be considered that these scenarios have not been subject to an in-depth LCA study: they are based on rough estimates, using ecoinvent 3 database processes and a specific set of assumptions. This becomes clear when comparing the results to those of previous studies. For example, while the analysis' system boundaries are different (i.e. the end-of-life is not included in this study), the environmental impact results of the non-recycled PET bottles are in line with those presented in (Horowitz et al., 2018). However, according to that study, the expected reduction in GHG emissions from using 100% rPET is lower (around 10%) than in the analysis presented here. This could be due to system boundary discrepancies and different underlying assumptions, but it also signals that further analysis work is needed to draw definitive conclusions on the environmental improvement potential of the CE strategies.

The same holds for the increase use of reusable bottles: as previous studies have shown, the potential reduction in GHG emissions due to their reuse is dependent on factors such distribution distance, reuse times and lifetime of the bottle (Ferrara et al., 2021; Tua et al., 2020). In their study, Ferrara et al. (2021) even state that is not possible to determine whether glass or PET packaging for mineral water is the most sustainable packaging solution, "since it depends on the variation of the key factors identified in the analysis" (p.11). Further studies could examine these presented scenarios in more detail, for example focusing on the collection system of secondary PET through the CORIPET network, and expanding the system boundaries to include the end-of-life.

In a next analysis, the inventory data for the baseline scenario could be further expanded through the inclusion of data on secondary packaging of purchased materials arriving at the plant, including the distribution of global e-commerce sales (expected to grow in the next years), and more details on the company's distribution network. Primary data on the production of the primary packaging materials would further strengthen the results. While time-consuming, the environmental impact analysis could be expanded with the economic- and social impact domains, as recommended in the SCEIA framework.

4.2. Application of the SCEIA framework

In addition to the environmental analysis, this study has also functioned as a pilot test case for the SCEIA framework. This framework aims to assess the sustainability impacts of CE strategies, before their introduction. Following the framework's modular nature and the relatively low experience of the company with respect to sustainability assessment (maturity level 1), not all steps of the framework were followed. Please see table 13 below for a checklist of the included phases of the framework. These included phases correspond to the implications for applying SCEIA framework as described in table A1. Reflections and directions for further research are offered in the next subchapters.

Table 13. Included phases of the SCEIA framework.

Phase	Step	Included yes/no	Justification and comments
1. Point of departure	1.1 Decision recognition	Yes	External drivers caused the need for making CE and sustainability-related decisions.
	1.2 Vision	Yes	Preserving the natural environment will allow the company to continue to deliver their product.
	1.3 Maturity assessment	Yes	Following the maturity table (see Appendix table A1), the company has maturity level 1.
2. Identification	2.1 Scope and stakeholder identification	Yes	The scope was determined, but stakeholder identification will take in a next step when the social impact will be included.
	2.2 Overview	Yes	An overview of resource- and energy flows has been established as part of the inventory phase of the following LCA. It is not yet fully complete due to the company's low maturity.
	2.3 Materiality assessment	No	This will be included when expanding to maturity level 2.
3. Diagnosis		Yes	Environmental impact assessment using LCA. In a next phase, the social- and economic dimensions will be (partially) included.
4. Development		Yes	Several CE strategies were formulated and included in the environmental analysis.
5. Selection		No	Selecting the optimal strategy using MCDA could be included in subsequent phases.

4.2.1. Point of departure

This phase of the SCEIA includes recognizing that a decision is to be made, developing a vision on CE and sustainability, and (self-) assessing the experience with sustainability assessment (maturity assessment). In further application of the framework, the vision might be expanded to include concrete impact reduction goals. Similarly, goals for realizing social impact could be added to the company's vision. Further research could be focused on formalizing the current 'maturity assessment' table, zooming in on CE- and sustainability assessment as a trajectory, or a process. A formalized description of each maturity phase, providing core activities depending on the context at hand, could be based on collaborations with additional companies.

4.2.2. Identification

While the scope of the analysis was established in dialogue with the company's management, an overview of the company's stakeholders will be added in a later stage, when the company enters its next assessment maturity phase. This overview of stakeholders will be particularly useful in conducting any social impact assessment, and when applying a materiality assessment (MA) to determine impact areas most material to the organization. A relevant remark on the overview of resource- and energy flows is that this overview has been created partially based on the company's physical accounting system. However, no formal MFA was used; instead, the material- and energy flows were established as part of the inventory phase of the following LCA. As expected, the data collection process was challenging, as indicated on previous literature on the application of LCA (Di Maio & Rem, 2015). Collecting information on the resource- and energy flows was time consuming but it should also be highlighted that the company was able to deliver fairly complete data. These data can be used in the future to update the analysis with more insights. The challenge of data collection also forms part of the ongoing assessment learning process (Lozano, 2015), and is expected to take less time during future assessment efforts.

4.2.3. Diagnosis

The focus of the application was on establishing an overview of resource- and energy flows in the baseline scenario, estimating their environmental impact using LCA, and estimating the impact of the hypothetical CE strategies most relevant to the company's management. Currently, the social- and economic dimensions have not been added, but the company has expressed interest in adding those in the following stages of the analysis. Applying the LCA method to CE strategies is subject to, as previously indicated in scientific literature and through the expert panel, certain challenges with respect to 'circulating' resource flows (Civancik-uslu et al., 2019). For example, the assumptions on the reuse time and rotations of the reusable glass bottles strongly determine their impact reduction potential. In the case of this study, LCA is considered merely as a method to assist decision-making processes, rather than assessing the 'absolute' impact of certain measures (Pryshlakivsky & Searcy, 2021). The same holds for the choice to not include the end-of-life phase, which might seem counterintuitive when discussing end-of-life extension options. This could be added in a future study, for instance involving the CORIPET consortium.

4.2.4. Development

Four CE scenarios have been included in the application of the framework. During the process of drafting these scenarios, discussions with the company's management indicated a variety of additional CE strategies, such as the use of different types of packaging (i.e. Tetra Pak, biobased plastics such as PLA), additional transportation options (i.e. transport by train) or, after extending the system boundaries, including the effect of increased recycling of different packaging types. Such additional CE strategies could be included in a next phase of the assessment trajectory. With respect to CE strategies already in place (the reuse of glass bottles), the SCEIA framework has shown to be able to integrate those into the analysis using a substitution approach.

4.2.5. Selection

No MCDA has yet been applied to select one or multiple of the assessed strategies. As a last remark, for the future inclusion of this step, it is highlighted that the outcomes of the impact assessment of the CE strategies are not directly connected to their practical feasibility. Market conditions are particularly influential and hard to predict while, e.g. in the case of using electrical trucks, the influence of available infrastructure in the region becomes pertinent. Therefore, the results should be interpreted to give a broad indication of their potential impact, aiding the decision-making process necessary to bring the mineral water sector into a sustainable future.

Appendix

Table A1. Maturity assessment table.

Maturity level of sustainability assessment	Company experience with CE- and sustainability assessment approaches	Implications for applying SCEIA framework
1	No life-cycle management assessment approaches (LCA, LCC, S-LCA) have yet been used, and resources flows have not been quantified.	• Focus on establishing baseline impacts (i.e. current situation) • Focus on expressing environmental impacts in CO2eq. • Make simplified overview of resource flows (no full MFA), if possible based on physical accounting system.
2	Some quantification of resource flows has been established, and simplified (external) tools have been used for impact quantification – for example only expressing the result in CO_{2eq}. The results of sustainability assessments are used for improvements in a limited, informal or ad hoc way. Sustainability assessment is focused on the environmental dimension.	• Establish baseline impact. • Expand environmental impacts to other impact categories, using LCA methodology. • Involve stakeholder to determine impact areas most material to the organization (materiality assessment) • Include limited social impact assessment (no full S-LCA) • Use CTI tool to establish more complete overview of resource flows. • Use baseline impact for setting strategic goals.
3	The company has extensively worked with – or outsourced – sustainability assessment tools. Life cycle management tools are used systematically and strategically to lower the impact of the company's activities. Sustainability assessment is applied in a holistic way, including the social dimension.	• From the baseline impact, use scenario analysis to determine improvement strategies. • More extensive impact assessment, including wider set of environmental and social impact categories. • Establish complete overview of resource- and energy flows using MFA. • Determine how CE strategies influence impact, select optimal strategy using MCDA methods.

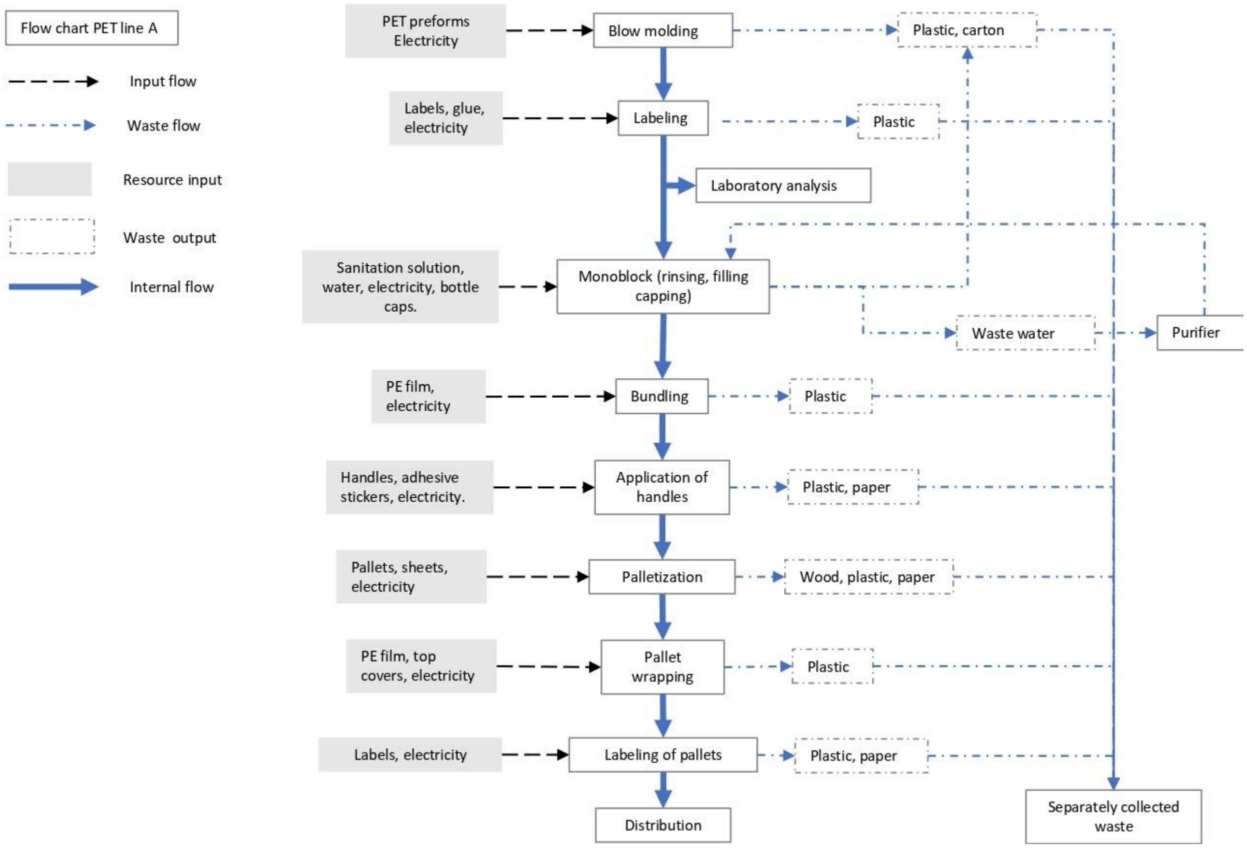

Figure A1. Flow chart for PET line A.

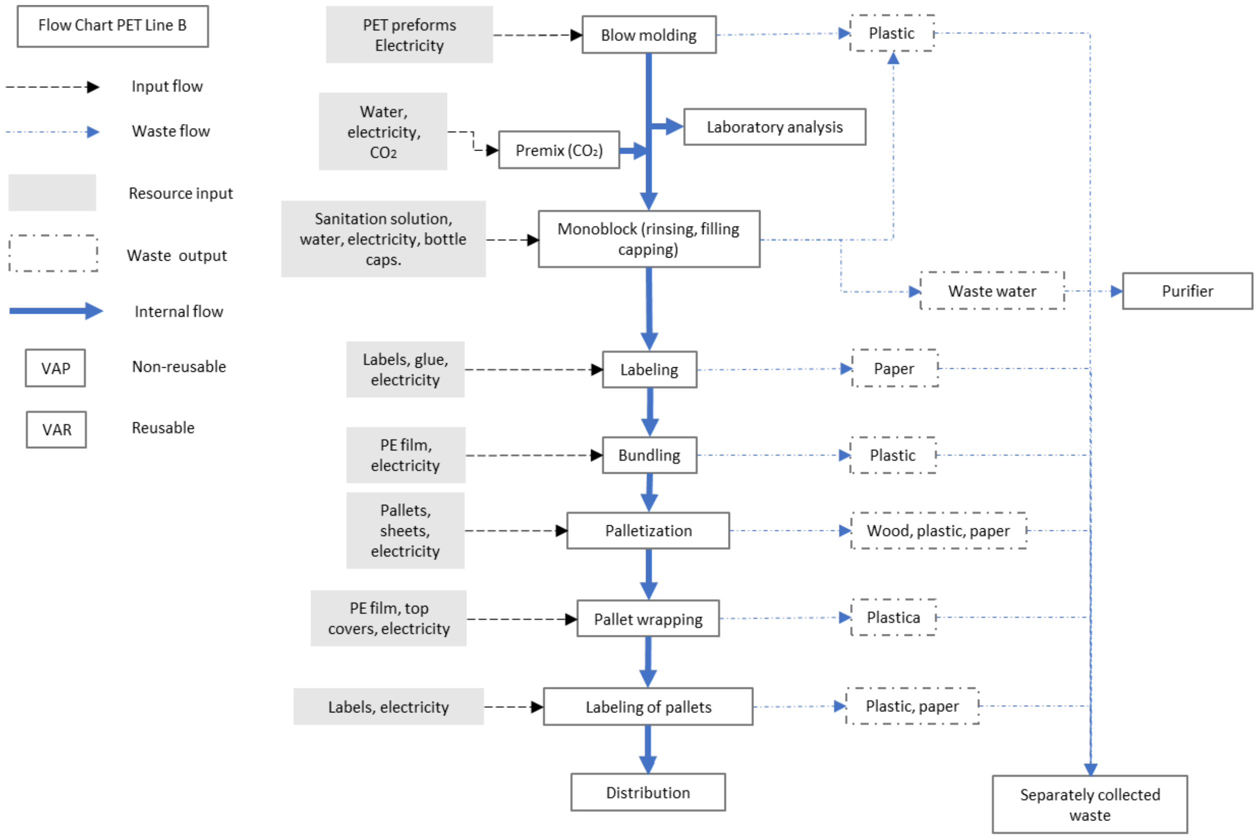

Figure A2. Flow chart for PET line B.

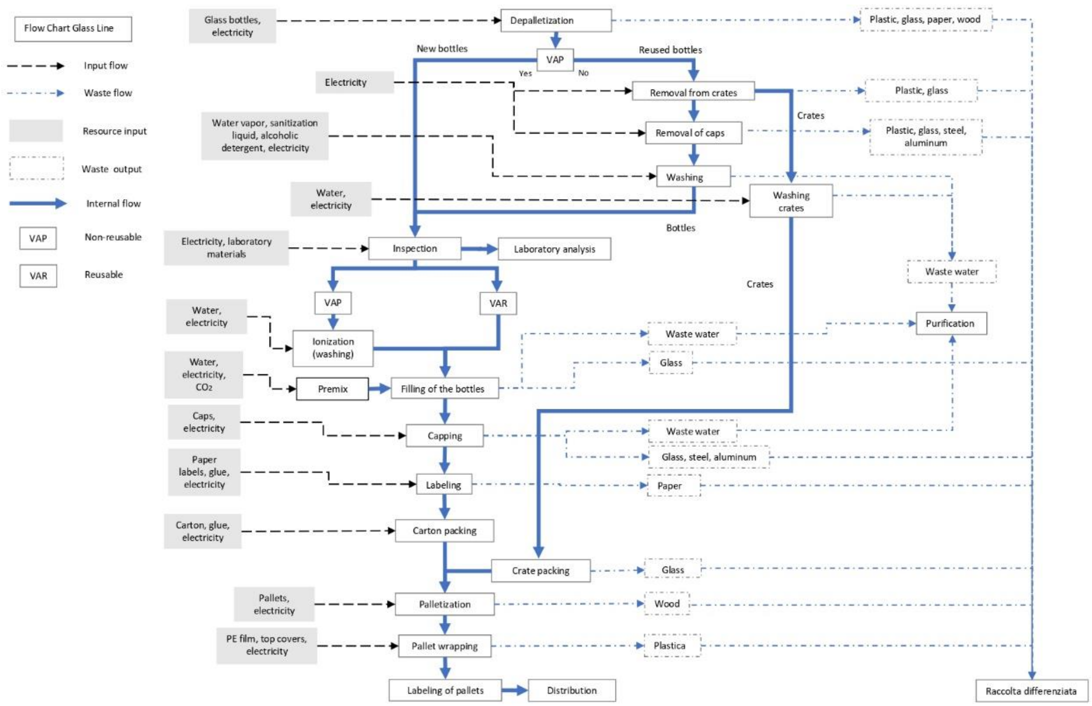

Figure A3. Flow chart for the glass line.

Table A2. Assumptions for electricity mix used in 2018.

Category	Source of electricity production	Share in 2018
Total renewable sources	Hydro, wind, solar, biomass	35.9%
Hydro	Hydro, pumped storage	0.4%
	Hydro, reservoir	9.1%
	Hydro, run-off river	5.1%
	Total	**14.7%**
Wind	Wind, <1MW turbine, onshore	1.6%
	Wind, >3MW turbine, onshore	0.5%
	Wind, 1-3MW turbine, onshore	3.5%
	Total	**5.6%**
Solar	Photovoltaic, 570kWp open ground installation	3.7%
	Photovoltaic, 3kWp slanted-roof installation, multi-Si	3.7%
	Total	**7.5%**
Biomass	Heat and power co-generation, wood chips	8%
Coal	Electricity production, hard coal	13%
Natural gas	Electricity production, natural gas, combined cycle power plant	13%
	Electricity production, natural gas, conventional power plant	4%
	Heat and power co-generation, natural gas, combined cycle power plant, 400MW	16%
	Heat and power co-generation, natural gas, conventional power plant, 100MW	10%
	Total	**43%**
Other petroleum products	Electricity production, oil	0.14%
	Heat and power co-generation, oil	0.43%
	Total	**0.57%**
Nuclear	Electricity production, nuclear, pressure water reactor	4%
Other sources	Electricity production, deep geothermal	2%
	Treatment of blast furnace gas, in power plant	1%
	Total	**3%**

Table A3. Assumptions for sensitivity analysis reuse time, lifetime and bottle recirculation.

Reuse time	Lifetime (years)	Recirculation per year
0	0	0,0
1	1	1,0
2	1	2,0
3	1	3,0
4	1	4,0
5	1,25	4,0
6	1,5	4,0
7	1,75	4,0
8	2	4,0
9	2,25	4,0
10	2,5	4,0
11	2,75	4,0
12	3	4,0
13	3,25	4,0
14	3,5	4,0
15	3,75	4,0
16	4	4,0
17	4,25	4,0
18	4,5	4,0
19	4,75	4,0
20	5	4,0
21	5,25	4,0
22	5,5	4,0
23	5,75	4,0
24	6	4,0
25	6,25	4,0
26	6,5	4,0
27	6,75	4,0
28	7	4,0
29	7,25	4,0
30	7,5	4,0

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Chapter 7: Conclusions and outlooks for further research

This research project, as part of WP 5.2 of Cresting, has investigated three primary interconnected research questions related to the assessment of CE and sustainability at company level. Firstly, following scientific unclarity on the purpose and methodological setup of CE assessment, the state-of-the-art of CE assessment was investigated. Then, company engagement with CE- and sustainability assessment was studied through an empirical analysis. This was followed by the design and validation of a CE and sustainability assessment framework to be used by companies planning to introduce CE strategies. The framework was tested in a pilot case study. This chapter briefly summarizes the scientific contributions resulting from the applied methodogies to answer the research questions; see figure 1 below for a summary of the project's conclusions. Next, this chapter focuses on the scientific connections between the different thesis chapters, proposing recommendations and directions for further research (chapter 7.2).

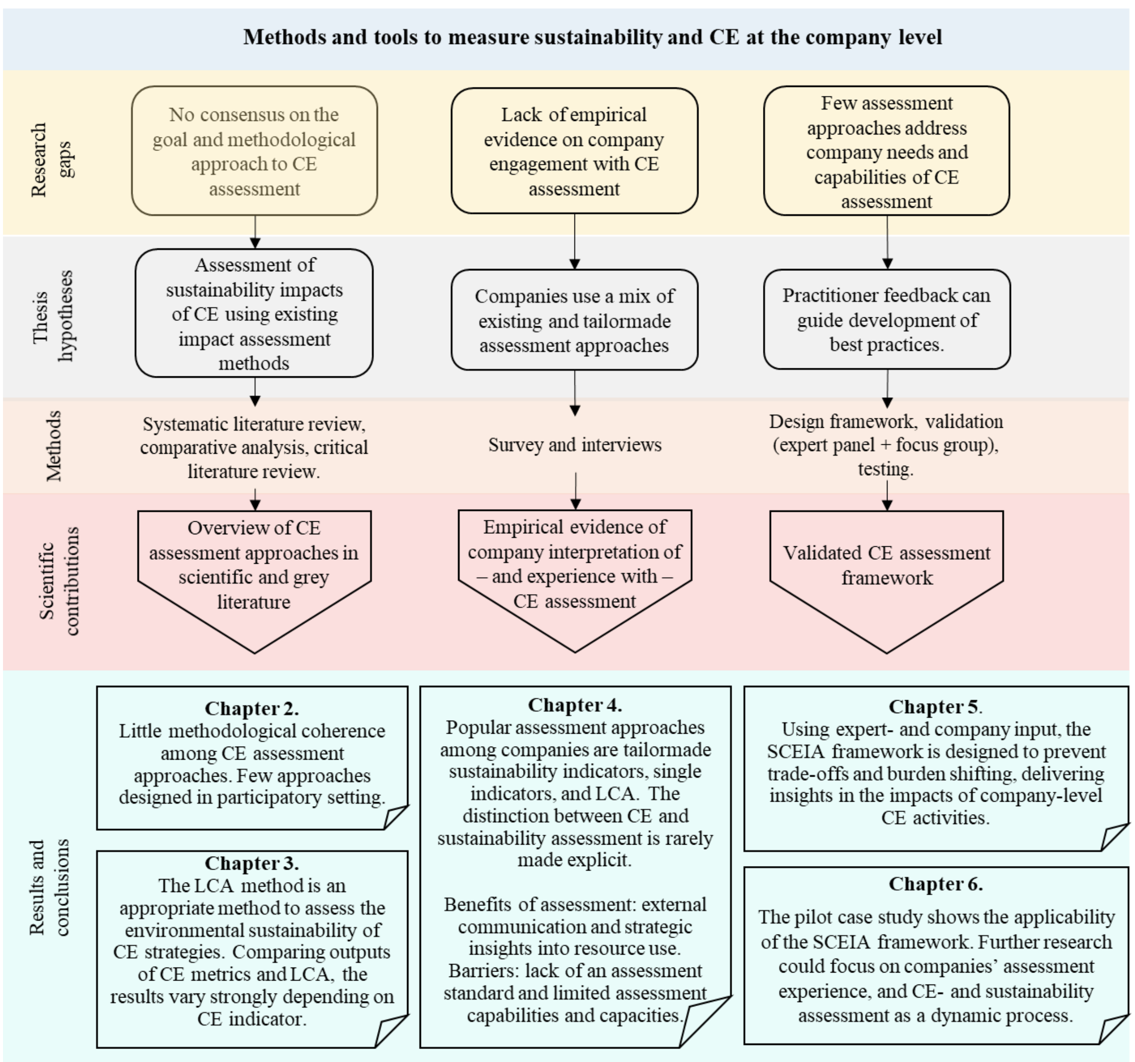

Figure 1. Scientific structure and chapter conclusions.

7.1. Conclusions

7.1.1. State-of-the-art of CE assessment

To provide initial context to the research topic and uncover prevailing gaps in literature, the first research question answered in this thesis was: *What is the current state-of-the-art of CE assessment at the micro level?* It was hypothesized that the unclarity on the goal and required methodologies of assessment would be confirmed, and that the LCA method to assess the impacts of CE would emerge as useful. A systematic literature review approach was used to inventory and category existing academic CE assessment approaches from product to supply chain level. Desirable properties were formulated after the application of a newly introduced review framework. Next, the second paper used a mixed-methods approach – a review-of-reviews and comparative analysis – to study to what extent grey literature (i.e. non-academic) CE assessment indicators and the LCA method are useful for CE assessment at micro level.

The presented collection of academic assessment approaches distinguishes itself from previous scientific literature reviews through (1) its focus on the micro level (company) perspective, (2) its critical review framework, containing (i) a general perspective, (ii) a descriptive perspective (methodological foundation), (iii) a normative perspective (addressing sustainable development as the end goal of CE), and (iv) a prescriptive perspective (participatory aspects and implementation guidance), and (3) the formulation of desirable properties of CE assessment, including: a holistic perspective to assessment, alignment with the principles of life cycle sustainability assessment (LCSA), the use of real-world data to test any new approach, and involving end-users in the design of the approach. These properties are formulated to guarantee accurate assessment of the sustainability of CE practices, while informing the design of future CE assessment approaches with a higher uptake by organizations. The recommendation to include the use of life-cycle methods such as LCA is investigated in more detail in the second paper. As previously shown in figure 1, the recommendations for desirable properties have also been followed in the design of the SCEIA framework.

The second paper explored the use of LCA to assess the environmental sustainability of CE practices, comparing its results to the application of CE metrics proposed in grey literature. Through reviewing previous literature reviews and studies that analyzed the application of LCA to CE strategies, it was found that LCA is considered an appropriate method to assess the environmental impact of CE strategies. Still, methodological- and practical challenges remain, such as its data-intensive nature and methodological (allocation-related) difficulties related to its ability to incorporate ‘loops’ of resource flows. The comparison between the results of LCA and the outcomes of applying grey literature metrics in two selected case studies showed that some care should be applied when using more narrowly defined metrics: strategies that carry good CE results, according to such metrics, might not deliver good environmental performance.

7.1.2. Company engagement with CE assessment

The second research question that was addressed in this thesis was: *How do companies engaged with CE assess CE & sustainability?* Following the scarce preliminary studies on this topic, it was hypothesized that companies use a mix of tailormade (i.e. self-designed) and existing assessment CE and sustainability approaches. To collect empirical evidence on company engagement with CE assessment, a semi-quantitative survey and semi-structured interviews were used.

A key finding is that tailormade assessment approaches, being based on either a life-cycle or direct impact approach, were frequently used by the participating companies. Secondly, it was found that a relatively large share of companies showed to be familiar with – and applied – the LCA method, even though it was generally considered time-consuming and quite costly. This finding supported the inclusion of LCA for CE assessment in the SCEIA framework (see next subchapter).

7.1.3. Design and validation of CE assessment framework

The last central research question was: *How to design best practices for CE assessment at the company level?* Following the results from the previously conducted systematic literature review, the comparative analysis and the overview of company assessment experiences, it was hypothesized that best practices of CE assessment build on existing assessment methods, are designed in cooperation with their end-users (companies), provide a holistic perspective on sustainability and are adjustable accordingly to the company at hand. A mix of methods was used to design and validate a new CE assessment framework (chapter 4), after which it was tested in a pilot case study (chapter 5).

In addition to building on the results from the previous chapters, the framework was designed through critically reviewing the connection between CE and sustainability, and extracting key properties from existing frameworks that (1) are being applied in practice and (2) respond to assessment objectives as formulated after the critical literature review (i.e. to enable the assessment of the sustainability impacts of CE practices). After its design, the framework was validated through an expert panel survey and focus groups with companies, after which the framework was adjusted according to the received feedback. This design-and-validation setup aimed to ensure that the framework responded well to real-world situations in which company capabilities could be limited, while avoiding the trade-off pitfall of preferring ‘circularity’ over sustainability. Simultaneously, by basing the framework’s phases on previous decision-making routines, it was explicitly embedded in the management context of companies with strategic sustainability ambitions.

In a last step of the research project, the SCEIA framework was tested in a pilot case study setting, in collaboration with a mineral water company. The framework was deliberately applied in a company with a low maturitury level, in order to test the framework without influences from previous culture, vision and practices. Due to this relatively low level of experience of assessment, a limited number of steps from the framework were applied. This corresponded to its modular nature, making it adjustable to the company's 'assessment maturity'. Only the environmental dimension of sustainability impact assessment was selected, and four CE strategies were evaluated: (i) the increased use of recycled PET (rPET) in the production process, (ii) the increased use of reusable glass bottles, (iii) using electric vehicles for distribution, instead of diesel trucks, and (iv) the use of on-site generated electricity from solar PV. The results show that all scenarios result in environmental benefits, while some caution with respect to the interpretation should be applied since a full LCA on each of them has not yet been conducted. While data collection for the environmental assessment was a challenge, and the results should be considered valid only under the specific assumptions used in the model, the SCEIA framework showed to be feasible in practice. The results from the expert panel survey, focus groups and pilot test case encouraged various perspectives on necessary further research, as explained below.

7.2. Outlooks for further research

7.2.1. Company needs and capabilities

Overall, company needs and capabilities in CE and sustainability assessment emerged as a research topic demanding further investigation. First of all, in the literature review, it was found that only a modest number of inventoried assessment approaches involved their end-user(s) in their design. This could partially explain the low uptake of assessment approaches in general – although this is, in itself, a statement that deserves further scientific investigation. In fact, the field of strategic management, carrying deep knowledge of company capabilities, and literature on sustainability assessment showed to be somewhat disconnected. It could be expected that providing CE- and sustainability assessment with a more solid scientific foundation on how companies *function* could lead to more feasible newly designed assessment approaches. This would involve research on the required soft (culture, leadership, employee engagement) as well as hard (data management infrastructure, allocated available resources, product design process) and strategic capabilities of companies with assessment ambitions. This type of research would ideally be conducted in collaboration with companies that have a track record of assessment. Literature seems not to have focused specifically on 'best practices' of companies that have successfully used assessment methods for longer periods of time, reducing their impacts based on the outcomes of these assessment practices. One of the common themes throughout this research project – that CE and sustainability assessment should not be seen as single, 'point-in-time' exercise but comprise an ongoing assessment learning process – could be studied in more detail, involving companies that have a longer-standing assessment practice. Their best practices in terms of developing appropriate capabilities, trainings, allocating resources, outsourcing activities but also the use and implementation of assessment results could then provide the foundation of future assessment approaches.

7.2.2. Using assessment in strategic decision-making

Another topic for further research, connected to assessment capabilities, is the use of CE- and sustainability KPIs in the *strategic* decision-making process of companies. While previous literature has investigated the use of e.g. environmental criteria in design, operations, logistics or manufacturing processes, their preferred embedding in strategic processes is less frequently described. Further insights into the application of CE- and sustainability assessment approaches in strategic decision-making could be investigated through an integrative- or scoping review. In the light of global challenges such as climate change and the biodiversity crisis, both legislation as well as market conditions will make it an economic necessity for companies to drastically reduce their environmental impact. Following the nature of strategic decisions, which are characterized by their high-impact nature and long-term time horizons, it is expected that the demand for assistance in conducting – but also interpreting – sustainability assessment on the strategic level will grow. The SCEIA framework has tried to provide some answers to questions of how to embed the assessment trajectory into the strategic decision-making process. Future research could, in dialogue with the private sector, expand the scientific foundation of formalizing this strategic sustainability decision-making process from an assessment perspective. This could foster a decrease of environmental impacts created by companies, while simultaneously driving fundamental social change. With respect to the latter, the use of S-LCA currently only takes place rarely, but its role in providing companies with insights on how to strategically manage their social impact could be investigated in more detail as well.

7.2.3. Expanding the pilot test case

Another apparent direction for further research lies in expanding the application of the framework in the pilot test case study, incorporating both the economic- and social dimensions of sustainability as well. For several reasons, this is expected to be more challenging in comparison to the environmental dimension. As briefly mentioned earlier, social impact assessment methods such as S-LCA have been subject to a shorter period of development, less awareness on their existence and methodology and, as indicated in the empirical part of this research, a lower application rate. While studies on the economic perspective, applying LCC, are more common, the inclusion of the economic dimension in a sustainability assessment remains somewhat controversial. The goal of conducting an LCC is not always entirely clear, and, as explained in chapter 5 of the thesis, part of the discussion entails the debate on whether (economic) growth should be part of the goal of sustainable development at all. For both S-LCA and LCC, a ‘transdisciplinary’ approach to uncovering the practicalities around their use and, perhaps more significantly, their ability to respond to company needs, could be used in a future study. With respect to LCA, some challenges remain as well, as described in chapter 2. It is expected that the increased application of LCA and the following methodological debates – both in science and practice - will contribute to solving challenges (e.g. allocation issues in multiple-loop scenarios) in the future.

7.2.4. Assessment as a process

Lastly, an interesting perspective that might require further attention is found in precisely such companies that have just begun their 'assessment journey': how can they be stimulated to better understand the impact of their operations, without overwhelming them with the large number of indicators and tools available? A remark heard multiple times throughout the research project was that companies are not always sure where to start. By focusing on assessment as a trajectory, or a process, starting small and slowly expanding, companies could be tempted to assess their impacts, convincing them that not dozens – if not more – environmental, social and economic indicators should be used in the decision-making process at once. A formalized description of such an 'assessment trajectory', based on real-world cases and providing e.g. a blueprint of core KPIs depending on the context at hand, could provide such companies with concrete assistance.

7.2.5. Feasibility vs. accuracy

Related to both company capabilities, available assessment methods as well as the formalization of the assessment trajectory is the emerging tension between (i) the accuracy and completeness of assessment and (ii) its feasibility for companies. This tension has formed a common yet unresolved thread throughout this research project, as it followed from the question: are companies recommended to make use of relatively simple, resource-efficiency centered CE metrics? While these metrics might require less financial resources to implement, i.e. because of less demanding data requirements, their results might lead to the implementation of strategies that are not sustainable. However, when a company opts for a more complete method such as LCA, the results might be complete and accurate, but the high barriers in terms of costs and complexity might lead the company to not assess at all. While no concrete solution to this dilemma exists yet, and it is acknowledged that resource-effiency based metrics could be of use in specific decision-making situations, this research project has followed the premise that, for CE to be a valuable concept, its outcomes should be sustainable and in line with the SDGs. Since scientific consensus exists that resource-efficient solutions do not always lead to sustainable impact, the need for the assessment of the sustainability impacts of CE strategies before their introduction becomes evident. However, it is also acknowledged that more complex but complete assessment methods such as LCA could pose a barrier to companies starting out their assessment journey. While the project has provided evidence that various companies are rapidly developing knowledge on the use of such tools, further research could expand on the accessibility of life-cycle based methods and tools, not only through their simplification, but primarely through investigating and driving a shared learning process between academia and the private sector. Such a shared learning process will have the potential to drive the increased uptake of sustainability assessment approaches, furthering the ability of science and practice to provide the evidence base for a more sustainable future.