Resources, Conservation & Recycling 151 (2019) 104498

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Review

Towards sustainable development through the circular economy—A review and critical assessment on current circularity metrics

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ARTICLE INFO

Keywords:
Sustainability
Circularity metrics
Life Cycle Assessment
LCA
Validity
Products
MFA
Recycling

ABSTRACT

The circular economy (CE) is perceived as a sustainable economic system where the economic growth is decoupled from the resources use, through the reduction and recirculation of natural resources. In the shift towards the CE, quantifying the circularity of products and services (or their contribution to the CE) is crucial in designing policies and business strategies, and prioritizing sustainable solutions based on evidence. New circularity metrics are being developed for that purpose, but they often present contradiction in both form and content, which contributes to confusion and misunderstanding of the CE concept. This review aims to map methodological developments regarding circularity metrics for products and services, in order to: (1) identify the foundations of circularity metrics used so far and their applications, (2) evaluate the validity of current circularity metrics, based on predefined requirements and a CE definition anchored in the sustainability concept, and (3) provide recommendations on how to measure circularity. The literature search provided a wide variety of CE metrics being developed and applied (seven measurement indices, nine assessment indicators and three assessment frameworks). However, none of them are addressing the CE concept in full, potentially leading to undesirable burden shifting from reduced material consumption to increased environmental, economic or social impacts. Additionally, new metrics underrepresent the complexities of multiple cycles and the consequences of material downcycling. Circularity metrics intended to sustainable decision making should be comprehensive enough to avoid burden shifting, and clearly indicate how the benefits of recycling are allocated between the primary and secondary products.

1. Introduction

The circular economy (CE), as opposed to the current linear economy, is seen as a sustainable economic system where economic growth is decoupled from resources use, through the reduction and recirculation of natural resources. The CE concept attracts increasing attention of governments, scholars, companies, and citizens as a necessary step to achieve sustainable development. This is evidenced by the recent EU policy (European Commission, 2015; European Commission, 2018a, b), national policy targets (e.g. CE packages from United Kingdom, The Netherlands and Norway), business sectors reports (EMF, 2016), and the increasing number of scientific articles. The European Commission's CE programme (COM(2015)614) envisions that by prolonging the value chains of products and services in the economy, a sustainable economic system could be established which will benefit industry, the environment and citizens.

Different strategies have been proposed as a way to move from a linear economy to a CE. These strategies are mainly carried out by industrial actors. The concepts behind those strategies include (but not limited to): sustainable and eco-design, energy and material efficiency measures, strategies defined within the three-R's waste hierarchy (reduce-reuse-recycle, sometimes expanded to 11 different R-strategies), business model innovation, industrial symbiosis, etc. (Reichel et al., 2016). The impacts or benefits generated by these circular strategies are often measured through the use of *circularity metrics*.

Companies, governments and academics have formulated various proposals to measure the circularity of services and products. Ideally, circularity metrics should provide an indication of how well the principle of CE is applied to a product or service. However, most of the published circularity metrics have been criticized for not representing the systemic and multidisciplinary nature of the CE (Saidani et al., 2017), and have a sole focus on measuring to what extent material cycles are closed. These approaches frequently overlook the characteristics of the circular loops (e.g. shorter or longer) and the multi-dimensional sustainability performance, i.e. environmental, economic and social.

Moreover, there is an increasing number and variety of indices and frameworks, resulting in an overabundance of indicators to measure resource efficiency and sustainability performance (environmental,

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https://doi.org/10.1016/j.resconrec.2019.104498
Received 15 May 2019; Received in revised form 6 September 2019; Accepted 13 September 2019
Available online 24 September 2019
0921-3449/

economic and/or social) (Pauliuk, 2018). The European Academies' Science Advisory Council provides a list with more than 300 indicators that could potentially be used to measure progress in CE (EASAC, 2016). Iacovidou et al. (2017a) found more than 60 environmental, economic, social and technical metrics that can be used to assess waste management and resource recovery systems, alone. Often, the metrics and indicators present contradiction in both form and content, which contributes to confusion and misunderstanding in public debates.

A possible cause for the wide variety of circularity metrics may lay in the unclear and diverse understanding of the CE concept by different stakeholders. Ideally, the design of such a metric or framework should start from the definition of CE, which should be in line with the ultimate goal: to achieve sustainable development. However, even though the CE concept was already coined several decades ago, its definition and conceptualization is still an open matter (Reike et al., 2018). A recent literature review found 114 different circular economy definitions within peer-reviewed articles, policy papers and consultancy reports (Kirchherr et al., 2017). The variety of these definitions reveals that the CE concept has different meanings for different stakeholders. Although most of the definitions depict CE as applying the 3R principles, some of them failed to notice the necessity of a systemic change (Kirchherr et al., 2017). Furthermore, many definitions did not highlight the role of the business models and consumers as CE agents. Only a few linked the CE concept to sustainable development in all three dimensions (society, economy and environment) (Kirchherr et al., 2017), which is one of the major shortcomings of most of the circularity metrics developed so far (Pauliuk, 2018; Saidani et al., 2017; Geng et al., 2012; Åkerman, 2016).

It is, therefore, important to agree with the definition and goals of CE before a CE strategy can be assessed. Here, we embrace the definition of CE proposed by Kirchherr et al. (2017, p. 229): "*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*". We endorse this definition because it respects the waste hierarchy while connecting the CE concept with the ultimate goal of sustainable development.

This study builds on such a definition of the CE concept to provide an overview of all the circularity metrics available in the public domain in the last decade. Previously, Linder et al. (2017) evaluated five circularity metrics, based on five requirements (content validity, reliability, transparency, generality and aggregation principles). The authors concluded that none of the reviewed circularity metrics was completely suitable to represent all five requirements. The metrics reviewed only focused on the suitability to measure the recirculation of materials. Elia et al. (2017) found 16 different studies measuring CE and evaluated the usefulness of the identified metrics in accordance with five environmental CE goals (reduced resources use, reduced emissions, reduced material waste, increased renewable share and increased product durability). Their evaluation considered nine different circularity metrics, although only environmental aspects were taken into account. Once more, none of the reviewed metrics fulfilled all the environmental requirements defined by the reviewers. Saidani et al. (2017) reviewed three circularity metrics (Material Circularity Indicator, Circular Economy Indicator Prototype and Circular Economy Toolkit) for five requirements addressing the features of the metric (systemic, integrated and operational, flexible, intuitive, and connected to all three sustainable development pillars). According to their evaluation, none of the three metrics fulfilled all requirements, and some requirements were only partly covered. The same authors published later a taxonomy of circular economy indicators, where multiple indicators and set of indicators used to measure or represent circularity were classified into 10 different categories (Saidani et al., 2018). All these studies highlighted the necessity of developing and applying adequate metrics to measure the circularity of products and services. A recent review has also shown that current CE metrics are not able to measure every CE strategy (Moraga et al., 2019).

These reviews provide a good description of the early metrics applied to measure CE. However, they do not evaluate their validity with respect to a CE concept rooted on sustainable development, and/or do not integrate the great number of new frameworks and indices emerged between 2017 and 2018. This article aims to map methodological developments regarding circularity metrics of products and services in order to: (1) identify the foundations of circularity metrics used so far and their applications, (2) evaluate the validity of current circularity metrics, based on predefined requirements and a CE definition anchored in the sustainability concept, and (3) provide guidance and recommendations on how to measure circularity.

While acknowledging that there are many metrics already developed that could be potentially used to measure circularity, this review focuses on the frameworks, indicators, and indices expressly developed and/or used to quantitatively measure CE strategies in products and services. Monitoring frameworks or other metrics intended to be applied at the regional, country or global levels are however also discussed.

This article is organised as follows: Section 2 contains the methodology for the literature review. Section 3 elaborates the results of the literature review including a description of the circularity metrics and case studies published so far (with an emphasis at the product/services level). In Section 4 the reviewed metrics are evaluated, the main challenges are discussed, and recommendations are made for circularity metrics. Section 5 draws the conclusions of the study.

2. Methodology

The method applied in this study consists of three steps: (1) Literature search on circularity metrics, (2) Definition of requirements for a circularity metric, and (3) review and evaluation of circularity metrics.

The following Sections 2.1 and 2.2 describe the method used for the literature search and for the definition of the requirements for a circularity metric. Such requirements are then used to evaluate the circularity metrics found in the literature search and provide recommendations on best practices for circularity measurement and assessment.

2.1. Literature search

In order to provide a global vision on how the scientific community is responding to key methodological issues to measure circularity, a literature review was conducted in August 2018 on the Web Of Science (WOS) Core Collection search engine. The search was focused in scientific articles or book chapters published in English from 2008 to August 2018. Online available metrics without a published methodological background were not considered into review.

The review consisted on an advanced search,[1] aimed at exploring the tools used for measuring circularity. The search was followed by a screening process, performed by reading the title and abstract of every result. The search obtained 259 results, of which only 60 articles were considered relevant. The discarded studies did not directly address the issue of measuring circularity in a quantitative way, or presented high similarity with other articles already included in the review. In addition, 4 relevant consultancy reports, 7 policy reports and 10 peer-reviewed articles found in the reference list of the reviewed articles were included.

The results of the literature review show an exponential increase in the number of publications regarding circularity metrics over the last 5

[1] Search string: ((TS = (measur*) OR TS = (quantif*)) AND (TS = ("circular economy"))) OR (TS = ("circular economy") AND TS = ("life cycle assessment" OR LCA)) AND LANGUAGE: (English) AND DOCUMENT TYPES: (Article OR Book Chapter) Indexes = SCI-EXPANDED, SSCI, A&HCI, ESCI Timespan = 2008-2018.

years, of which over 70% were published between 2017 and the first half of 2018. Out of the 72 scientific articles reviewed, 48 (67%) contained case studies on measuring or assessing the contribution of products, services or regions to the CE, and the remaining 24 provided discussions on metrics that may be used for that purpose. 57% of the reviewed articles are focused on proposing, applying or expanding existing methodologies, such as LCA or Material Flow Analysis (MFA) the rest (43%) propose, develop and/or test new methodological frameworks or indicators.

2.2. Requirements for a circularity metric

The first step to evaluate a circularity metrics is to define a set of requirements that the metric should meet in order to adequately measure progress towards the CE. This set of requirements can refer to the reliability, validity and/or the utility of the metric (Bannigan and Watson, 2009):

- *Validity* refers to the degree that a metric measures what is intended to measure e.g., does it really represent progress in the circular economy?
- *Reliability* refers to the consistency and robustness of the metric, e.g., would it give the same results by different practitioners or occasions? Is it transparent?
- *Utility* refers to how practical the metric is e.g., is it flexible and easy to implement?

Previous reviews have defined the requirements for a circularity metric by considering either the *validity* of the metric, such as Elia et al. (2017) and Pauliuk (2018), or/and the *utility* and *reliability* of the metric (transparent, reliable, operational and flexible), as in Saidani et al. (2017) and Linder et al. (2017). Even though utility and reliability are necessary characteristics for every sustainability metric, this review focus on the validity of the metric rather than on the other features, since one of the main aims of this review is to evaluate the validity of current circularity metrics based on a CE definition rooted in the sustainable development concept.

The validity requirements for a CE metric were defined by building on the requirements proposed by previous CE studies and reviews, which are in turn based on different sets of CE goals. The sources considered to define the CE requirements include four review articles (Linder et al., 2017; Pauliuk, 2018; Elia et al., 2017; Saidani et al., 2017), two consultancy reports (De Wit et al., 2018; EMF, 2015), and one policy report (Potting and Hanemaaijer, 2018). A detailed description of the requirements and goals described in each source can be found in the Supporting Information (Table 2).

Although the CE requirements are labelled differently in the reviewed studies, most of the studies covered to some extent the five first requirements as described in Box 1. Such requirements are desirable outcomes from the application of circular strategies. However, the second requirement (reducing emission levels) received less attention, and was only included in two studies (Elia et al., 2017; Pauliuk, 2018) and one policy report (Potting and Hanemaaijer, 2018).

The aforementioned five requirements directly address the contribution of the circular product/service to the environmental quality, but do not directly address the economic prosperity and social equity for current and future generations. Only the reviewed policy report and one study considered social and economic requirements, such as improvement in social indicators or having more added value per resource input (Pauliuk, 2018). Other studies on circularity metrics were more indulgent with these requirements, labelling them as "complementary risk indicators" (EMF, 2015), or giving general indications such as "connected to all three sustainability pillars" (Saidani et al., 2017).

To fully represent the CE concept, as defined in the introduction of this article, we propose to add three extra requirements reflecting on the economic prosperity and social equity: 6) Creating local jobs at all skill levels, (7) economic value added creation and distribution, and (8) increase social wellbeing. The three additional requirements are also found in the EU action plan for a CE communicated by the European Commission (EC) in 2015, which stated that the CE would boost the EU's competitiveness by protecting the environment but also by creating new business opportunities with increased local jobs, and new opportunities for social integration and cohesion (COM(2015)614).

The defined 8 CE requirements (described in Box 1) will be considered as evaluation criteria for the validity of the reviewed circularity metrics. The evaluation will qualitatively assess if the proposed metrics are able to measure progress in each of the defined goals.

3. Description of circularity metrics

This section describes and evaluates all the metrics developed and used in the reviewed literature to measure and assess the contribution of strategies, products, and services (hereinafter, systems) to the CE.

The circularity metrics found in the literature can be categorised into two groups:

(1) *circularity measurement indices* aimed at providing a value expressing how circular a system is. These indices were developed by defining the main attribute of the CE (e.g. recirculated materials in a product), to afterwards assign it a numerical scale, which ranges from 0 to 100%, and represents the circularity degree.
(2) *circularity assessment tools* aimed at analysing the contribution of circular strategies to the principles of CE. This group of metrics is focused on the environmental or economic impacts in society of the circular strategy, rather than on the intrinsic circularity. This group can be further distinguished into *CE assessment indicators*[2] and *CE assessment frameworks*, where the former ones use single (or aggregated) scores, and the latter ones are assessment tools providing multiple assessment indicators that can be adapted to specific case studies.

In both cases, the underlying goal of the tools is to provide an indication on the extent that the CE principles are followed. Fig. 1 shows the classification of circularity metrics as described in this review. This review found seven circularity measurement indices, nine CE assessment indicators and three assessment frameworks. Although the three assessment frameworks were initially not developed for assessing circularity, they have been widely applied for this purpose (50% of the reviewed articles applied or proposed LCA or derived indicators as main circularity metric, and 12% proposed MFA). Likewise, as shown in Fig. 1, some ad-hoc circularity assessment indicators were also based on the LCA methodology.

It is common in the CE literature to classify circular strategies or interventions by the levels to which those strategies are applied: *micro* level (applied to products, companies or organizations), *meso* level (ecoindustrial parks), and *macro* level (regions, cities, countries or the global economy) (Ghisellini et al., 2016). This classification has also been used for CE metrics (Lonca et al., 2018; Pauliuk, 2018; Saidani et al., 2017). However, this direct application of circular strategy application levels to assessment levels can be misleading and create confusion, since the understanding of the *micro*, *meso* and *macro* levels differs within the assessment disciplines. For instance, even though LCA is an assessment tool applied mainly at a product level, it can adopt a macro-level approach when intended to support macro-level decisions regarding national policies or sector strategies for technologies, services

[2] The words *index* (plural: indices) and *indicator* have slightly different meanings. Although the terms are generally used interchangeably, indices are typically composite measures of the attributes of a general dimension (e.g. human development index), while indicators are observations intended at assessing progress or changes with respect to an intended outcome (e.g. Greenhouse gas emissions).

Box 1
Validity requirements to be used for the evaluations of CE metrics.

CE validity requirements
1. Reducing input of resources, especially scarce ones
2. Reducing emission levels (pollutants and GHG emissions)
3. Reducing material losses/waste
4. Increasing input of renewable and recycled resources
5. Maximising the utility and durability of products
6. Creating local jobs at all skill level
7. Value added creation and distribution
8. Increase social wellbeing

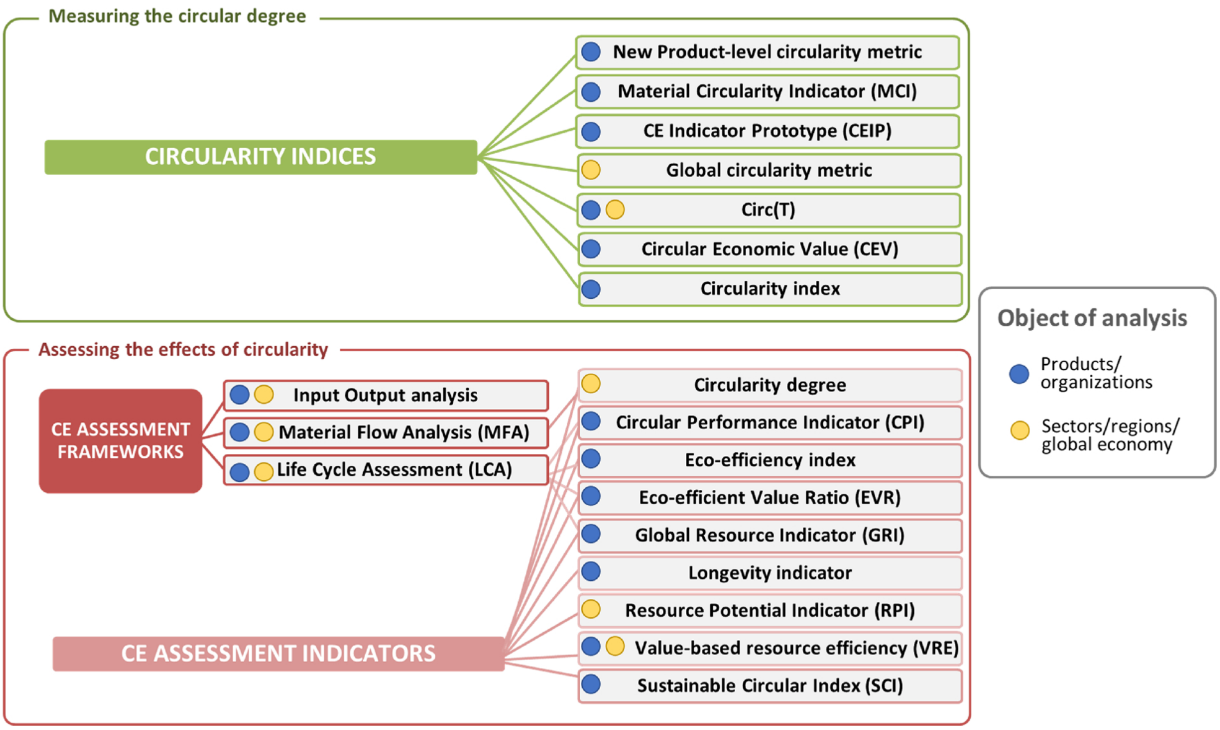

Fig. 1. Classification of reviewed circularity metrics. *Additional indicators applied within the assessment frameworks are described in detail in Table 2.

Table 1
Summary of the reviewed circularity indices, including measurement basis and case studies (Env = Environment, Eco = Economy, Soc = Society).

Indices	Source/Developer	Unit	Env.	Eco.	Soc.	Case studies
New Product-level circularity metric	(Linder et al., 2017)	Economic value recirculation	x	x		Starter engines
Circ(T) or Cumulative Service Index	(Pauliuk et al., 2017)	Material recirculation over period of time	x			Steel (Pauliuk et al., 2017) Cr and Ni in Steel (Nakamura et al., 2017)
Material Circularity Indicator (MCI)	(EMF, 2015)	Material recirculation (0-1 index)	x			Unspecified widget (EMF, 2015) Used tires (Lonca et al., 2018) Tidal energy device (Walker et al., 2018) Catalytic converter in heavy off-road vehicles (Saidani et al., 2017)
Circularity index	(Cullen, 2017)	Circularity degree (%)	x			Energy intensive materials
Global circularity metric	(De Wit et al., 2018)	Material recirculation	x			The global economy
Circular Economy Indicator Prototype (CEIP)	(Cayzer et al., 2017)	Circularity degree (%)	x			Leather making (Cayzer et al., 2017) Catalytic converter (Saidani et al., 2017) Tidal energy device (Walker et al., 2018)
Circular economic value (CEV)	(Fogarassy et al., 2017)	Circularity degree (%)	x			Future Budapest 2024 Olympic Games (just a proposal)

or basket of products. However, LCA is not an appropriate tool to assess the performance of the global economy as a whole, and other tools such as MFA would be more appropriate (Giljum et al., 2011).

To avoid confusion, this review proposes to categorise the indicators and frameworks in two groups, attending to the object of analysis and not to the level of application: 1) products/services/organizations and 2) sectors/regions/global economy. The metrics marked with a gradient of grey (from light to dark grey) in Fig. 1 can be applied for both categories.

Additional details on the different types of frameworks and indicators are contained in the following sections.

3.1. Circularity indices

Circularity indices are devised to represent the circularity degree of a system, and are represented by a number ranging from 0 to 1 (or 0–100%). Table 1 provides an overview of the seven circularity indices identified from the literature review, their developers, the units, the sustainability dimensions addressed and the case studies reported in the literature.

All these indices give a measure of the circularity of a system, but the understanding of what circularity is differs in each case. For instance, the *new product-level circularity metric* created by Linder et al. (2017) defines circularity as "the fraction of a product that comes from used products" (Linder et al., 2017, p. 551). They argue that a circularity index should only be focused at the materials reuse, and other values corresponding to the CE concept (such as environmental quality) should be measured through additional indicators. This argument indicates a divergence between their definition of circularity and the CE concept, where circularity relates to only one of the goals of CE (material reuse).

Other indicators such as the *Circ(T)* and the *Global Circularity Metric* are also based on a mono-dimension circularity concept, i.e. by considering a mere material recirculation and covering only (and partially) the *resource efficient* CE goal. For instance, the *Global Circularity Metric* measures the global economy circularity by "the share of cycled materials as part of the total material inputs into the global economy" (De Wit et al., 2018, p. 22) using data from Input Output statistics and projections from a computable general equilibrium model (Hatfield-Dodds et al., 2017). The *Circ(T)* in turn, builds on MFA to provide the relative measure of the cumulative mass of a material present in a system, over a certain time interval, in terms of an ideal reference case where the material is kept functional throughout the entire accounting period *T* (Pauliuk et al., 2017). Even though the focus is only material circularity, the developers of these last indices agree that other goals such as material saving, value retention, environment conservation and climate mitigation should be also considered.

The tool *Circularity Index* is based on material circulation, but includes the notion of quality by the ratio of energy required for material recovery to energy required for primary production. This approach tries to avoid the risks of achieving resource circularity by increasing the energy use.

The *Material Circularity Indicator* (*MCI*) developed by the Ellen MacArthur Foundation (EMF) and Granta Design is a micro level index built upon a more complex definition of product circularity, which is expressed as "the extent to which linear flow has been minimised and restorative flow maximised for its component materials, and how long and intensively it is used compared to a similar industry-average product" (EMF, 2015, p.19). Since their index does not account for the environmental and socioeconomic risks of the analysed systems, additional indicators are proposed to cover the other goals of the CE.

The *Circular Economic Value (CEV)* and the *Circular Economy Indicator Prototype (CEIP)* both build on the concept of the MCI. The CEV represents the circularity of the system by accounting for reduced use of virgin materials, reduced output of waste, increased use of renewable energies and increased energy output during EoL. The *CEIP* index is calculated by choosing predefined answers to a series of 15 questions on product design, manufacturing, commercialization, in-use and end-of-life (Cayzer et al., 2017). Then, a final score (in %) is determined by aggregating the obtained scores for each answer.

Except for the *CEIP*, all these indices address resource efficiency by using the mass of materials as the basis of calculations. Additionally, the *new product-level circularity metric* combines the mass of materials with their economic value, while the *MCI* and the *Circ(T)* combine the mass of materials with their temporal duration. By combining resource use with temporal and economic values, these indices attempt to account for the desired extended utility or economic value added by the circular system respectively. The *CEV* also includes renewable energy balances in the calculation, while the circularity index includes energy use.

These indices also measure circularity at different levels: the *MCI*, *CEIP, CEV, circularity index* and *new product-level circularity metric* are applied at a material/product/organization level, the *global circularity metric* at a global level, and the *Circ(T)* can be applied both at a product level or a sector level (e.g., the use of steel globally). The *new product-level circularity metric,* the *Circ(T)* and the *global circularity metric* have been each tested by the developers on the same case studies (see Table 3).

3.2. Circularity assessment tools

Circularity assessment tools measure the burden or value created by a circular system. These tools are usually applied to determine which circular strategy should be favoured, or whether the adoption of a circular strategy would increase the sustainability of an existing system. The circularity assessment tools are classified in two groups: assessment frameworks and assessment indicators. The first group are methods used to provide several indicators assessing different aspects of the circularity of a system (that can be adapted to a specific case), while the second group of tools give such assessment through one only indicator (e.g. the resource potential indicator). Both type of tools can provide burden-based indicators (e.g., CO_2 eq., kg mineral resources, or MJ eq. fossil fuels), and/or value based indicators, i.e. measured on economic or temporal units (e.g. € or years), and based on the economic value added or the extended utility of the analysed system.

3.2.1. CE assessment frameworks

The reviewed CE assessment frameworks are constructed based on three "backbone" methodologies: namely: *LCA, MFA and Input Output analysis*. An overview of the reviewed case studies applying assessment frameworks is provided in Table 2.

3.2.1.1. Life cycle assessment. LCA is a tool to assess the environmental impacts of product or services along the entire life cycle. The concept was first proposed in the 60′s, and has been standardised by ISO 14040- 14044 (ISO, 2006a, b), the ILCD (International Reference Life Cycle Data System) handbook and PEF (Product Environmental Footprint) by the Joint Research Center (JRC) (Wolf et al., 2010; Zampori and Pant, 2019). There is a wide range of environmental impact categories suitable to be analysed by LCA, from resources (fossil fuels, minerals, land and water), to ecosystem services (e.g. eutrophication, acidification and ecotoxicities) and human health (human toxicities, particulate matters).

LCA is one of the tools mostly applied to quantify and evaluate the benefits/impacts of CE strategies, and/or to choose between different circular strategies. This review found 18 case studies using LCA to explicitly assess circular products or strategies, including studies on food products, waste management systems, consumers products such as microwaves and washing machines, industrial sectors, and materials such as paper, concrete, steel, etc. Additionally, this review found three case studies applying circularity ad-hoc indicators developed from the LCA methodology (see Section 3.2.2).

For decades, LCA has been used to assess the environmental impacts of different end-of-life (EoL) alternatives for products and services (Villanueva and Wenzel, 2007; Laurent et al., 2014; Cooper and Gutowski, 2017). The use of LCA to evaluate circular strategies is driven by the holistic methodology and the accumulated experience on EoL assessments. An EoL activity is by nature a multioutput processes when combined with valorisation or recycling processes: it delivers the waste

Table 2
Summary of the reviewed circularity assessment frameworks (Env = Environment, Eco = Economy, Soc = Society).

Framework	Env.	Eco.	Soc.	Unit	Case studies	Set of indicators/categories used[a]
Life Cycle Assessment (LCA)	x	x	x	Impacts (e.g. kg CO_2 eq/functional unit)	Aluminum cans (Niero and Olsen, 2016; Niero et al., 2017)	ILCD method
					Concrete with glass waste (Deschamps et al., 2018)	Impact 2002 method
					Insulation materials (Nasir et al., 2017)	IPCC 100a method
					Cellulose nanofibers (Delgado-Aguilar et al., 2015)	ILCD method
					Used tires (Lonca et al., 2018)	ReCiPe endpoint method
					Municipal solid waste (Tomic and Schneider, 2017)	Primary energy return based index
					Norwegian WtE sector (Lausselet et al., 2017)	Climate change, human toxicity, eutrophication, ozone depletion (ILCD)
					Organic waste management (Cobo et al., 2018)	Carbon footprint through ReCiPe method
					Green and food waste (Oldfield et al., 2018)	CML midpoint method (only climate change, acidification and eutrophication)
					Greywater management (Dominguez et al., 2018)	Environmental Sustainability Assessment (ESA) method
					Electric/ electronic waste (Rigamonti et al., 2017)	ILCD method
					Italian tannery cluster (Daddi et al., 2017)	ILCD method
					Microwave oven (de Almeida et al., 2017)	Cumulative Exergy Demand (RIPEx)
					Washing machines (Lieder et al., 2017)	GHG emissions + life cycle costs
					Second hand shop products (Castellani et al., 2015)	ILCD + Cumulative Energy Demand
					Food waste (Cristobal et al., 2018)	ILCD method
					Pork value chain (Noya et al., 2017)	ReCiPe Midpoint
					Tidal energy device (Walker et al., 2018)	Carbon footprint
Material Flow Analysis	x	x		Mass flows (eg. Kg iron)	The global economy (Haas et al., 2015)	Circularity degree, Processed material per capita, Stock growth, Biodegradable flows and Throughput
					China's highway traffic system (Wen and Li, 2010)	Direct Material Input, Domestic Processed Output, Resource consumption and Pollutant emissions
					Printed circuit boards within an industrial district (Wen and Meng, 2015)	Resource productivity (RP)
					Global demand of metals (Wang et al., 2018)	Per capita metal use stock, Total resource efficiency and recycling rates
					Reuse of technology components (Busch et al., 2017)	Material In-use stock, primary material demand reduction and EoL outflows
					Swiss waste management system (Haupt et al., 2017)	Closed and open-loop collection and recycling rates
					Pulverized fly ash (Iacovidou et al., 2017b)	Complex Value Optimization for Resource Recovery Evaluation (CVORR)
Input Output	x	x	x	Impacts (e.g kg CO_2, MJ energy demand, t of waste)	Waste of nations worldwide (Tisserant et al., 2017)	National solid waste footprint
					Guiyang city (Fang et al., 2017)	Carbon footprint
					Circular strategies at a European and UK level (S. J. G. Cooper et al., 2017)	Energy savings (through primary energy extraction and exergy dissipation)
					Circular strategies for ferrous sulphate and waste cooking oil	GHG, virgin resource use, recovered waste

[a] Most of the LCA are conducted following different impact evaluation methods that include multiple indicators representing up to 16 different impact categories. These are: ILCD (EC-JRC, 2011), CML (Leiden University, 2015), ReCiPe (Goedkoop et al., 2009), IMPACT 2002 (Jolliet et al., 2003).

Table 3
Summary of the reviewed circularity assessment indicators (Env = Environment, Eco = Economy, Soc = Society).

Indicator	Source/Developer	Unit	Env.	Eco.	Soc.	Case studies
Reuse Potential Indicator (RPI)	(Park and Chertow, 2014)	Potential material reuse	x	x		Coal combustion by-products
Value-based Resource efficiency (VRE)	(Di Maio et al., 2017)	Money (value added)	x	x		40 Dutch economic sectors
Longevity indicator	(Franklin-Johnson et al., 2016)	Time (months)	x	x		Precious metals in mobile devices
Sustainable circular index	(Azevedo et al., 2017)	Weighted score (multidimensional)	x	x	x	Untested
Eco-efficiency index (EEI)	(Laso et al., 2018a)	Money (value added and environmental impacts)	x	x		Canned anchovies
Circular Performance indicator (CPI)	(Huysman et al., 2017)	Ratio of environmental benefits	x			Post-industrial plastic waste
Eco-efficient Value Ratio (EVR)	(Scheepens et al., 2016)	Ratio of environmental burden to economic value	x	x		Water recreation park
Global Resource Indicator (GRI)	(Adibi et al., 2017)	Mass (kg Fe-eq/functional unit)	x			Wind turbines
Circularity degree	(Haas et al., 2015)	% Recycled materials	X			The global economy

management of a product, and also creates recycled products. This situation is generally considered as a modelling problem, since the burdens and credits created by the EoL activity need to be allocated amongst the different provided products.[3] The ISO standards recommend a hierarchy procedure to account for this multifunctionality.[4] But the procedure is not sufficiently detailed in open-loop recycling processes, where the analysed product is recycled into a different product which has a different function and life cycle. This has been a well-known methodological issue in LCA. The allocation of environmental impacts (burdens) or benefits (credits) between primary and secondary/recycled products are often modelled based on the following groups of approaches, which are depicted in Fig. 2:

a) The *100:0 approach, or cut-off approach*, assumes that the recycled product is made from waste that does not have any economic value. Therefore, the recycled product uses a burden-free feedstock, and the burdens of the recycling activities are allocated to the recycled product. The primary (or previous) product does not get any credit or burden from recycling. This approach is easy to apply and straightforward to communicate because it naturally follows the technical and business boundaries.
b) In the *0:100 approach, or EoL recycling approach*, the recycled product does not get any credit. Such credits, plus the burdens of recycling, are allocated to the producer of the recycled material (primary product). It is commonly assumed in this approach that the primary product (that gets recycled) should get credit for avoiding future primary production, in a so-called substitution approach. Such credits equal the amount of virgin production that is avoided due to the use of the recycled product.
c) The *50:50 approach* where the burdens and credits from recycling are shared equally between the primary and recycled or recovered products. Variations of this approach relate to the extent to which the life cycle activities are shared between the primary and recycled product. For instance, the PEF recommendation builds on the 50:50 approach, by equally sharing the burdens and credits of the virgin primary production (cradle), the recycling process, and the final disposal (grave), amongst the different products of the cascade system (Allacker et al., 2017; European Commission, 2013). The PEF EoL formula also includes a quality correction factor to address the consequences of downcycling, typically based on economic values, but also on other relevant underlying physical relationships. This method is comprehensive and especially suited for use in product policy support applications (Allacker et al., 2014).

The approach most typically applied to deal with open-loops in the reviewed 18 CE LCA case studies is the *0:100 approach* with *substitution* (61% of the case studies), followed by the *100:0* or *cut-off approach* (17%). One study applied the PEF formula for EoL situations, and the rest of studies either did not mention the applied method, or allocation was not required. One study applied both the *cut-off* and the *system expansion* approaches to evaluate green and food waste treatments (Oldfield et al., 2018). The authors concluded that when evaluating waste valorisation strategies, impacts from the primary production must be considered in the secondary product (no cut-off approach), and the quality of the recycled product should be integrated in the evaluation of the primary product. Otherwise, the focus of the assessment can be placed in the amount of waste processed (the more the better), instead of in the quality of the recovered material, which is key for the CE.

3.2.1.2. Material flow analysis. MFA takes into account the state and changes of each material flow of a system, by the calculation of mass balances over time within a defined space. This tool was first applied to cities metabolisms and pollutants research in specific regions in the 70's, and has been widely applied in many other field over the last decades (Brunner and Rechberger, 2016). Flows are measured in terms of their mass which gives information of the amount of materials used, but not about the quality of the material (e.g. downcycled plastic) or the scarcity of the material. The main challenges inherent to MFA studies are data uncertainty and information availability. Nevertheless, due to its flexibility and simplicity, it can be applied at every analysis level – macro, meso and micro.

This literature review found 7 case studies where the circularity of different economies or products was assessed through MFA or MFA derived indicators/frameworks. We can distinguish two main working approaches for understanding the circular use of resources: material flow accounting and material flow modelling. MFA accounting tracks

[3] The problem could be avoided by enlarging the system boundaries, and combinedly assess every product of the cascade system (e.g. by calculating the integrated total impact of the products in the system). This would be the preferred option as indicated by the ISO hierarchy (system expansion). However, usually the goal of the study requires a differentiation of impacts between the products in the system.

[4] The hierarchy for dealing with multifunctionality processes defined by the ISO standards (ISO, 2006a): (1) subdivision of activities for each by-product/function whenever possible, (2) system expansion to include in the boundaries all the products generated by the activities involved in the life cycle, or (3) partitioning of inputs and outputs based on physical or economic properties.

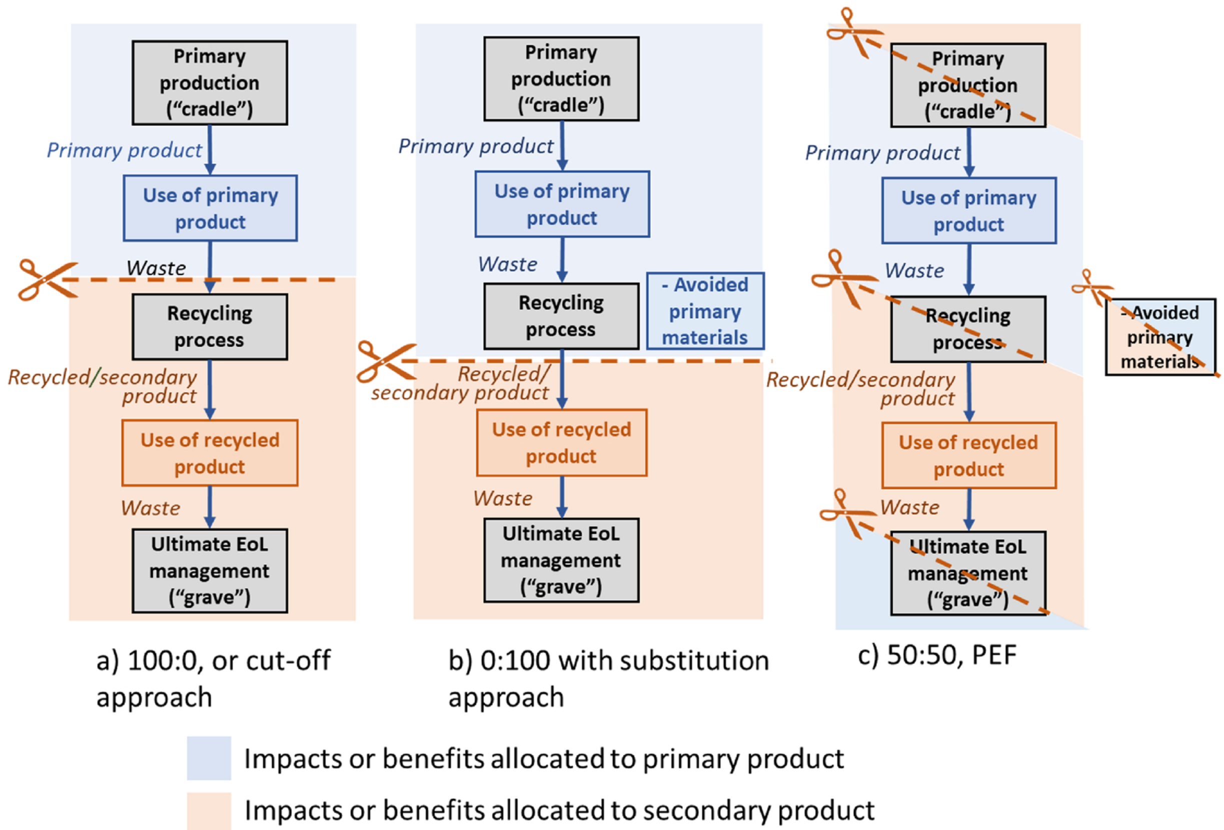

Fig. 2. Common approaches to allocate impacts and credits in LCA between first and next cycles, based on reviewed literature (schematic simplification).

all sources of the materials entering, being stored or leaving the system, to identify patterns and comparisons among systems. MFA modelling supports the understanding of the full dynamics of a given system, allowing for forecasting.

Four case studies used MFA accounting to assess the circularity of systems. Wen and Li (2010), studied the total material flows corresponding to the Chinese highway traffic system. The authors suggest the (reduction of) overall waste per unit output as a metric for future studies. Haupt et al. (2017) studied the Swiss waste management system in 2012 focusing on increasing the resource efficiency, and suggesting the recycling rate (and not collection rate) as a circular indicator. Still, the authors suggest the need of further indicators to properly address environmental impacts. Wang et al. (2018) also considered material circularity as the EoL recycling rate of materials. The authors studied the material flows within the anthropogenic cycle of 55 metallic elements from 1900 to 2013, highlighting that a 100% circular process is impossible to achieve, due to unavoidable leakages. Finally, Wen and Meng (2015) chose the resource productivity (RP) indicator to evaluate the CE performance of industrial parks. The indicator is calculated by dividing the industrial added value of enterprises by the direct material inputs used in the production of printed circuit boards. The authors found that industrial symbiosis practices result in higher RP values, reflecting a better (re)use of resources, and supporting the development of a CE.

Among the MFA modelling studies, Haas et al. (2015) estimated the material flows of the global economy for year 2005. They defined the circularity degree as the share of actually recycled materials out of total processed materials. The circularity degree is provided with another four: processed material (PM) size per capita (t/cap), stock growth (% net stock additions out of PM), biodegradable flows (biomass % of PM) and throughput (% domestic product output. Another study used dynamic MFA to assess the implications of recycling and reuse strategies within the electricity generation and transport systems on the Isle of Wight (Busch et al., 2017). The study focuses on material efficiency using recycling and reuse rate as indicators. Their results indicated a decrease in material use for both recycling and reusing strategies. The authors acknowledge that accounting for other environmental, economic and social impacts is desirable, and therefore, advocate for an increased cooperation among MFA and sustainability practitioners. A third case study developed a framework to assess the optimal circularity degree for different systems (Iacovidou et al., 2017). This framework, titled Complex Value Optimization for Resource Recovery Evaluation (CVORR), consists of three phases: i) system synthesis (where the system is defined), ii) system analysis (where the modelling occurs) and iii) system refinement (where decision analysis of outputs occurs). The first two phases are rooted on material flow analysis. The third phase encompasses a reflection process where the outputs of the model are evaluated. In this phase, multicriteria analysis is used to support decision making processes. This framework was used by Millward-Hopkins et al. (2018) as part of an integrated assessment for resource recovery systems.

3.2.1.3. Input output analysis. IO analysis was developed to describe and analyse the economic interdependence between the different sectors within a regional, national or international economy. The IO analysis framework has been often extended to analyse the environmental and socio-economic impacts associated with the activities of such sectors (Leontief, 1970). Due to the top-down approach of the tool, it has been also applied by the LCA community as a way to compensate for the shortcomings of process-based LCA (e.g. avoiding cut-off criteria that leaves out of the analysis minor processes, and expanding the scope from the product level to the national/global level) (Corona et al., 2016). Waste IO models, as developed by e.g. Nakamura and Kondo (2009) are especially interesting in the context of the CE, since they contain the economic and physical exchanges between different economic sectors, together with the generated waste types and waste treatments. IO analysis has been also integrated with process-based LCA, creating the hybrid IO-LCA methodology. Such approach increases the complexity of the methodology, but brings together the best modelling practices of both methodologies. This review found four studies applying different variations of the IO framework to evaluate the sustainability of CE strategies in national and international regions. Cooper et al. (2017) analysed the effect of applying different CE strategies on the energy savings in the supply chain of G&S, at a European level and at a UK national level. They used complementary energy and exergy metrics (energy extraction and energy dissipation) and a multiregional supply-use table to estimate the energy saved by the CE strategies at a macro scale (including direct economic rebound effects). Tisserant et al. (2017) developed a harmonized IO multiregional solid waste account for 48 world regions in the year 2007, and used it to quantify the solid waste footprint of national consumption (measured in tonnes of waste generation per capita), at a global level. Fang et al. (2017) used a hybrid IO-LCA model to analyse the carbon footprint of Guiyang city (China), while (Genovese et al., 2017) used hybrid IO-LCA to assess the performance of circular strategies in the ferrous sulphate and waste cooking oil supply chains.

3.2.2. CE assessment indicators

As described in Table 3, this literature review found four stand-alone CE assessment indicators, four CE assessment indicators derived from the LCA methodology, and one indicator derived from the MFA framework (see the MFA section for more details).

The *longevity indicator* is a non-monetary, value based approach to measure the length of time that a material is retained in a product system (Franklin-Johnson et al., 2016). The indicator is calculated by considering the initial lifetime of the material/product and the durability gained due to reuse and recycling. The decrease of quality in the recycled materials is not addressed by the indicator (100% of quality is assumed). In products with materials presenting different durability, their longevity should be aggregated following an unspecified weighting procedure.

The *resource potential indicator (RPI)* is a measure of the intrinsic value for reuse that a material has, taking into account the technological availability for recycling such material (Park and Chertow, 2014). It is calculated considering the average share of the material that can be economically recovered at a macro level considering the currently available technologies for recycling.

The *value based resource efficiency (VRE)* indicator was developed by Di Maio et al. (2017), who defined circularity as "the percentage of the value of stressed resources incorporated in a service or product that is returned after its end-of-life." (Di Maio et al., 2017, p. 163). Di Maio et al. (2017) assume that the market value of stressed resources can represent both the material scarcity (market driven) and the social and environmental externalities (in the form of taxes) created by a system. The VRE is thus calculated considering the value added produced by a system, divided by the weighted sum of the used resources in such system (in volume), using the resources market prices as weights.

The *sustainable circular index (SCI)* is a composite indicator representing the degree of sustainability and circularity of a company or organization (Azevedo et al., 2017). The indicator is developed considering four different dimensions: economic, social, environmental, and circularity. By this approach, the developers are separating the concept of circularity from that of sustainability, understanding circularity as the degree of material circulation. The developers suggest a list of indicators for each dimension (based on ISO 14031 and the Global Reporting Initiative), that are normalized using the minimum-maximum method (Zhou et al., 2006), weighted using the Delphi method (Chan et al., 2001) and aggregated based on simple additive weighting.

3.2.2.1. LCA-derived assessment indicators. The *Eco-Efficient Value Ratio (EVR)* (Scheepens et al., 2016) and the *Eco-efficiency index (EEI)* (Laso et al., 2018b) rely on monetization techniques to develop an indicator that integrates both environmental and economic criteria. In both indicators, focus is placed on an increase of value added that would render benefits to both the producers and the consumers, under the assumption that such indicator also represents the value that consumers are willing to pay for such a service. Additionally, higher prices would prevent rebound effects, since consumers would not have more money available to buy additional products. Their main difference lies in the format and methods to develop the indicator. The *EEI* is composed by the sum of the value added and the life cycle single score environmental impact from the ReCiPe method. In the *EEI*, the environmental impacts (damages) are estimated in physical units, and the monetization takes place as a final weighted step considering the preferences of the stakeholders. In turn, the *EVR* indicator represents the ratio of environmental burden to the value added of the analysed product (Scheepens et al., 2016). It uses marginal prevention costs (based on Best Available Technologies in Europe) to monetize environmental externalities.

The *Global Resource Indicator (GRI)* developed by Adibi et al. (2017) is a new midpoint characterization indicator to assess the impacts of resource use in LCA. It is based on the scarcity, geopolitical availability and recyclability of resources. The scarcity is represented by the extraction rates and the available reserves of each resource in the earth crust, and is derived from the CML characterization factors. The geopolitical availability is represented by the homogeneity of distribution of natural reserves. If a resource is abundant but concentrated in a few countries, the geopolitical stability of such countries becomes important. The recyclability is calculated by considering the recycling rate of the resource (the share of an element in discard that is recycled) and the dispersion rate (the share of resources lost into the environment that cannot be recovered).

The *Circular Performance Indicator (CPI)* was developed by Huysman et al. (2017) and is defined as the ratio of the environmental benefit obtained from a waste treatment option over the ideal environmental benefit that could be achieved according to the material quality. These environmental benefits relate to the reduced consumption of natural resources, and are represented by the Cumulative Exergy Extraction from the Natural Environment (CEENE). The calculation of the CPI relies on predefined quality factors for the analysed materials (e.g. high quality for recycled materials that can substitute virgin materials).

4. Discussion and evaluation of circularity metrics

Table 4 contains the evaluation of the metrics described in Section 3, considering the validity requirements described in Section 2.2. As described in the table, none of the current circularity metrics are addressing all the predefined requirements. Most of the CE measurement indices and single assessment indicators are measuring progress in only a few of the defined goals, and none of them fulfil the requirements regarding *emissions levels*, *employment, and socio-economic improvements* measurement (except for the LCA-derived assessment indicators). This narrow scope of the circularity metrics is a shortcoming, since metrics that exclusively measure progress in a few CE goals could lead to burden shifting. For instance, a circular strategy may increase resource recirculation at the expense of additional environmental burden elsewhere, as reported by several case studies, e.g. on organic waste treatment (Cobo et al. (2018) and concrete recycling (Cullen, 2017). Circular strategies may also increase circularity by exporting materials for recycling in places with low environmental and health standards, increasing social impacts somewhere else (Iacovidou et al., 2017b).

CE assessment frameworks are more suitable to cover multiple CE goals and avoid burden shifting, although they are more complex to apply and interpret. Still, none of the reviewed frameworks were used to evaluate progress in every CE goal. Although some assessment frameworks could be expanded to cover several sustainability dimensions under the same scope (e.g. LCA and Input Output), few case studies actually did it. For instance, LCA can be expanded to LCC (life cycle costing) and S-LCA (social LCA) to provide a socio-economic evaluation (UNEP-SETAC Life Cycle Initiative, 2009; Zamagni et al., 2013; Hunkeler et al., 2008), however, only two studies implemented LCC and no studies looked at social life cycle impacts. Among the assessment frameworks, LCA is the most suitable, since it is able to cover all the

Table 4
Evaluation of the reviewed circularity metrics according to the defined requirements in Box 1 (P = Partially considered, X = Fully considered, *Considered when expanded).

	TOOL	Methodology source	1. Resources	2. Emissions	3. Material waste	4. Ren./recycl. share	5. Durability & utility	6. Jobs	7. Value added	8. Social wellbeing
Measuring	Product-level circularity metric	(Linder et al., 2017)	P			P			P	
	Circ(T) or Cumulative Service Index	(Pauliuk et al., 2017)			X	P	X			
	Material Circularity Indicator (MCI)	(EMF, 2015)	P		X	P	X			
	Circularity index	(Cullen, 2017)			X					
	Global circularity metric	(De Wit et al., 2018)	P			P				
	Circular Economy Indicator Prototype (CEIP)	(Cayzer et al., 2017)	P		P	P				
	Circular Economic Value (CEV)	(Fogarassy et al., 2017)	P		X	X				
Assessing	Reuse Potential Indicator (RPI)	(Park and Chertow, 2014)	P		X					
	Value-based Resource efficiency (VRE)	(Di Maio et al., 2017)	X						X	
	Longevity indicator	(Franklin-Johnson et al., 2016)	P				X			
	Sustainable Circular Index (SCI)	(Azevedo et al., 2017)	P			P	X	X	P	P
	Life Cycle Assessment (LCA)	(ISO, 2006a)	X	X	X	X	X	*	*	*
	LCA- Circular Performance Indicator (CPI)	(Huysman et al., 2017)	P		X		P			
	LCA- Eco-efficiency index (EEI)	(Laso et al., 2018b)	X	X	X	P	X	X		
	LCA- Eco-efficient Value Ratio (EVR)	(Scheepens et al., 2016)	X	X	X	P	X	X		
	LCA- Global resource indicator (GRI)	(Adibi et al., 2017)	X		X	P	X			
	Material Flow Analysis	(Haupt et al., 2017), (Busch et al., 2017)	P		X	X			*	
	Input Output analysis	(Leontief, 1970)	P	X	X			*	X	

X = The metric fulfils the goal; P = The metric partially fulfils the goal; * = The metric can be extended to also fulfil the goal.

requirements when applied at a product/service level. Within the context of CE, MFA is used to evaluate the performance of recycling and reuse practices. MFA is more suited than LCA or I/O methods to examine different scenarios over long periods of time. However, it does not consider the environmental or social impacts related to the system. IO analyses are suitable to evaluate CE strategies at an inter/national level, however, they are not so appropriate to analyse strategies at a product level, since most of the IO models lack from detailed and disaggregated information for each technology and unit process. They are also based on static accounts for a determined year, therefore, innovative and up-to-date technologies, often used in the CE, may not be well represented.

4.1. Evaluation of circularity metrics and recommendations

This section contains the detailed evaluation of the circularity metrics against the CE requirements defined in Section 2.2. Recommendations on how to fulfil each requirement are also provided.

4.1.1. Resource use and scarcity evaluation

All CE measuring indices and assessment indicators focus on measuring the amount of natural resources used by the systems, but most of them fall short to integrate scarcity or criticality of such resources, and therefore, are partially suited to fulfil the requirement *resource use and scarcity*.

Both the *Product-level circularity metric* and the *VRE* argue for economic values (costs in the first case, and market value in the second) as indicators for the scarcity of resources, and as an optimum way to measure and aggregate the use of different resources in a single value. However, social and environmental externalities are currently not fully integrated in the form of taxes or costs for most of the materials and products, and therefore, these indicators fail to actually represent the scarcity, emission levels, or socio-economic impacts of the assessed systems.

Studies based on MFA achieve the measurement of *resource use*, but fail to measure to what extent the analysed system increased the stress of the resource's natural reserves, i.e. the scarcity of the resource. The LCA framework and derived indicators are more appropriate to measure the scarcity of resources, since it is a parameter typically included in resource depletion evaluation methods. The LCA-based *GRI* indicator is specially aimed at fulfilling the *natural resources and scarcity* requirement. The advantage of the *GRI* over the traditional LCA resources indicator lays on the inclusion of geopolitical availability and potential recyclability of resources into the calculations.

4.1.2. Recycled content and recycling rates

One of the main challenges in measuring the circularity of products and services is related to the allocation of impacts between the initial cycles of products (or materials) and their subsequent recycled or recovered cycles. This issue links with the "open-loop recycling" problem described within the LCA methodology in Section 3.2.1. In cases where the materials are recycled into the same products/functions, these credits are translated into reduced virgin material use (i.e. in a closed loop). However, when materials are recycled into new products/functions (e.g. open-loop recycling), the reviewed metrics have different approaches to allocate the credits between the recycler and the user of recycled materials, and to account for the decrease of quality (downcycling).

The general tendency in the reviewed metrics is to give credits to the products that are being recycled, i.e. the *0:100 approach* with substitution. However, some metrics give credits to the products using the recycled material (i.e. the 100:00 or cut-off approach), and in many cases, the approach is not clear or specified. The circularity index *Circ(T)*, and the assessment indicators *longevity indicator* and *RPI,* assign the benefits of recycling to the product/material being recycled, following a closed loop approach. In those metrics, the question of how to allocate impacts/benefits in open-loops remains unanswered. The *VRE* (which can be applied to both sectors/regions and products) does not clearly specify how inputs and value added would be quantified for cascade systems with products involved in open loops. The *MCI* choses to consider both the upstream recycled content and the downstream recycled materials in a *50:50 approach,* independently of open-loop or closed-loop recycling. The *new product-level circularity metric gives* credits to the products using the recycled/reused material, independently of the loop characteristics (following a *cut-off approach*). In such case, products would be preferable if they are using recycled/reused content, no matter whether they are designed to be recycled, or reused. The CEIP is not based on value or impacts, and therefore does not need to allocate between products and functions (the product scores better when using recycled content and also when recovering materials at the EoL). The SCI, circularity index and CEV are not based on products (but organizations, materials and events), and therefore do not specify how to deal with the allocation problem.

The LCA practitioners have been dealing with this problem for many years, and propose different approaches to deal with open loop recycling, as explained in the LCA section. The choice of one or another approach is a hot topic in both the industry and the academic sectors. For instance, the steel industry advocates for the *0:100 with substitution approach*, where the recycling of steel avoids future primary production, and such credits are assigned to the product being recycled (Broadbent, 2016). Their main arguments relate to: (1) rewarding the product being recycled induces a zero waste policy, where products are designed to be recycled and not wasted, and (2) there is a continuous demand of scrap, and therefore, secondary materials will be always used (there is no need to reward its use in new products). However, for other products whose secondary materials still do not have a stable and increasing market (e.g. most plastics materials), rewarding the use of recycled content would be more appropriate than rewarding the recycling of materials that do not clearly substitute virgin materials. The middle-ground proposal by the EC PEF method (50:50 approach) could be the solution, but it has been also criticised by some industries under the argument of not sufficiently rewarding recycling (Schrijvers et al., 2016). However, there seems to be a general trend against cut-off approaches for open loop recycling in CE metrics. A cut-off approach assumes that waste is going to be recycled/reused without accounting for further burdens, which does not properly represent the consequences of waste generation (Ilic et al., 2018) and the quality of the recoverable material.

Downcycling of materials should be approached by including a quality correction factor in the secondary material. However, most of the reviewed metrics fail to include such quality corrections. Nevertheless, some authors recognize its relevance and consider it as a future step (e.g the developers of the *GRI*). Only the LCA derived indicator *CPI* (Huysman et al., 2017) and the Circ(T) circularity index explicitly include quality factors (high quality for secondary materials that can directly substitute high quality virgin materials).

The inclusion of quality factors is specially challenging in open loops (e.g. plastic bottles recycled into park benches). Some authors argue that we should prioritize closed loop recycling, where secondary materials are used to fulfil the same function as in the first cycle (Graedel et al., 2011). However, the production of high quality secondary materials could also generate higher environmental impacts (or consume higher volume of critical resources) than the downcycling of such material. In such contexts, the burdens of recycling activities and the benefits of replacing alternative materials should be jointly evaluated to determine if an open loop recycling is preferable to a closed loop recycling (Haupt et al., 2017). Such comparison would only be allowed by a comprehensive assessment metric able to measure both the resource use and the environmental impacts produced (e.g. *LCA*).

4.1.3. Emissions levels and renewable resource share

Only LCA derived indicators were able to measure the goal of decreased emission levels, since most of the LCA evaluation methods include impact categories related to polluting emissions. Additionally, IO analysis also allowed to estimate GHG emissions with a top-down approach.

Even though all the circularity indicators give a measure of the recycling activities involved in the system, most of them fall short to measure the increased renewable share in materials. For instance, the

MCI, *product-level circularity metric* and the *Circ(T)* are only measuring the technical cycles (abiotic resources), while CEIP only accounts if there is use of renewable energies. Even though the *global circularity metric* does account for renewable resources, it aggregates all types of resources together independently of their use or their renewable/fossil nature, hindering the interpretation and value of the metric (e.g. fuels and biomass are accounted as input, but they are used for energy, which is mostly dissipated and therefore cannot be recirculated). Better practices are found in some MFA studies, where other side indicators related to biodegradable flows are jointly used to provide a more comprehensive assessment (Haas et al., 2015).

None of the reviewed LCA studies included an evaluation of the *renewable share of materials* in their results; although it could be assessed through the Cumulative Energy Demand evaluation method (Goedkoop et al., 2008).

4.1.4. Longevity and utility

Both the *Circ(T)* and the *MCI* measuring indices include the *increased utility* of materials/products by combining the mass of materials with their temporal duration. Additionally, the *longevity indicator* (CE assessment indicator) has the main focus of evaluating for how long materials are kept before disposal, and therefore, the indicator is mainly focused in the CE goal of increased durability. However, measuring the increased utility in time duration instead of in utility duration (times used) could lead to erroneous conclusions in such products where increased lifetime is not linked with increased use of the material or product. For instance, there is no benefit on keeping a discarded smartphone in a drawer at home instead of disposing it for material recovery. Therefore, it is recommended to measure utility in the number of times that a product or service is provided instead of the length of time that the product or service can be provided.

For those metrics based on the LCA framework, the *durability and utility* of products can be indirectly assessed through the use of the functional unit and the associated reference flows, which are calculated by considering the lifetime of the product and the estimated number of uses during such lifetime. With such calculations, the methodology gives preference to those products that can be used for longer, or more precisely, more times (utility). All the impacts in LCA should be provided per functional unit, and therefore, the length and intensity of use is generally quantified in the assessment.

4.1.5. Economic value added, employment and social improvements

The requirements regarding economic and social value added have received less attention than the environmental ones. There are few circularity indices and assessment indicators that integrate in their metrics the economic value added of products or services (through the economic conception of value added as gross output minus intermediate inputs). The *EEI*, *VRE* and *EVR* assessment indicators give preference to products that maximise the value added while minimising the material consumption or the generated environmental impacts, which builds on the concept of eco-efficiency. When MFA is combined with the resource productivity indicator (as a measure of the monetary yield per unit resource), results also provide economic information about the value added of the product/system. Social metrics, in contrast, are practically absent in the reviewed CE metrics, even though many authors highlight the necessity of including the assessment of social aspects (Banaitė, 2016; Geng et al., 2012; Iacovidou et al., 2017b; Pauliuk, 2018; Veleva et al., 2017). Some assessment indicators derived from the S-LCA framework have been proposed, (e.g. by (EMF, 2016; Pauliuk, 2018), but the incipient nature of S-LCA is an impediment for its wider use.

None of the CE metrics explicitly consider consumer behaviour dynamics in their evaluations. Such dynamics are especially relevant for consumer products, since their circularity level is highly influenced by the consumer's choice – or access to – the appropriate end-of-life treatments. Only Haas et al. (2015) touched upon consumer responsibility awareness, pointing to the need of a decrease – or at least stagnation – of the consumption rate.

4.1.6. Measuring CE progress in sectors, regions and national economies

Several authors claim that the macro-level CE metrics are overall best developed than the micro-level CE metrics (Ghisellini et al., 2016; Cayzer et al., 2017). However, many of the metrics currently used in CE national monitoring frameworks were not originally developed or tailored for measuring CE. For example, key CE indicators used by EU countries and China have important shortcomings, such as recycling rates that only measure the amount of material sent for recycling, instead of the material value produced by the recycling process (Di Maio and Rem, 2015).

Macro-economic progress is traditionally measured with a mix of descriptive, efficiency and performance indicators (EASAC, 2016; European Commission, 2018b; EEA, 2016). These include burden-based assessment indicators measured in impact units or physical flows, and/or value-based indicators measured in monetary terms. Based on previous European monitoring frameworks for resource efficiency (EURES), the EASEC suggests measuring CE indicators in terms of three different layers: (1) using thematic indicators for measuring system change towards CE, such as market, technological and social indicators, (2) creating a dashboard of assessment indicators able to measure macro-level environmental burdens (with e.g. MFA), and (3) selecting a lead performance indicator, such as GDP divided by domestic material consumption (DMC). The European Environment Agency (EEA) monitoring system also follows such structure.

Groups of thematic indicators are often at the basis of monitoring frameworks, as many of these are designed to help policy-makers assessing CE system developments at a macro-level. For example, the French government introduced different indicators under the theme 'CE market development': number of industrial and territorial ecology projects, household spending on product repair and maintenance, employment generated in CE activities, and mass of recycled raw materials in production processes. Several frameworks also mention innovation and technological advance as important indicators of CE development, measured in number of patents related to recycling processes and secondary materials (European Commission, 2018b) or publications (Potting and Hanemaaijer, 2018).

At the level of eco-industrial parks (EIPs) or economic sectors, CE is measured with the help of assessment tools and indicators based on MFA, IO or micro-level environmental metrics. For example, Geng et al. (2014) proposes emergy analysis as an MFA extension based on thermodynamics and systems theory, which can potentially also be adapted to measure product supply chains. Unlike most other indicators based on material flows, it indicates the quality of input flows, thereby considering the CE key principle of a hierarchy of resource reuse options. Pilouk & Kootatep propose a three-tiered index for assessing EIPs performance (green, gold, platinum). The platinum level adds social indicators (e.g. happiness of the surrounding community) to the list of eco-efficiency and waste management indicators.

At the macro level, new lead indicators proposed at the level of cities, regions, and nations, relate material consumption, wastes or impacts, to monetary terms. These efficiency indicators combine classic economic metrics with either environmental sciences metrics – e.g. 'water consumption per GDP' – or with material flow indicators – e.g. GDP in relation to abiotic domestic material intensity. These recent advances can be seen as important step in developing more valid measurement and assessment tools at a macro level. The reviews by Elia et al. (2017) and Iacovidou et al. (2017a, b) suggest that some assessment indicators based on established assessment frameworks have potential to be extended to measure CE at meso and macro-level, for example the LCA-derived assessment indicator *CPI* (Section 3.2.2), or the MFA model from Haas et al. (2015). However, constructing integrated monitoring and macro-level frameworks on measuring CE development at different levels constitutes one of the main challenges. For example, the EEA (2016) identified a lack of compatibility among material flow indicators and waste indicators, and commissioned further research to increase the compatibility for CE monitoring frameworks.

Consequently, Eurostat was commissioned to explore the possibilities for linking waste data to material flow data EEA (2016). The systemic integration among measurement dimensions (levels) and methods as introduced in this paper, currently forms a fundamental limitation on CE measurement and monitoring at the level of national and global economies. Still, macro-economic frameworks clearly comply better with the CE requirements defined in this review, as they typically suggest to combine several assessment tools and metrics, whereby they naturally tend to include social, economic and environmental indicators in a more balanced way.

5. Conclusions

The CE is expected to be the optimal pathway to sustainable development. Even though the focus of most circular strategies is to increase the material circularity of a system, such circularity should be simultaneously sustainable for the environment, economy and society. For that reason, this review evaluated current circularity metrics by considering eight CE validity requirements anchored in the sustainable development concept. When evaluating all the reviewed circularity metrics against such requirements, we found that none of the current circularity metrics are addressing all of them. One of the main reasons is the diverse understanding of the CE concept, which in some cases is reduced to a mere material recirculation. Such an approach could be useful when aimed at information purposes (e.g. to what extent are materials recirculated), but due to its narrow scope, should not be used as the sole indicator supporting sustainable decision making, or to claim sustainability superiority. Additionally, circularity metrics based only on the material recirculation degree are not suitable to measure the absolute decrease on resources use (which should be a priority in CE), and may be masking a burden shift towards increased energy consumption or polluting emissions. However, material circularity degrees are easier to apply and communicate to the public, and are playing an important role in increasing public awareness about CE. Nevertheless, there are some assessment frameworks, such as LCA (and derived indicators) that have shown high potential in addressing all the goals of the CE at the product and service levels.

Based on the literature review, LCA was found to be the most used framework to assess circular strategies. The question still remains on how to translate results at a product or service level (e.g. LCA indicators on different product categories), to a regional or global level. When measuring the progress of the CE at a macro level, main impediments are related to data availability and incompatibility, as well as system complexity, which leads to rebound effects hard to identify and measure. As Korhonen et al. (2018) point out, gains on one scale can be losses at another scale of the system, and aggregating results at different scales may risk double counting and overstate effects. Additionally, this review did not address the reliability and utility of the reviewed metrics, which should be assessed in the future, together with the ability of the metrics to represent the systemic nature of the CE.

In short, the major challenges of current circularity metrics relate to (1) difficulties in measuring the CE goals in all the sustainability dimensions, (2) evaluating the scarcity of used materials, and (2) underrepresenting the complexities of multiple cycles (multifunctionality) and the consequences of material downcycling. This review found that most of the metrics are still far to be able to represent the benefits of different waste valorisation options. Even mature tools such as LCA, that have been developing for decades, have still not consensually solved how to model the complexity of open-loop recycling. Encountered good practices include the combination of system expansion approaches with 50:50 approaches where benefits are shared between the recyclers and the users of recycled materials.

Finally, a good circularity metric, aiming to measure the contribution of circular strategies to sustainable development, should be comprehensive enough to avoid burden shifting from reduced material consumption to increased environmental, economic or social impacts. Such metric should clearly indicate how the benefits of recycling are allocated to the recyclers and the users of recycled materials, and should measure the increased value through increased product utility and economic value added measurements. It is also recommended that future methodologic developments build on current sustainability assessment frameworks such as LCA or MFA, instead of developing completely new metrics where complex EoL modelling will take a long route to be consensually and standardly addressed.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.resconrec.2019.104498.

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